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Bi-Level Demand-Sensitive LED Street Lighting Systems

ESTCP Project EW-201017

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14. ABSTRACT – This report documents a solid-state lighting technology demonstration at the Naval Surface Warfare Center (NSWC), Carderock Division in West Bethesda, MD where light-emitting diode (LED) luminaires were substituted for existing High Pressure Sodium (HPS) street lighting units, and an intelligent lighting control system was deployed to allow additional energy savings. The demonstration results show average electricity savings of 74% with the conversion of HPS to the demonstrated LED street lighting system. The annual electricity savings of the LED as compared to its HPS counterparts were recorded at 11,060 kWh, which can be translated to avoided CO2 emission savings of 16,081 lbs during the same period. The new LED-based system is expected to pay back its investment within 6 years with the adjusted internal rate of return of 9.77%. Staff at the Naval Surface Warfare Center (NSWC), Carderock Division, reported high satisfaction with the light quality and operation of the newly installed LED street lighting system.

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Acronyms

AIRR	:	Adjusted internal rate of return
BLCC	:	Building life-cycle cost
CALiPER	:	Commercially Available LED Product Evaluation and Reporting
CCT	:	Correlated color temperature
CRI	:	Color rendering index
DOD	:	Department of Defense
DOE	:	Department of Energy
fc	:	Footcandle
HERF	:	Hazards of Electromagnetic Radiation to Fuel
HERO	:	Hazards of Electromagnetic Radiation to Ordnance
HERP	:	Hazards of Electromagnetic Radiation to Personnel
HID	:	High intensity discharge
HPS	:	High-pressure sodium
IENSA	:	Illuminating Engineering Society of North America
L_{ave}	:	Average luminance (footcandle)
L_{min}	:	Minimum luminance (footcandle)
L_{max}	:	Maximum luminance (footcandle)
LED	:	Light Emitting Diode
MV	:	Mercury vapor
MH	:	Metal halide
NEMA	:	National Electrical Manufacturers Association
NIST	:	National Institute of Standards and Technology
NPV	:	Net present value
NSWC	:	Naval Surface Warfare Center
PIR	:	Passive InfraRed
SIR	:	Savings to investment ratio
SPAWAR	:	Space and Naval Warfare

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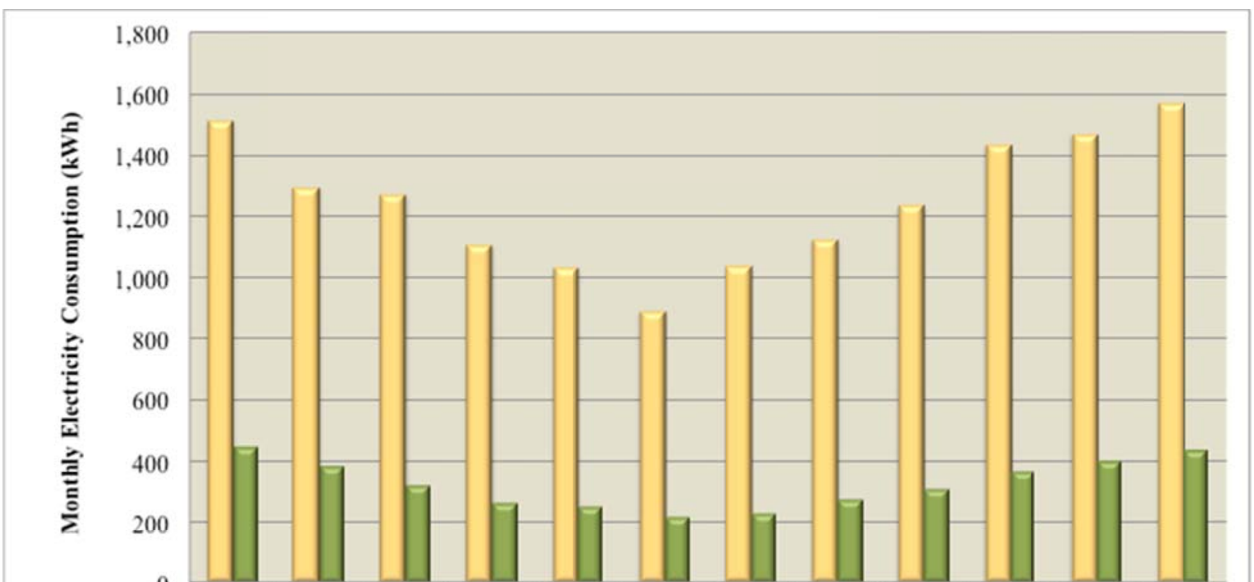
Lastly, the team would like to thank Mr. Michael Barbe and colleagues in Building A for taking time out of their busy schedule and providing us escort and access to the electric room during our monthly system checks.

Executive Summary

This report documents a solid-state lighting technology demonstration with a demand-sensitive feature at the Naval Surface Warfare Center (NSWC), Carderock Division in West Bethesda, MD – in which light-emitting diode (LED) luminaires were substituted for existing High Pressure Sodium (HPS) street lighting units. This project was supported by the U.S. Department of Defense under the Environmental Security Technology Certification Program (ESTCP).

During the course of the project, Virginia Tech and Old Dominion University, working in collaboration with Echelon Corp., developed, deployed and evaluated operational performance of a smart bi-level demand-sensitive LED lighting system for outdoor street lighting applications that allows dimming as well traffic sensing capability through a centralized controller. The existing eight (8) units of HPS lamps were monitored for one year to capture their electrical energy consumption and operational performance, including illumination level and color rendition index. The set of LED lamps, together with their sensing and control unit, were then installed; and post-installation monitoring was performed during the subsequent year.

Results indicate a significant reduction in energy usage at about 74% electricity savings with the conversion of HPS to the demonstrated LED street lighting system. This is shown in Fig. 1, where monthly electricity consumption (kWh) of the HPS and LED street lighting systems during the monitoring period are compared. The data were recorded during a series of monitoring periods between January and December 2011 for the HPS system, and between January and December 2012 for the new LED system.

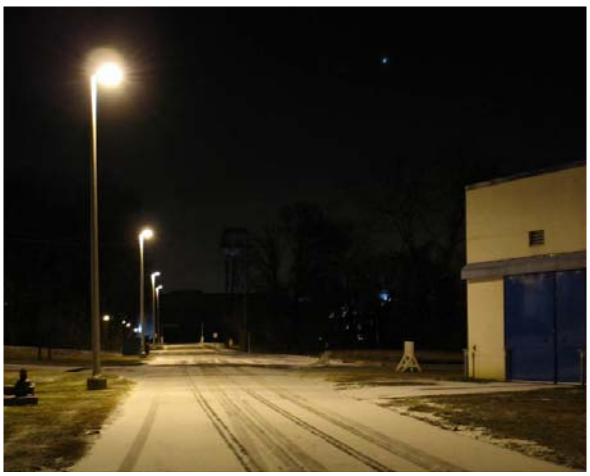


	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
HPS (2011)	1,514	1,290	1,270	1,103	1,030	890	1,034	1,119	1,232	1,431	1,468	1,572
LED (2012)	444	385	319	264	253	218	232	275	309	364	397	433

Fig. 1. Monthly electricity consumption (kWh) of the HPS and LED systems

The annual electricity savings of the LED as compared to its HPS counterparts were recorded at 11,060 kWh, which can be translated to avoided CO_2 emission of 16,081 lbs during the same period. The new LED-based system is expected to pay back its investment within 6 years with the savings-to-investment (SIR) ratio of 2.15 and the adjusted internal rate of return (AIRR) of 9.77%.

Feedback from individuals at the Naval Surface Warfare Center (NSWC), Carderock Division, indicates a high level of user satisfaction with the light quality and operation of the newly installed LED street lighting system. Users also experienced a significantly better light quality (see Fig. 2) and a 100% reduction in mercury waste disposal requirements. The system is also 100% available and reliable without any failure since its installation.



Existing High Pressure Sodium (HPS) Lamps

Newly Installed LED Street Lighting System

Fig. 2. Light quality comparison

Overall, the project has successfully demonstrated how existing street lighting units can be made more efficient using the current state-of-the-art technologies and prudent engineering in the design and operation of the lighting control systems. The outcome of this project also includes best practices and field experience that can help with the full-scale implementation in other DoD facilities around the U.S. The project is expected to lead to significant cost and energy savings, as well as contribute to reduce carbon dioxide emissions for DoD.

1.0 Introduction

This project entitled "bi-level demand-sensitive LED street lighting systems" was initiated in May 2010. The objective was to replace a set of streetlights at the Naval Surface Warfare Center (NSWC) - Carderock Division in West Bethesda, MD with a more energy efficient and intelligent street lighting system. This project demonstrated how existing street lighting units can be made more efficient using the current state-of-the-art technologies and prudent engineering in the design and operation of the lighting control systems. This report includes description of the demonstrated technology, assessment of the performance and cost of the demonstrated system, as well as field experience data that can help full-scale implementation to replicate this hardware/software deployment experience in other DoD facilities around the U.S.

1.1 Background

In a typical DoD facility, outdoor lighting is used to provide for the safety of nighttime traffic operations for pedestrian pathways, roadways, parking lots, storage centers, housing, and areas around the base perimeter. Three major lamp types are common for outdoor lighting applications. These are high intensity discharge (HID), fluorescent, and incandescent. HID lamps are the most prevalent technologies being used for street lighting applications due to their high lumen output. The most common HID lamps are mercury vapor (MV), metal halide (MH) and high-pressure sodium (HPS). Of these three types, HPS and MH are predominant. MH lamps offer superior color quality with a bright white light output, while most HPS lamps offer greater efficiency at the expense of color rendition index with amber light.

Almost all streetlights and parking lot lights being deployed today at many DoD installations are not dimmable. Adding the dimming feature when the full light intensity is not needed and allowing the light to increase its intensity during the presence of foot/vehicle traffic can result in significant savings in electricity use, thus saving money and reducing the bases' carbon footprint.

The Light Emitting Diode (LED) is emerging as the most energy efficient technology for lighting applications. At the start of this project in early 2010, there were several ongoing pilot projects on LED lighting. These pilot projects mainly focus on replacing existing streetlighting units with a more energy efficient LED streetlighting system. As an example, the U.S. DOE has established the Commercially Available LED Product Evaluation and Reporting (CALiPER) Program [1] to support the testing of a wide array of solid-state lighting products available for general illumination. In addition, the U.S. DOE also showcases these high-performance LED products through the GATEWAY demonstration program [2]. Table 1 summarizes selected LED pilot projects for outdoor streetlights and parking lots supported by the DOE's GATEWAY program.

Table 1. Selected LED pilot projects participated in the DOE's GATEWAY [3]

Locations	Nature of project	Project initiation	No. of Units	Features
Washington, D.C. [4]	Parking structure lighting	Spring 2011	19	Occupancy sensors
Washington, D.C. [5]	Underground parking garage	Fall 2011	19	Occupancy sensors
Philadelphia, PA [6]	Roadway lighting	Spring 2011	Multiple	N/A
New York City, NY [7]	Walkways	Spring 2012	1,500	N/A

Findings from these projects indicated that the potential for energy savings of energy efficient LED-based streetlights is as much as 50% compared with that of the traditional high-pressure sodium lamps. The savings are even more when LEDs are compared with metal halide lamps.

When compared to its HID counterpart, LED can be dimmed without any impact on its life and color output [8, 9]. Thus, some projects also explored dimmable features of LEDs with occupancy sensors for parking garages. Among these DOE's GATEWAY projects, the parking garage project in Washington, D.C., showed greater savings than other projects, as these LEDs can be dimmed. A similar project includes dimmable LED implementation at the parking lot of the University of California Davis [10]. There are a few more LED streetlight demonstration projects in Ann Arbor, Michigan [11] and San Jose, CA [12].

Toward the end of this project in 2013, LED lighting systems have become more commonly accepted and selected municipalities have already upgraded their streetlighting systems to LED, such as in Arlington, VA. The highlight of this work, which is the integration of demand-sensitive features onto the intelligent control of LED streetlighting systems, has yet to be realized commercially. With the LED technology becoming a more common practice, it will help in project transition into large-scale deployments.

1.2 Objective of the Demonstration

The objective of this demonstration project was to deploy an energy efficient LED street lighting system with an intelligent controller as a retrofit to an existing system at the Naval Surface Warfare Center (NSWC) - Carderock Division in West Bethesda, MD.

Specifically, the objectives of this demonstration were:

(a) To provide a technology demonstration to validate the performance and expected operational costs and benefits of the bi-level demand-sensitive LED street lighting systems for energy efficiency as described above;

(b) To get the technology ready to be transferred by working with the Carderock Division Headquarters to evaluate technology acceptance, seek feedback, and provide appropriate guidance to assist in full-scale deployment;

(c) To provide field experience data and an energy efficiency streetlight model that can be replicable in other DoD installations around the U.S. The findings and guidelines to be developed are expected to support and facilitate regulatory and end-user acceptance as well.

1.3 Regulatory Drivers

There are many policies, regulations, executive orders, and legislative mandates that serve as drivers for implementing this new technology for energy conservation. The most significant drivers of energy efficiency in the DOD and other Federal buildings are [13]:

- The Energy Policy Act of 2005
- Federal Leadership in High Performance and Sustainable Buildings. Memorandum of Understanding of 2006
- Executive Order 13423 Strengthening Federal Environmental, Energy, and Transportation Management of 2007
- The Energy Independence and Security Act of 2007
- Army Energy Security Implementation Strategy of 2009
- Executive Order Executive Order 13514—Federal Leadership in Environmental, Energy and Economic Performance of 2009
- Unified Facilities Criteria (UFC) 3-400-01 Energy Conservation, with changes of 2008.

2.0 Technology Description

This section describes an overview of the demonstrated technology, and summarizes its advantages and limitations.

2.1 Technology Overview

The demonstrated technology is a smart bi-level demand-sensitive LED lighting system for outdoor street lighting applications that allows dimming as well as traffic sensing capability through a centralized controller. The highlights of the demonstrated system include the following characteristics:

- The use of LED light fixtures for energy saving, better light quality, and infrastructure savings
- The integration of streetlight controllers to enable bi-level and demand-sensitive features
- The integration of traffic sensors for detecting moving traffic
- The use of a smart server to perform light control

The building blocks of the demonstrated system include: (1) LED light fixtures, (2) streetlight controller, (3) traffic/photocell sensors, and (4) a smart server, as shown in Fig. 3.

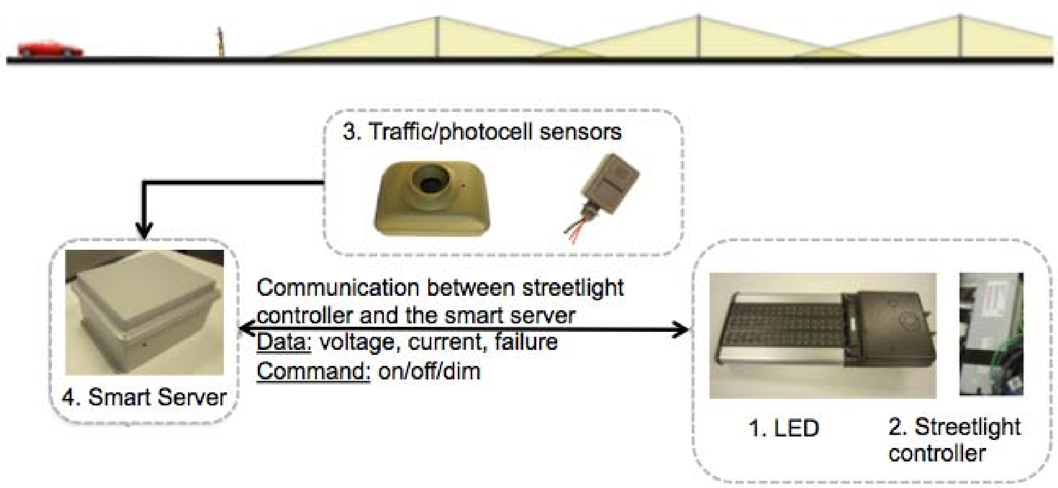


Fig. 3. Technology overview

The system is designed such that all LEDs are turned ON after the sunset (with a photocell sensor), and its light intensity is dimmed in two stages (80% intensity from 9pm to 11pm and 60% intensity from 11pm to 4am) to allow additional energy savings. As soon as foot/vehicle traffic is detected, the light intensity is set back to 100% for about five minutes. All LEDs are turned OFF simultaneously at sunrise.

One photocell sensor is used to detect sunset and sunrise times. It provides inputs to the smart server to allow controlling all LEDs to be ON after sunset and OFF after sunrise. Several traffic sensors are used to allow detecting foot and vehicle traffic at the demonstration site. These sensors provide input to the smart servers to allow turning up the light intensity of the LED units when foot/vehicle traffic is detected.

Each building block of the demonstrated system is explained in greater details below.

Building Block 1: LEDs

Light Emitting Diode (LED) is an electronic light source based on the semiconductor diode that has been commonly used in electronic circuits for decades. Compared with their HID counterparts, LEDs can deliver comparable luminous efficacy, have longer life, provide better light quality and have instantaneous responses [14]. In addition, LEDs contain no mercury in lamps. Note that, in terms of luminous efficacy, although several commercially available LEDs are currently not at the efficacy level of their HID counterparts, latest research indicates that LED sources are continually improving in this regards and are expected that they will achieve higher level of luminous efficacy performance in the future.

Recently, induction lighting has become a light source of interest for many applications. Similar to LED, induction lighting lamps deliver high energy efficacy (lumen/watt), high color rendering index (CRI) of greater than 80. Manufacturers claim an operating life of more than 60,000 hours, but this claim is yet to be proven. There are, however, some disadvantages to induction lighting: (1) as the shape of the lamp is large, it requires special housing which can be a challenge for retrofit applications; (2) due to their slow response at low temperatures such lamps may not have instantaneous response resulting in longer restrike times after being shut off; and (3) the induction lighting has mercury in lamps, unlike LEDs which are mercury-free. The mercury content in induction lighting raises disposal issues. For these reasons, LEDs have been chosen as the preferred technology for this demonstration project.

Characteristics of various light sources, including LED, HID and induction lighting, are summarized in Table 2.

Table 2. Characteristics of various light sources

	LED	HID			Induction lighting
		High Pressure Sodium (HPS)	Metal Halide (MH)	Mercury Vapor (MV)	
Efficacy (lm/W)	70-150	50-130	65-115	24-60	70-100+
Color rendering index (CRI, %)	85-95	20-25	65-90	40-50	80-85
Life (hours)	50,000-100,000	7,500-24,000+	5,000-20,000+	12,000-24,000+	60,000-100,000
Warm-up time	Instantaneous	3-4 min	2-5 min	5-7 mins	Instantaneous with 75-80% output
Re-strike time	Instantaneous	0.5-1 min	10-20 min	3-6 mins	Instantaneous
Mercury (mg)	0	10-50 mg	10-1000 mg	10-1000 mg	In solid form

Selection of an appropriate LED luminaire for the project was a significant undertaking. The process involved identifying potential luminaire suppliers that offered products, which were suitable for the lighting application. Suitability requirements included:

- Output which would meet minimum required lighting levels
- Capability for reduced power (dimmed) operation
- Control system interface capability
- Aesthetic compatibility with other lighting on the site

After significant research it was determined that three manufacturers had products that would meet most or all of the requirements listed above - Beta Lighting, Hubbell Lighting and Lithonia Lighting. Since these products were relatively new to the marketplace at the time of project initiation, there were significant performance differences between the different LED luminaires. To aid in the luminaire selection process, several products from each of the above listed manufacturers were evaluated by performing simulations to predict the lighting (illumination) performance that could be expected based upon the configuration of the test site. Results of this study are presented in Appendix C.

After considering the various LED luminaire options, the decision was made by NSWC Carderock Division that "cobra-head" style roadway luminaires should be employed. The unit selected is manufactured by Beta Lighting, Inc. – model #STR-LWY-2M-HT. This luminaire utilizes 90 LEDs with a drive current of 525mA in the full output state and 350mA in the reduced output (dimmed) state. A second potential supplier, Hubbell Lighting Inc., was contacted concerning the availability of an aesthetically equivalent luminaire, however they were unable to offer a unit that would meet that requirement.

The specification of the selected LED luminaires for the demonstration is summarized in Fig. 4.

Mfr.:	BetaLED
Model:	STR-LWY-2M-HT-09-D-UL-BZ-DIM5-R
Description:	Streetlight, LEDway, Type II Medium optics, Horizontal Tenon, 90 LEDs, Series D, Universal 120-277V, Bronze, Dimmer Option, Nema Photocell Receptacle.
Quantity:	Eight (8)

Fig. 4. Specifications of the LED luminaires selected for the demonstration

Building Block 2: Streetlight Controllers

A streetlight controller acts as an interface between the LED light fixture and the smart server (to be discussed under Building Block 3). This building block allows polling information, such as failures, alarms, voltage, current, power, energy and number of burning hours, from the streetlights. Furthermore, this device also allows the smart server to send switch on/off and dimming commands to control the light fixtures. Each streetlight controller has a built-in filter for power line carrier (PLC) for lighting control that ensures clear signals received/transmitted within the lighting system, as well as communication module that can communicate directly with the smart server.

The streetlight controller selected for the project is from Echelon, model number: CPD3000, as summarized in Fig. 5. One streetlight controller is required for each LED luminaire.

Mfr.:	Echelon
Model:	CPD3000
Description:	Outdoor lighting controller (OLC). Interfaces with the light fixture enabling its control and operation (On/OFF and Dimming).
Quantity:	Eight (8)

Fig. 5. Specifications of the outdoor streetlight controller (OLC) selected for the demonstration

Building Block 3: Traffic/Photocell Sensors

Traffic sensors are placed on the roadway of interest to allow detection of moving traffic (both foot and vehicle traffic). In general, the vehicles' headlights allow visibility only about 350 feet ahead [15]. Turning up the streetlight intensity once the vehicle is at least 350 ft ahead of the first light pole helps improve the visibility beyond that provides by the headlights.

Traffic sensors selected for the demonstration is the Dakota Alert system, which comprises a receiver (DCR-2500) and a set of passive infrared (PIR) motion transmitters (DCMT-2500). Their specifications are shown in Fig. 6. The project also requires an event counter (Dent Instruments TOUC-3G), shown in Fig. 7, which is used to record on/off transitions of motion transmitters.

Mfr.:	Dakota Alert
Model:	DCR-2500 and DCMT-2500
Description:	4-channel wireless motion detector kit consisting of a remote station passive infrared (PIR) sensor and a base station receiver with four Form C relay and one 12Vdc outputs. RF 433.92 MHZ, Range 2500 ft.
Quantity:	One (1) receiver (DCR-2500) Four (4) PIR motion transmitters (DCMT-2500)

Fig. 6. Specifications of traffic sensors selected for the demonstration

Mfr.:	Dent Instruments
Model:	ContactLogger TOUC-3G
Description:	Event counter used to record on/off transitions of devices, in this case, the form C outputs of the motion detector
Quantity:	Four (4)

Fig. 7. Specifications of the traffic counter selected for the demonstration

Signals from a photocell are also needed to allow turning ON and OFF all LED luminaires during sunset and sunrise, respectively. The photocell EM-24A2 selected for the demonstration is shown in Fig. 8.

Mfr.:	Watt Stopper	
Model:	EM-24A2	
Description:	Low voltage photocell for controlling exterior lighting. Consists of a normally open relay contact that closes when ambient light level drops below a preset dark setpoint.	
Quantity:	One (1)	

Fig. 8. Specifications of the photocell selected for the demonstration

Building Block 4: Smart Server

The smart server is responsible for recording lamp status, energy use and running hours from the streetlight controllers; collecting data from traffic sensors; and controlling the light status (ON/OFF/dim). The smart server can be programmed such that during high foot traffic periods, i.e. evening hours, the light intensity can be left on at 100%, if necessary. During low foot traffic periods on the other hand, the light can be dimmed to a lower preset number. The light intensity can be increased to 100% level when foot/vehicle traffic is detected. This intensity gradually decreases after several (preset) minutes of inactivity.

The smart server selected for the demonstration is iLON SmartServer 72103R-440 from Echelon. See Fig. 9. To allow the SmartServer to receive data from LED luminaires and issue appropriate control signals, Bibaja's PLC277 power line coupler – shown in Fig. 10 – is used to provide coupling from 277V AC mains to allow power line communication between the Echelon's iLON SmartServer and outdoor lighting controllers (OLCs).

Mfr:	Echelon	
Model:	iLON SmartServer 72103R-440	
Description:	Programmable smart energy manager with built-in web server and streetlight segment control. Built-in LonWorks transceiver for power line coupling (PLC) with other controllers and devices.	
Quantity:	One (1)	

Fig. 9. Specifications of the smart server selected for the demonstration

Mfr:	Bibaja
Model:	PLC277-3PH
Description:	Signal coupler between the SmartServer and the outdoor lighting controllers (OLCs) over the 277 Volts power line. LonWorks compatible.
Quantity:	One (1)

Fig. 10. Specifications of the power line coupler selected for the demonstration

Each building block of this demonstration project is mature and commercially available today. For example, LED luminaires are available through a number of lighting manufacturers, e.g., BetaLED and Hubble. The outdoor lighting controller module and the SmartServer are also commercially available today as free-standing products from Echelon. PIR sensors, such as those from Dakota Alert, Inc., are also widely used for detecting foot/vehicle traffic. The new and innovation part of this research is the integration of these building blocks to provide a demand-sensitive and intelligent street lighting application that can deliver substantial energy savings and environmental benefits. While existing LED deployments may include dimmable parking lot lights with motion detection, the idea of sensing incoming foot and vehicle traffic to control a strip of streetlights is new and unique.

2.2 Technology Development

Overall technology integration is shown in Fig. 11. As shown, the outdoor light controller (OLC) is installed at the base of each light pole. An OLC is responsible for controlling the ON/OFF/dim status of an LED luminaire according to the command sent by the iLON SmartServer via a 2-way communication over the power line. The SmartServer also gets control inputs from traffic and photocell sensors via hardwire connections to control the status of each LED luminaire.

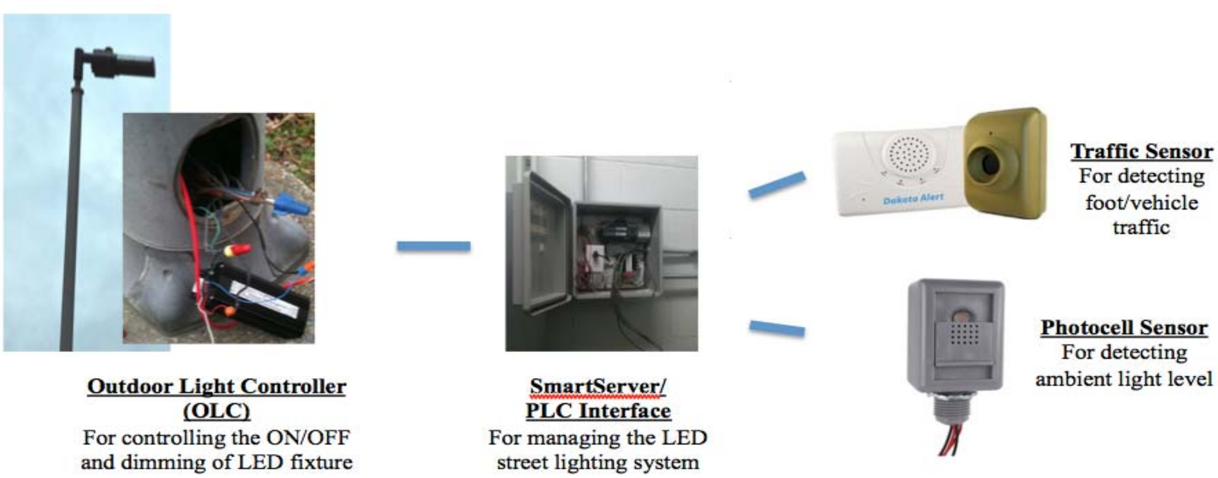


Fig. 11. Overall technology integration

The iLON SmartServer is the heart of the demonstrated street lighting system. It is a programmable device mostly used for managing, controlling and monitoring energy use. Its operation is based on freely programmable modules (FPMs) which are available for specific applications such street or building lighting control, HVAC, and building energy management, as well as for tasks such as process scheduling, alarming and data logging and analysis. The SmartServer is a network device with a built-in web server and communication interfaces such as Ethernet and RS232, which facilitates the control and management of devices connected to it from anywhere.

The iLON SmartServer utilizes a built-in transceiver based on the LonWorks protocol (ISO/IEC 14908-1 and 3) to communicate with controllers having similar transceivers. The SmartServer utilized in this project is the “PL edition” and has streetlight segment control applications and functions built-in to enable it interface with street light controllers (OLCs) embedded at the luminaires. It is coupled to the power line via a LonWorks-compatible coupler (Bibaja PLC277-3PH). In this case, the Echelon CPD3000 OLCs connected to the luminaires also have built-in LonWorks transceiver, which enables them to communicate with the SmartServer over the power line.

Although the SmartServer is capable of streetlight control by itself, for this project, the standard Echelon FPM used for streetlight segment control was modified to meet the requirements of the site. That is, to incorporate control signals from a photocell switch and motion sensors so as to determine the dusk to dawn operation envelope as well as the light level of the streetlights. Integration of the iLON SmartServer with the power line coupler and traffic/photocell sensors is illustrated in Fig. 12.

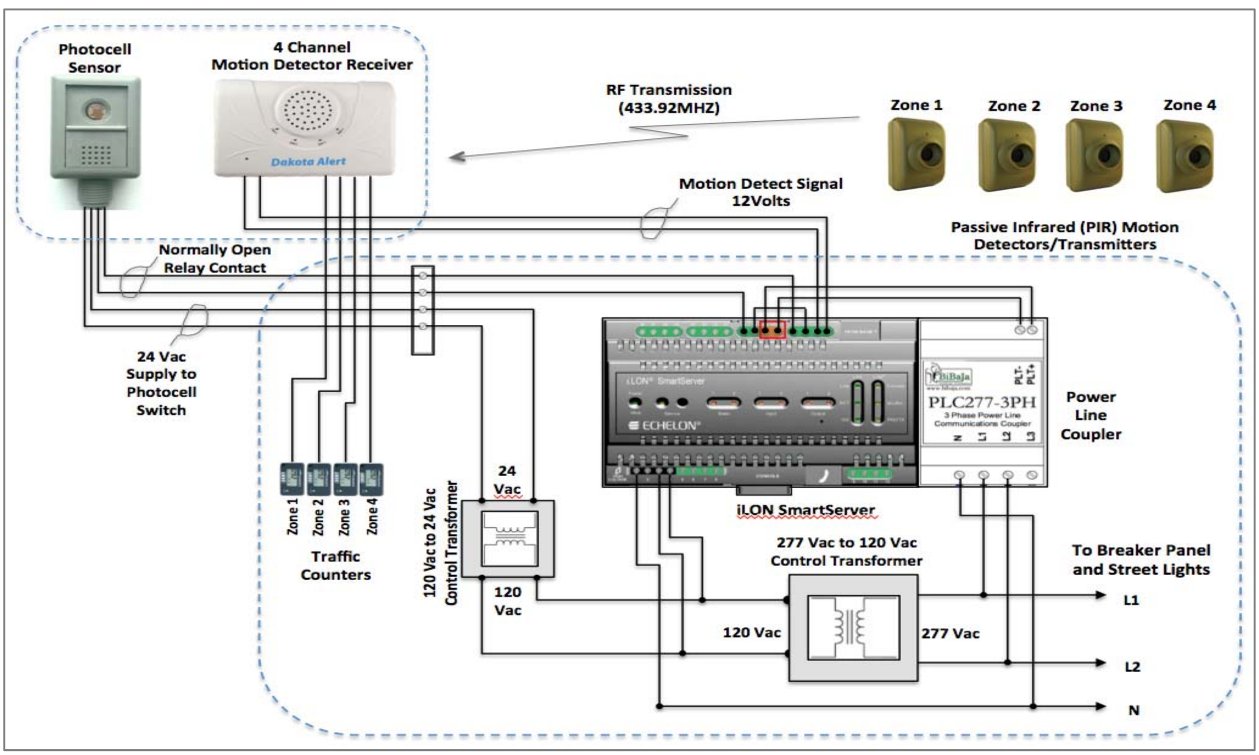


Fig. 12. Technology integration schematics

The iLON SmartServer (72103R-440) and the power line coupler (PLC277-3PH) are installed in a waterproof enclosure as shown in Fig. 13.

The SmartServer needs 120Vac power supply, which is obtained from a built-in 277Vac to 120Vac transformer. The power line coupler needs 270Vac power supply, which is fed directly from the street light circuit.

The SmartServer is configured to accept external digital input signals (via terminals 13-14 and 15-16) from the motion detector receiver (DCR-2500) and the photocell sensor (EM-24A2), which in this implementation is installed within the proximity of the enclosure to allow hardwire connection.

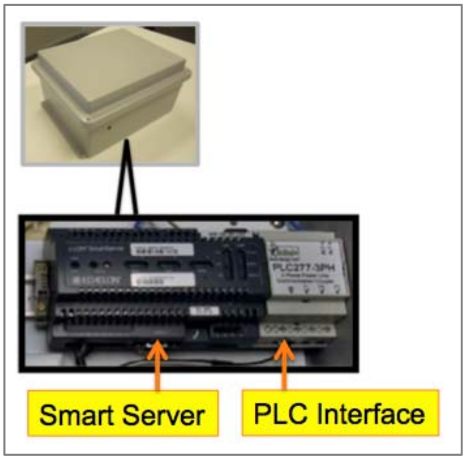


Fig. 13. SmartServer and PLC interface in a waterproof enclosure

The motion detector receiver (DCR-2500) unit is equipped with one 12Vdc output terminal as well as four Form C relays (one for each zone). Each Form C relay gets activated for a duration of 10 seconds when a motion detect signal is received from the associated PIR motion detectors (DCMT-2500) in the field through radio frequency (RF) transmission at 433.92MHz. Four such PIR motion detectors/transmitters are installed at four locations at the demonstration site to detect foot/vehicle traffic in four different zones. Traffic data of each zone are recorded separately by an associated traffic counter (TOUC-3G) dedicated for that zone. The 12Vdc signal generated by the motion detector base unit is then fed to a digital input (terminals 13-14) of the SmartServer, informing the SmartServer of the presence of foot/vehicle traffic. This in turn allows the SmartServer to turn up the light intensity of LED luminaires to 100% when such a triggering event is detected.

The photocell sensor (EM-24A2) is low voltage light sensor with a normally open (N/O) relay contacts as its output. Thus, the relay is open during daylight and closes when the ambient light gets dark. To convert the relay’s Open/Close status into a digital input, its contacts are connected in series to a low voltage DC source, thereby generating an ON/OFF signal by switching the voltage source. Such a voltage source is available on the SmartServer itself on terminals 19-20 which provides 12Vdc supply. The signal generated by switching the DC voltage at terminal 19-20 was then fed to one of the digital inputs (terminals 15-16) of the SmartServer. Overall, input signals from the photocell sensor inform the SmartServer of sunset/sunrise time, which in turn allows the SmartServer to turn ON all LED luminaires during the sunset and turn OFF all LED luminaires during the sunrise. The photocell sensor receives 24Vac supply from the enclosure box, which is derived by adding a 120Vac to 24Vac transformer.

Since the iLON SmartServer also has a built-in astronomical clock (which allows the SmartServer to know the exact sunset/sunrise times for particular locations), this feature is used to supplement photocell operation in case of photocell malfunction. This is as shown in Fig. 14 where the SmartServer is configured to accept inputs from the photocell from 45 minutes before the sun rises to 90 minutes after the sun rises; and from 90 minutes before the sun sets to 35 minutes after the sun sets. Outside these periods, the SmartServer is configured to ignore inputs from the photocell. Furthermore, if the photocell fails to detect sunrise/sunset during the specified periods, the SmartServer is configured to override the photocell input and it follows its built-in astronomical clock to switch ON/OFF all LED luminaires at dusk and dawn.

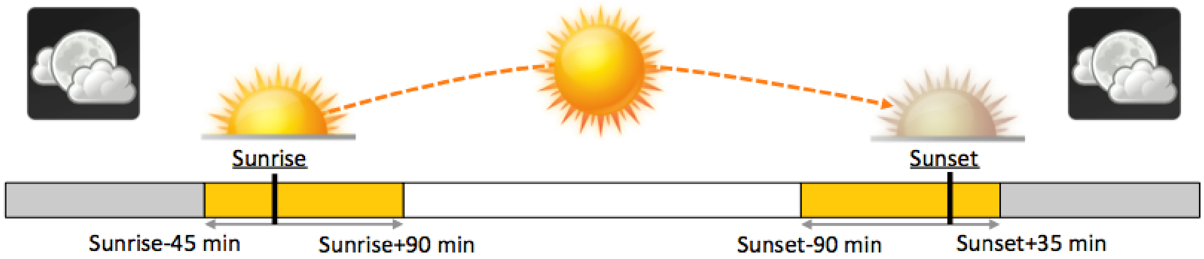


Fig. 14. Photocell operation

To design the operating schedule of LED luminaires, different illumination levels were tested against the recommended level of illumination requirements on roadways. Based on discussions with personnel at the base and their illumination requirements, the project team decided to dim LEDs to 80% of rated illumination level after 9 pm. This provided electricity savings with insignificant changes in their illumination output. As the foot/vehicle traffic at the demonstration site is almost negligible between 11pm and 4am, the project team set the LED illumination level at 60% during these hours to allow additional energy savings. The operation schedule and intensity of LED luminaires are summarized in Table 3.

Table 3. Operation schedule of LED luminaires at the demonstration site

	Standby	w/ the presence of foot/vehicle traffic
Sunrise – Sunset	OFF	OFF
Sunset – 9:00 PM	100%	100%
9PM – 11PM	80%	100%*
11PM – 4AM	60%	100%*
4AM – Sunrise	100%	100%

* Traffic counter = 5 minutes

As shown, the LED luminaires are set to OFF during the daytime, and ON after sunset. The LED luminaires are ON at 100% intensity when frequent foot/vehicle traffic is expected, i.e., between sunset and 9pm, and between 4am and sunrise. The luminaires are dimmed at 80% intensity after 9pm, and at 60% intensity after 11pm. The current setting is such that once foot/vehicle is detected, the SmartServer increases the light intensity of LED luminaires to 100% for 5 minutes. Then the light intensity is gradually decreased to its original illumination level before the detection of foot/vehicle traffic.

2.3 Advantages and Limitations of the Technology

By deploying the demonstrated technology, the issue of energy efficiency is addressed by the integration of *LED light fixtures* with a smart server for area light control, and *traffic sensors* for sensing traffic movements and adjusting lighting levels accordingly. Each light fixture has *a* *built-in streetlight controller* that allows the fixture to transmit its status information to *the SmartServer*.

In particular, the demonstrated LED street lighting system delivered the following advantages over the current technology being deployed at the Carderock Division Headquarters.

- *Superior luminous efficacy:* luminous efficacy is the ratio of luminous flux output (lumen) to power input (watts). It describes how well visible light is provided from a given amount of electricity. LEDs provide the best performance when compared with other traditional outdoor lighting technologies. For example, HPS lamps that consume 400 watts of power can deliver the equivalent luminous flux output to the LED lamps that consume about 150 watts of power.
- *Superior light quality:* LEDs deliver superior light quality with a high color-rendering index (CRI). CRI is a measurement of a light source's accuracy in rendering different colors based on a 0-100 scale. More natural color (i.e., blues are true blue, reds are true red, as if objects are under the sun) appears with higher CRI. In addition, the use of white lights dramatically improves sensitivity and image quality captured by security cameras as these cameras are more sensitive to the white light from LEDs.
- *Longer Life:* LEDs are expected to last longer than 50,000 operating hours and require no electronic ballast. This is in contrast to HPS bulbs, which have to be replaced every 3 years (approximately 10,000 operating hours), and their ballasts need to be replaced every 6 years. This implies that there is no maintenance costs associated with bulb replacements for at least 12 years assuming average 11 hrs/day operation.
- *Instantaneous response time:* While LEDs have instantaneous response time, it takes HID lamps some few minutes (2-7 minutes) during start up to achieve 90% of their full light output. After a lamp has been on for a period of time and then extinguished, it cannot be immediately turned back on. This period of time is called the re-strike time, which varies from 0.5-20 minutes for HID-type lamps. See Table 2.

  Reduction in waste disposal: All HIDs contain Mercury, while LEDs are mercury free. Mercury is a high level environmental pollutant and can lead to nerve damage.
- *Wider range of voltage input:* Voltage drop is a typical problem experienced at the end of a long power distribution line, especially in a streetlight circuit. To prevent voltage drop, the local electric utility typically delivers higher voltage at the sending end to compensate for the voltage drop. This requires a capacitor bank along the distribution line to boost the voltage. As the LED unit can accept wider input voltage range, i.e. 120-277Vac, than HPS (195-277Vac), this allows to accommodate more streetlight units with no capacitor banks. This unique feature, therefore, results in additional savings on electrical infrastructures for a newly constructed street lighting project.

The limitation of the demonstrated LED street lighting system is summarized below.

- *Initial costs:* The cost of LED light fixtures is still high. However, with the maturity of technology, the cost is dropping at a rapid rate and the luminous output is also increasing every year.

3.0 Performance Objectives

We designed, developed and deployed an energy efficient LED street lighting system as a retrofit to an existing system at the Naval Surface Warfare Center (NSWC) - Carderock Division in West Bethesda, MD. The demonstrated technology is based on light emitting diodes (LED) that allow dimming as well traffic sensing capability through a centralized controller. As the pilot demonstration, the project team replaced eight (8) high-pressure sodium (HPS) lamps at the demonstration site with the more energy efficient and demand sensitive LED street lighting systems.

The demand-sensitive LED technology was evaluated based on the criteria discussed in Sections 3.1-3.3.

3.1 Quantitative Performance Objectives

(a) Electricity consumption reduction

One of the key performance objectives for this demonstration project is to measure the reduction in electricity consumption. The metric for this performance objective is the annual electricity saving (kWh) from the street lighting load. Data requirements are the measurements of electricity consumption (watts, volts, amps) of the existing street lighting system and the new street lighting system. The success criterion is that the new street lighting system based on LED technology can deliver at least 50% or more electricity saving, compared to the existing HPS system.

(b) Carbon footprint reduction

Carbon footprint reduction is another performance objective of this demonstration project. The metric for this performance objective is the annual carbon footprint saving in lbs of CO_2. Data requirements are the measurements of electricity consumption (kWh) of the existing street lighting system and the new street lighting system to be installed. Once the electricity consumption data is obtained, the carbon footprint can be calculated by multiplying the electricity consumption (kWh) by the local CO_2 emission rate (lbs/kWh). The success criterion is that the new street lighting system based on LED technology can deliver at least 50% or more in carbon footprint reduction.

(c) Economic performance

Economic performance is another key performance objective of this demonstration project. The metrics for this objective include net present value (NPV), savings to investment ratio (SIR), payback period (year), and adjusted internal rate of return (AIRR). The National Institute of Standards and Technology (NIST) Building Life-Cycle Cost (BLCC) Program for MILCON Analysis is used to calculate the economic metrics.

Data requirements are the capital costs of the HPS and LED light fixtures ($) and associated control/monitoring infrastructure, the maintenance costs (man-hour or $/yr) of both HPS and LED street lighting units, electricity rate schedule for Carderock, MD ($/kWh), annual operating costs of the existing HPS and LED street lighting systems and the service life of both HPS and LED light fixtures (years or hours). Discount rates are available as default values in the NIST's BLCC program.

The success criteria are that (1) the new system provides lower NPV than the existing HPS system; (2) the new system delivers SIR of 1.5 or greater; (3) the new system delivers payback period of less than or equal to 7 years; and (4) the new system delivers AIRR of 5% or greater.

(d) Illumination performance

The metric for this performance objective is the illumination level in footcandle (fc) measured within the area covered by the lamp. Data requirements are the illumination measurements (fc) of the existing street lighting system and the new street lighting system. The new street lighting system must meet the recommended maintained luminance values as specified by the Illuminating Engineering Society of North America (IESNA) [17]. The minimum recommended maintained luminance values for collector roads in commercial environments is 0.8 fc.

(e) Color temperature performance

The metric for this performance objective is the color temperature measurement in °K within the area covered by the lamp. Data requirements are the color temperature measurements (°K) of the existing street lighting system and the new street lighting system. The success criterion is that the color temperature of the new system is at least 4000°K as compared to 1600-2100°K delivered by the existing HPS units.

(f) Mercury waste reduction

The LED-based light fixtures do not contain mercury. Therefore, they provided significant reduction in mercury waste. The metric for this performance objective is the amount of mercury in milligram (mg) saved by using the LED light fixtures instead of the existing HPS light fixtures. The mercury waste reduction can be determined by estimating the amount of mercury content (mg) in each of the existing HPS lamps, multiplying by the number of lamps being replaced during the project lifetime. The success criterion is that the new street lighting system based on LED technology delivers 100% reduction in mercury disposal requirements.

3.2 Qualitative Performance Objectives

(g) Qualitative satisfaction in terms of user acceptance

The qualitative performance objective is to measure end-use acceptance and light quality. The metric for this performance objective includes survey, feedback, and color photographs. A set of survey questions was distributed to evaluate user satisfaction and acceptance in light quality. In addition, the color photographs were taken to compare the light quality at the demonstration site before and after the installation. Success criteria include positive feedback and high level of user satisfaction with the new street lighting system.

3.3 Operational Performance Objectives

(h) System availability

One of the operational performance objectives is the system availability. The metric for this performance objective is the amount of time that the overall system is operational and ready to operate. The availability of the overall system can be derived from the availability of each component of the demonstrated system, including LED luminaires, their outdoor lighting controller (OLC), the SmartServer, traffic sensors and the photocell sensor. Data required is the system logs that record status of each component of the demonstrated system. The success criterion is that the system has at least 95% availability.

(i) System reliability

The other operational performance objective is the system reliability. The metric for this performance objective is the amount of time the system performs as designed. These conditions include:

- All LED luminaires are switched ON at sunset;
- All LED luminaires are switched OFF at sunrise;
- All LED luminaires are dimmed at pre-selected times;
- Selected LED luminaires increase their intensity to 100% when foot/vehicle traffic is detected; and their intensity is gradually decreased to the previous level after a pre-set time.

Data required are the system logs that record LED output performance and traffic detection. The success criterion is that the system delivers at least 95% reliability.

3.4 Performance Objectives and Results

Table 4 summarizes, for this demonstration project, methods of measuring and assessing performance and expected operational costs, as well as criteria for success for each performance objective described in Sections 3.1-3.3.

Table 4. Performance Objectives

Performance Objectives	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
(a) Reduction in electricity usage (kWh)	Energy savings from street lighting load (kWh)	Electrical measurements (watts, volts, amps) of old/new systems	>50% energy saving	~ 74% electricity savings
(b) Reduction in carbon footprint (lbs of CO_2)	Reduction in carbon emission (lbs of CO_2)	Electricity consumption (kWh); and CO_2 emission rate (lbs/kWh)	> 50% reduction in carbon footprint	~ 74% CO_2 emission reduction
(c) Lower cost of ownership over the lifetime	- Net present value (NPV) - Savings to investment ratio (SIR) - Payback period - Adjusted internal rate of return (AIRR)	Electricity consumption (kWh); electricity rate schedule ($/kWh); maintenance (man-hours or $/yr)	The new system is evaluated based on the following criteria: - $NPV_{LED} < NPV_{HPS}$ - SIR >= 1.5 - Payback <= 7 yrs - AIRR >= 5%	- NPV_{LED} ($27,291) < NPV_{HPS} ($35,959) - SIR = 2.15 - Payback = 6 yrs - AIRR = 9.77%
(d) Illumination levels	Illumination level	Illumination levels in footcandle (fc)	Average luminance >= 0.8 fc[1]	1.4 fc during full intensity; 0.86 fc during dimmed state
(e) Color temperature performance	Correlated color temperature (CCT)	Color temperature measurement (°K)	CCT >= 4000°K compared to existing CCT of 1600-2100°K	> 4000°K
(f) Reduction in mercury waste	Amount of mercury in milligram (mg)	Mercury content in existing lamps	100% reduction in mercury disposal requirements	100% reduction in mercury disposal requirements
Qualitative Performance Objective				
(g) User acceptance and light quality	Survey, feedback, photographs	Feedback from individuals, including level of security and comfort, light quality, retrofit ability; photographs before and after the installation	Positive feedback and high level of user satisfaction	Positive feedback and high level of user satisfaction
Operational Performance Objective				
(h) System availability	The amount of time the system is operational or ready to operate	System logs that record status of each component of the system	> 95% availability	100% availability
(i) System reliability	The amount of time the system performs as designed	System logs that record LED output performance and traffic detection	> 95% reliability	100% availability

[1] Minimum recommended maintained luminance values for collector roads in commercial environments is 0.8 fc.

4.0 Facility/Site Description

This section provides a concise summary of the Carderock Division Headquarters of NAVFAC Wash (NFW). This includes the site section process, site location and operations, site conditions, and site-related permits and regulations.

4.1 Site Selection

To identify potential demonstration sites, the Virginia Tech team contacted the DoD service liaison, *Mr. Paul Kistler*, P.E., C.E.M., Energy and Utilities Department at Naval Facilities Engineering Service Center, Port Hueneme, CA, during the proposal preparation phase. Mr. Kistler worked with the team to identify nine NAVY facilities, which showed interest to participate in our LED pilot project. These include: Carderock MD site of NAVFAC Wash (NFW), West Bethesda (MD), Washington Navy Yard, Indian Head Division Naval Surface Warfare Center (IHDIV, NSWC), Naval Surface Warfare Center Dahlgren Division (NSWCDD), Dahlgren, PAX river, NSA Oceana, Naval Station Norfolk (VA) and NAVFAC Midlant, Portsmouth (VA) Site.

After some initial phone calls and survey of existing lighting service on the base, the Virginia Tech team visited three sites and had detailed discussions with the sites' facilities engineers. These were: Carderock MD site of NAVFAC Wash (NFW), the Indian Head Division Naval Surface Warfare Center (IHDIV, NSWC) and Naval Surface Warfare Center Dahlgren Division (NSWCDD). After further discussions and evaluations of the existing electrical circuits for suitability for retrofit as well as convenience to monitor traffic and data collection, the Virginia Tech team approached Carderock MD site of NAVFAC Wash (NFW) for hosting this pilot project. They agreed to host this demonstration project.

The following observations and discussions refer to our visits to Carderock, MD site of NAVFAC Wash (NFW), Indian Head Division Naval Surface Warfare Center (IHDIV, NSWC) and Naval Surface Warfare Center Dahlgren Division (NSWCDD).

- *Lamp type:* While a majority of existing luminaires in Carderock is high-pressure sodium (HPS), metal halide (MH) is commonly used at Indian Head and Dahlgren. MH requires higher power consumption to deliver the equivalent luminaire when compared to HPS, but HPS requires higher maintenance as the ignition section tends to fail often.
- *Streetlight circuit configuration:* A typical streetlight circuit configuration, as appeared in Carderock and Dahlgren, is that a few streetlights are fed by a separate streetlight circuit, and this arrangement is repeated from one set to the next on the same street. Typical voltage levels of a streetlight circuit can be 277V or 480V. Streetlights in Indian Head, on the other hand, are fed directly by overhead distribution transformer. This is an old setup that exists in very few bases.

Out of the three sites we have visited, Carderock is our chosen demonstration site. The reason being that, firstly; the streetlight circuit in Carderock represents the most common streetlight circuit in majority of NAVY installations. Secondly, the existing HPS luminaire in Carderock is more energy efficient than the MH deployed at Indian Head or Dahlgren. As we demonstrated that LED light fixtures can provide better savings than the existing HPS units in Carderock, then the demonstrated LED light fixtures can definitely provider greater savings when compared with MH luminaires deployed elsewhere.

4.2 Facility/Site Location and Operations

The selected demonstration site is located at:

Location: Naval Surface Warfare Center, Carderock Division Headquarters

Address: 9500 MacArthur Blvd., West Bethesda, MD 20817.

The Carderock Division Headquarters is a large research and development facility that carries out full spectrum testing, evaluation, engineering and support tasks for the Navy's fleet of ships, subs and vehicles.

Fig. 15. Location of the NSWC Carderock Division Headquarters

The facility has, since 2003, initiated and implemented a number of energy consumption reduction measures including refurbishing cooling towers, installing energy efficient lighting in buildings, and upgrading control and operation of HVAC systems throughout the compound, earning it an award from the Department of Energy (DoE) Federal Energy Management Program. This demonstration project complements the facility's building energy efficiency improvement measures by extending it to the outside, i.e., street lighting.

The selected demonstration site is on Bill Morgan Road of the Carderock Division Headquarters. See Fig. 16.

Fig. 16. Street name (left) and an existing HPS light fixture (right) - Photo Courtesy of Carderock

The location of the site where the demonstration took place is illustrated in Fig. 17.

Fig. 17. Aerial view of the demonstration site (Source: Google Earth)

4.3 Facility/Site Conditions

The purpose of this demonstration project was to replace the eight existing square box streetlight fixtures with advanced and efficient LED lighting system that meets or exceeds the street lighting requirement standard, while at the same time, consuming less power. The facility/site conditions related to the service road and its traffic, as well as existing luminaries are discussed below.

a) The service road and the traffic

The service road contained eight (8) HPS luminaires, as shown in Fig. 17. It connects a research facility (the building on the bottom left corner) to the fire station (the building on the right). Traffic on this road involves both foot and vehicle traffic. Vehicle traffic is generally at a very low speed, i.e. 15 miles per hour. Foot traffic is generally generated by researchers who work in the research facility and commute to and from their housing inside the base. This traffic can be any time from 6AM to 11PM. Additionally, there can be people jogging very early in the morning, starting from 4AM.

b) The luminaires

The eight (8) luminaires are fed by electricity drawn from the nearby building (Building A located in the middle of the street). The details of the street lamps are summarized below:

Lamps in use:	400W high-pressure sodium lamps (model# LU400)
System Voltage:	277 Volts
Pole Height:	30 feet
Pole Distance:	Approximately 175 feet apart

4.4 Site-Related Permits and Regulations

The Naval Surface Warfare Center, Carderock Division, is a U.S. NAVY facility and, as such, access is restricted to the public. Outside project counterparts are required to obtain entry permits from the Visitor’s Center at the gate on every visit. Other general requirements include citizenship or permanent residency.

The Carderock facility undertakes sensitive and secure research and testing activities and therefore requires that all wireless and/or radio frequencies as well as equipment be approved prior to implementation onsite. A systems data sheet must be completed for each wireless transmitting and receiving component and submitted to the Space and Naval Warfare Systems Command (SPAWAR) for approval.

5.0 Test Design

This section provides the detailed description of the system design and testing to be conducted to address the performance objectives described in Section 3.0.

5.1 Conceptual Test Design

To evaluate the performance objectives, eight (8) units of the existing HPS streetlights were replaced with the demonstrated bi-level demand-sensitive LED street lighting system for the purpose of this demonstration. Performance objectives were evaluated both quantitatively and qualitatively.

1) *Conceptual test design to evaluate quantitative performance objectives*

As discussed in the performance objective table (Table 5), qualitative performance objectives include (a) electricity consumption reduction, (b) carbon footprint reduction, (c) economic performance, (d) illumination performance, (e) color temperature performance and (f) mercury waste reduction.

1.1) Electricity consumption and carbon footprint:

To measure the reduction in electricity consumption, a data acquisition system (DENT Instruments ElitePro – See Fig. 18) was installed at the distribution box feeding the streetlights (located in Building A).

Model:	DENT Instruments ElitePro
Description:	Data logger used to record voltage (V), current (A), electricity (kW, kVAR), power factor (PF) of the street lighting circuit
Quantity:	One (1)

Fig. 18. Specifications of the electrical data acquisition unit for the demonstration

The purpose is to record time-series electric power consumption (voltage, current, real and reactive power of both the existing HPS lamps and the new system based on LED technology. These measurements allow comparison of electricity consumption profiles, as well as voltage, of the existing HPS and the demonstrated LED street lighting systems.

Once the electricity consumption data is obtained, the carbon footprint can be calculated by multiplying the electricity consumption (kWh) by the local CO_2 emission rate (lbs/kWh).

1.2) Economic performance:

The life cycle cost analysis was conducted to compare the economic performance of the HPS and LED systems. Our economic performance analysis relies on the NIST's Building Life-Cycle Cost (BLCC) Program for MILCON Analysis. Components of the life cycle costs are: capital costs (e.g. costs of light fixtures, including ballasts for the HPS lamps), maintenance costs (e.g. costs to perform lamp maintenance, including the costs to replace the fixtures after their service life), and annual operating costs (e.g. costs of electricity). To measure the economic performance of the demonstrated system, the following information was collected:

- Capital costs of the HPS and LED light fixtures ($) and associated control/monitoring infrastructure
- Maintenance costs (man-hour or $/yr) of both HPS and LED street lighting units
- Electricity rate schedule for Carderock, MD ($/kWh)
- Annual electricity consumption (kWh/year) of both HPS and LED systems
- Service life of both HPS and LED light fixtures (years or hours)

1.3) Illumination and color temperature performance:

To measure the illumination and color temperature performance, the Minolta XY-1 Chroma meter is used. See. Fig. 19. The equipment readouts include illuminance value[2] in footcandle or lux, and correlated color temperature[3] in °K. The purpose is to record these parameters in the area under the street lighting units of interest in the luminaire test area as indicated in Fig. 20.

Model:	Minolta XY-1 Chroma Meter
Description:	Meter for illumination and color temperature measurements for recording illumination (footcandle) and correlated color temperature (°K) of HPS and LED luminaires.
Quantity:	One (1)

Fig. 19. Specifications of the meter for illumination and color temperature measurements

[2] Illuminance (footcandle) is a measure of the amount of light incident on a 1-sq ft surface. One footcandle is equivalent to one lumen/sq ft, or approximately 10.764 lux. Footcandle is a common unit of measurement used to calculate acceptable lighting levels of indoor or outdoor spaces.

[3] Correlated color temperature (CCT) is a parameter used to characterize the spectral properties of a light source. The standard unit is Kelvin (°K). Lower color temperature (<3000°K) appears yellowish white, while higher color temperature (>5000°K) appears blueish white.

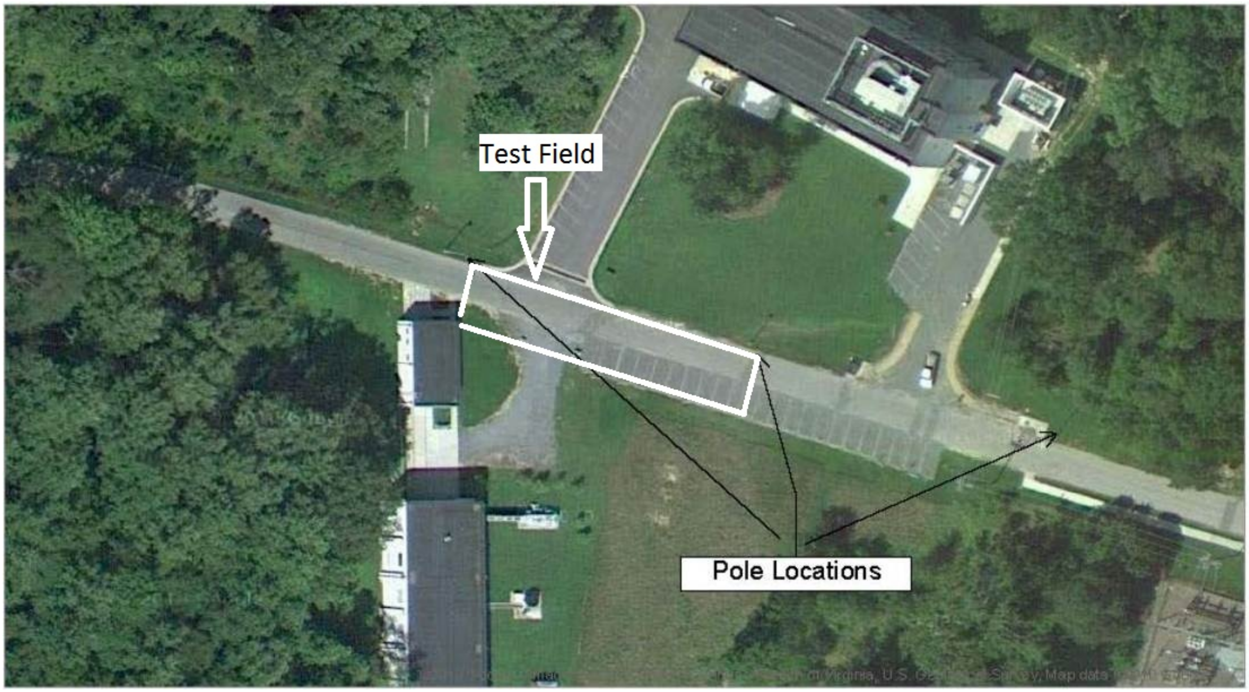


Fig. 20. Overhead view of luminaire test area

The measurements were performed at specific locations (A1-K3) between two light poles, as shown in Fig. 21. Along the street, between the two light poles, any two measurement coordinates (i.e., A1-B1, B1-C1, etc.) are 17.25 feet apart. The street of interest is about 26 feet in width. Across the street, the measurements start from the location right under the light poles to 26.25 feet away from the light poles at 8.75 feet increment (i.e., A1-A2, A2-A3, etc.).

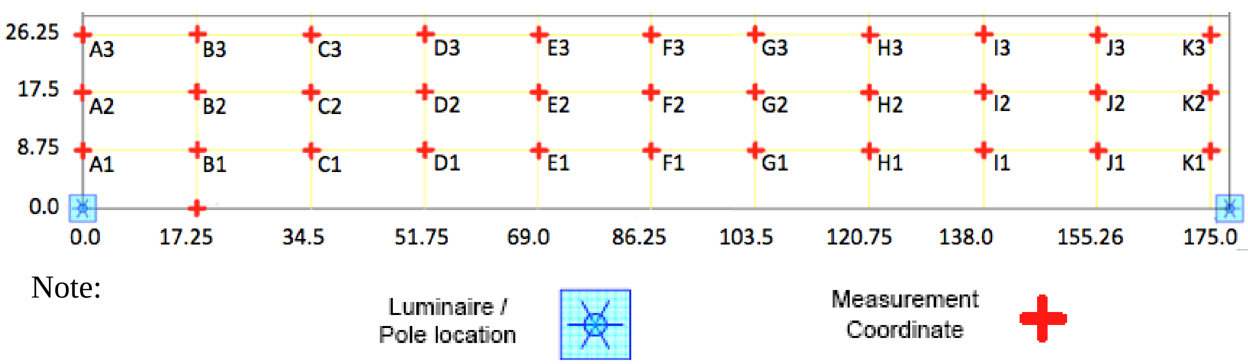


Fig. 21. Illumination/color temperature measurement layout

The measurements were performed twice: before and after the installation of the demonstrated LED street lighting system. This is to compare the illumination and color temperature characteristics of the existing HPS and the demonstrated LED units.

1.4) Mercury waste reduction:

Since LED light fixtures do not contain mercury, mercury waste reduction can therefore be determined by estimating the amount of mercury used in the HPS lamps. This is the amount of mercury used in the existing HPS luminaires (LU400), which can be obtained directly from the literature.

2) Conceptual test design to evaluate the qualitative performance objectives

A set of survey questions was used to evaluate the qualitative performance objectives, which include user satisfaction and acceptance in light quality. These questions include:

(1) How satisfied are you with the overall performance of LED lighting?
(2) How satisfied are you with the visibility improvement offered by the LED streetlights for you as a driver?
(3) How satisfied are you with the visibility improvement offered by the LED streetlights for you as a pedestrian?
(4) Do you feel that the new streetlights give off the right amount of light, or are they too bright or too dim?

The survey form is attached in Appendix H. In addition, the color photographs were taken in order to compare the light quality at the demonstration site before and after the installation.

3) Conceptual test design to evaluate the system availability and reliability

The performance of the overall system was evaluated by determining the system availability and reliability. The system availability can be derived from the availability of each component of the demonstrated system. The system reliability, on the other hand, can be determined by the amount of time the system performs as designed. System logs that record component status and LED output performance are used.

5.2 Baseline Characterization

Baseline characterization was captured in terms of both electricity consumption and illumination measurements of the existing system.

1) Electricity consumption measurements:

A data acquisition system (DENT Instruments ElitePro) was installed at the distribution box feeding the streetlights in Fall 2010 to record the following data:

Table 5. Data recorded by the DENT Instruments ElitePro

	Parameter (unit)	Sampling Rate
Data logged	Phase Voltage (Volts)	Every 5 minutes
	Phase Current (Amps)	Every 5 minutes
	Average Real Power (kW)	Every 5 minutes

Power consumption data of eight (8) HPS light fixtures from January 2010 to December 2011 are summarized in Table 6. A complete set of measurement data for the HPS luminaires is provided in Appendix D.

Table 6. Power consumption data of 8 HPS light fixtures (January-December 2011)

	Average Voltage (Volts)	Average real power (W) per lamp	Average hours ON	Electricity consumption (kWh)
January 2011	277.2	428.5	13.8	1,514
February 2011	278.5	430.8	12.7	1,290
March 2011	279.5	432.5	11.9	1,270
April 2011	278.1	429.3	10.7	1,103
May 2011	278.3	427.3	9.7	1,030
June 2011	276.2	425.0	9.0	890
July 2011	274.2	420.5	9.8	1,034
August 2011	275.9	423.8	10.7	1,119
September 2011	278.1	427.1	12.0	1,232
October 2011	279.5	429.7	13.4	1,431
November 2011	278.9	425.3	14.4	1,468
December 2011	277.6	424.8	14.9	1,572
Total kWh				14,953

2) CO_2 emission:

The average CO_2 emission factor (lbs/kWh) for Maryland was used to multiply the total electricity consumption (kWh) of the street lighting systems of interest to obtain the total CO_2 emission of HPS units in lbs. The CO_2 emission factor for Maryland is provided in the NIST's BLCC program at 1.454 lbs/kWh. Therefore, eight HPS lamps generated 14,953 kWh*1.454 lbs/kWh = 21,742 lbs of CO2/year.

3) Illumination measurements:

The illumination (fc) measurements were taken on October 26, 2010 at 4:30AM in the luminaire test area, as shown in in Fig. 22.

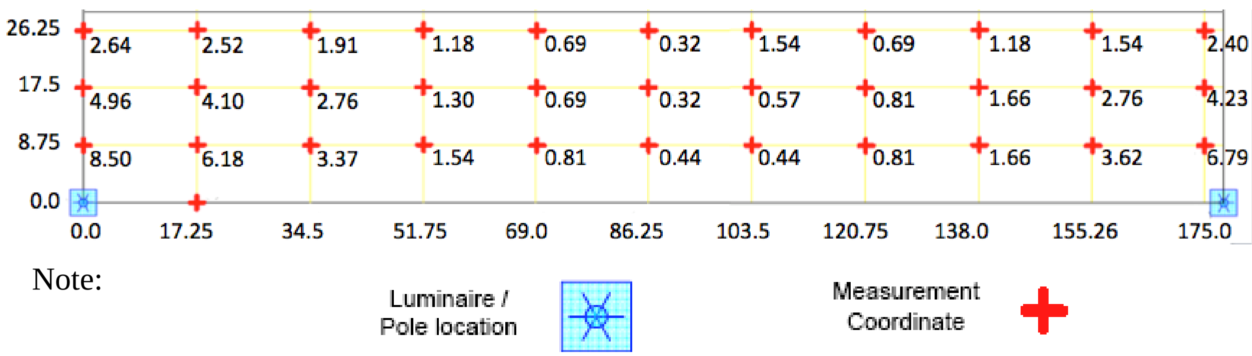


Fig. 22. Illumination measurement (fc) as a function of distance in feet along the street (x-axis) and across the street (y-axis).

Using the recorded illumination measurements as presented above, the illumination plot is as shown in Fig. 23. The illumination level varies from 0.32 fc (dark blue) to 6.79 fc (dark brown), depending on the distance from the light poles.

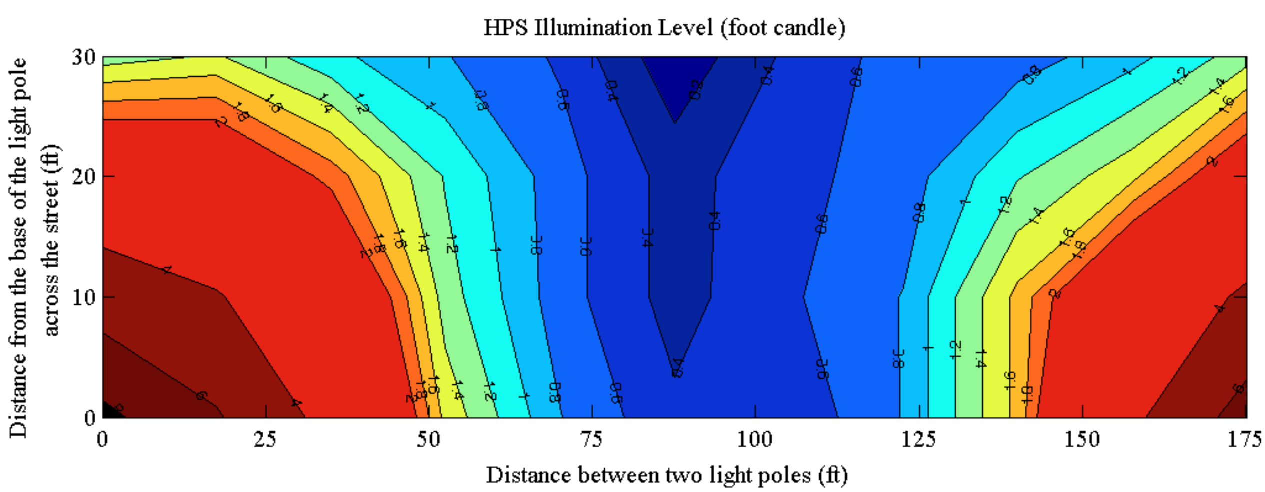


Fig. 23. Illumination in fc as a function of distance in feet along the street (x-axis) and across the street (y-axis)

The above illumination plot indicates some areas where the illumination level delivered by the existing HPS units falls below 0.8 footcandle.

4) Color temperature measurements:

The correlated color temperature (CCT) measurements in °K were taken on the same day, as presented in Fig. 24.

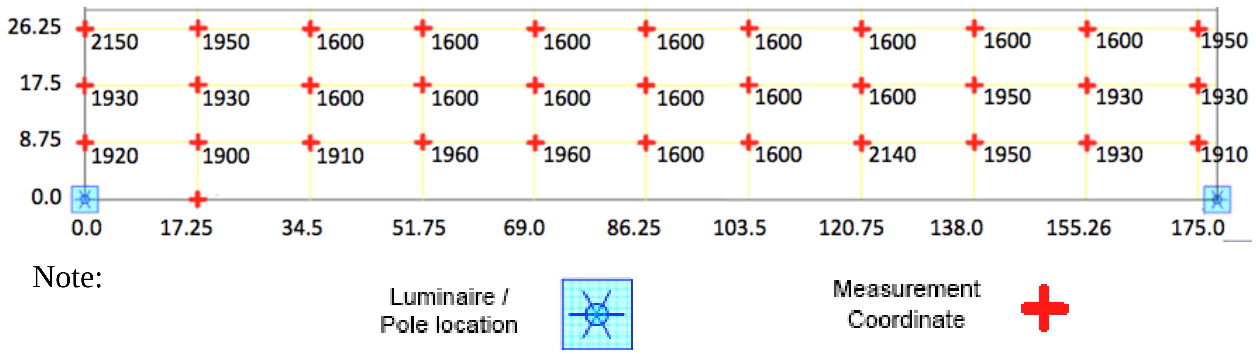


Fig. 24. CCT measurements (°K) as a function of distance in feet along the street (x-axis) and across the street (y-axis).

Using the recorded CCT measurements as presented above, the illumination plot is as shown in Fig. 25. The CCT measurements vary from 1600 °K to 2100 °K. This indicates the yellowish white color output of the existing HPS lamps.

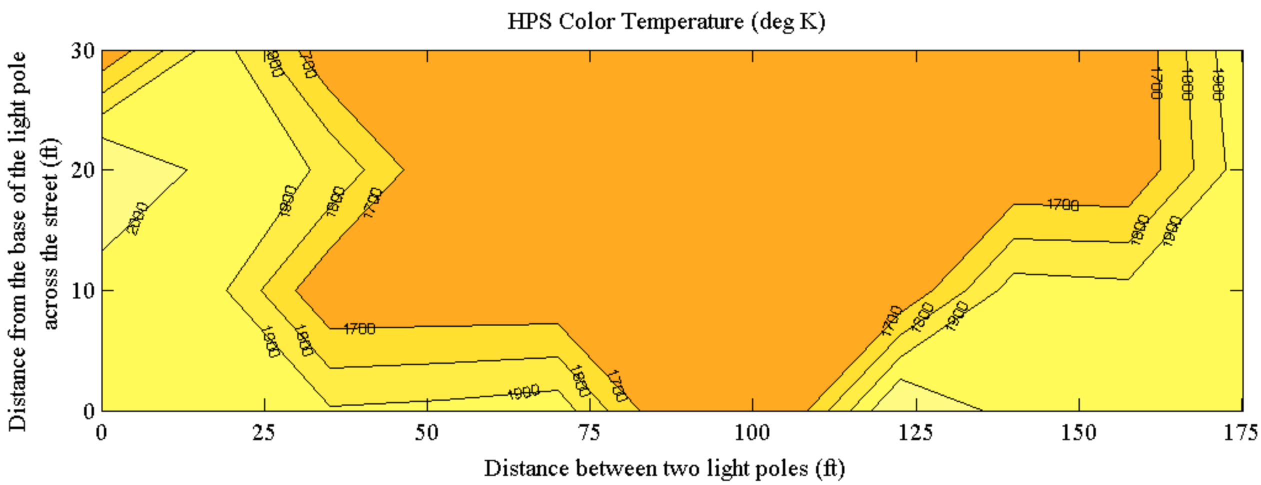


Fig. 25. (a) CCT (°K) as a function of distance in feet along the street (x-axis) and across the street (y-axis); and (b) CCT scale

Fig. 26 is a photograph that illustrates the light quality of the existing HPS lamp, taken at the site on December 14, 2010.

Fig. 26. Light quality of the existing HPS streetlight, taken at Carderock on December 14, 2010

4) Mercury in HPS lamps:

According to the data published by Green Purchasing Institute [16], each of the existing HPS lamps used in Carderock, model LU400, contains approximately 11-30 mg of mercury.

5.3 Design and Layout of Technology Components

The demonstrated system comprises four technology components, as shown in Table 7. Table 7 also summarizes the number of units and locations that the equipment was installed.

Table 7. Technology components, number of units and installation locations (See Fig. 27)

No	Technology components	Number of units	Installation locations
1	LED light fixtures	8	On top of eight light poles to replace existing HPS luminaires
2	Streetlight controllers	8	At the base of each light pole
3	Traffic sensors	4	#1 - At the beginning of the street (the 1st light pole) #2 - At end of the street (the 8th light pole) #3 & #4 - At the two entrances of Building A
4	SmartServer	1	Inside building A

The layout of technology components is presented below.

Fig. 27. Layout of technology components (Source: Google Earth)

The SmartServer is located indoors in the utility room of the building A in an enclosure box next to the breaker panel sourcing the power to the streetlights. See Fig. 28 (a).

(a)

(b)

(c)

Fig. 28. (a) SmartServer in an enclosure box; (b) Photocell sensor and motion receiver; (c) Installation of OLC at the base of a light pole

The sensor assembly, i.e., the motion detectors’ receiver base unit, is in a weatherproof enclosure box that is located outside on the northwest corner of the building. See Fig. 28 (b).

The photocell switch is on top the sensor box with its photocell exposed to the northwest sky. To compensate for the orientation and the wooded and shaded surroundings, its slider window is fully opened. As required by code, the low voltage signal wiring between the sensor box outside and the SmartServer is routed in EMT conduit.

At each lamppost, the power is connected to the outdoor lighting controller (OLC), which is located inside the base of the light poles and accessible via a small opening. See Fig. 28 (c). From the OLC, separate lines carry filtered power and control signals to the luminaire's driver circuit.

The motion detectors is located at four strategic locations, i.e., one each at the opposite ends of the service road served by the streetlights, while the rest were placed by the two main entrance doors in Building A.

Fig. 29 shows how a motion detector is placed by one of the main entrance of Building A.

Fig. 29. Motion detector installed on the wall next to the entrance of Building A

5.4 Operational Testing

This demonstration project involves the following steps, as summarized in Table 8.

Table 8. Project timeline

Task	Date
Task 1: Initial field visit	May 2010
Task 2: Pre-installation monitoring	August 2010 – December 2011
Task 3: Technology integration and controller development	August 2010 – September 2011
Task 4: Pre-factory acceptance testing	September 2011 – December 2011
Task 5: Demonstration plan submission	August 2011
Task 6: System installation and adjustment	December 2011 – March 2012
Task 7: Post-installation monitoring	January 2012 – May 2013
Task 8: Final report submission	October 2013

The controller development (Task 3) has already been discussed in Section 2.0, and the pre-installation monitoring (Task 2) has already been discussed in Section 3.0. This section focuses on the pre-factory acceptance testing (Task 4).

During the pre-factory acceptance testing phase, the project team performed the following steps:

(1) Testing of the LED control system

The testing performed was intended to familiarize with the function and operation of the control system designed for the LED luminaire provided by Beta Lighting (model LEDWay). The controls associated with this project include and Echelon LONworks server with power line carrier interface, a photocontrol sourced from Kele, Inc. (EM-24A2), and a wireless motion sensor/receiver combination of unknown manufacture.

During the test, the function of the luminaire with regard to operating state and intensity level is to conform to the following schedule (LED – light emitting diode luminaire):

- LED is ON at 100% intensity between sunset and 9PM
- LED is ON at 80% intensity between 9PM and 11PM
- LED is ON at 60% intensity between 11PM and 4AM
- LED is ON at 100% intensity between 4am and sunrise
- LED is OFF between sunrise and sunset
- With any movement detection between 9pm and 4am, all lights stay on at 100% intensity for 5 minutes before resuming the above program.

Test results are summarized in Appendix E, indicating that the control system performed as expected.

In addition, two more tests were performed:

- First test: with the replacement of the photocontrol with a short circuit. This would be the typical failure mode of a passive lighting photocontrol. Test results are available in Appendix E. These results are consistent with expectations. The introduction of a short circuit in place of the photocontrol would indicate that the time is past sunset and that the luminaire should be enabled. During the interval of time surrounding sunrise however the control system would not operate the luminaire as expected which suggests a more complicated interaction between the photocontrol and the Echelon components than originally assumed.
- Second test: with the replacement of the photocontrol with an open-circuit. Test results are also summarized in Appendix E. This test indicated that the absence of the photocontrol would not allow luminaire operation until one hour after sunset, at which point the Echelon controller disregarded the photocontrol logic.

These tests were conducted to prove that the overall system operation could still operate correctly in case of photocell failure. This demonstrates the robustness of the demonstrated LED control system design.

(2) Outdoor testing for an LED luminaire for an extended period of time (1 month) to ensure the operation of the SmartServer with inputs from the traffic/photocell sensors.

An LED unit was temporary installed, together with the SmartServer, a traffic sensor and a photocell sensor at an outdoor location in Maryland. The operation of the LED lighting unit, in terms of its ON/OFF/dim at specific times of each day, was observed for one month. The operation was as expected.

5.5 Sampling Protocol

To ensure a thorough evaluation of performance parameters, adequate volume of data were collected.

- Electricity usage readings were taken every five (5) minutes using a data logger installed at the site. This allowed us to examine system performance at a granular resolution level.
- For the illumination and CCT measurements, the sampling protocol employed was based upon the Illuminating Engineering Society of North America (IESNA) measurement guideline LM-50-99: "Guide for Photometric Measurements of Roadway Lighting Installations".
- Redundant data sampling was incorporated in the procedure to ensure the quality assurance in case of any spikes or bad data reading. For example, the illumination and CCT measurements were read a couple times at a particular measurement coordinate and the final values were averaged and presented in this report.

- All equipment was also calibrated according to the instructions provided in the handbooks from the respective manufacturers. In particular,

  - DENT Instruments ElitePro was calibrated by the manufacturer, DENT Instruments located at 64 NW Franklin Ave. Bend, OR 97701, and came with the manufacturer calibration certificate. The calibration reference instruments used are Hewlett Packard 34401A Multimeter, Serial #s US36014292, US36082468 and Hewlett Packard 6253A Dual Power Supply, Serial #241A-07086.

  - The calibration of the Minolta Chroma meter was performed by Micro Precision Calibration Inc. located at 21331 Adamson Drive, Grass Valley, CA 95949. The calibration certificate indicates that the manufacturer's calibration procedure was employed. It appears as though the calibration reference used was a model 407206 Light Meter from Extech Instruments.

5.6 Sampling Results

1) Electricity consumption measurements:

Power consumption data of eight (8) LED light fixtures from January 2012 to December 2012 are summarized in Table 9. A complete set of measurement data for LED luminaires is provided in the Appendix F.

Table 9. Power consumption data of 8 HPS light fixtures (January-December 2011)

	Average Voltage (Volts)	Average real power (W) per lamp	Average hours ON	Electricity consumption (kWh)
January 2012	278.3	122.0	14.8	443.9
February 2012	281.3	130.6	12.7	384.6
March 2012	280.3	111.9	11.5	319.3
April 2012	281.7	107.6	10.2	264.2
May 2012	253.1	109.9	9.3	253.1
June 2012	276.4	107.7	8.4	218.3
July 2012	274.0	107.9	9.0	231.9
August 2012	278.1	112.0	9.9	274.5
September 2012	280.2	116.5	11.0	308.7
October 2012	281.3	120.0	12.3	364.4
November 2012	280.9	124.6	13.3	396.8
December 2012	280.2	125.7	13.9	433.1
Total kWh				3,893.0

2) Illumination measurements:

The illumination (fc) measurements were taken in the luminaire test area when LED is at 100% intensity, as presented in Fig. 30. These measurements were taken at around 4:30AM on March 5, 2012.

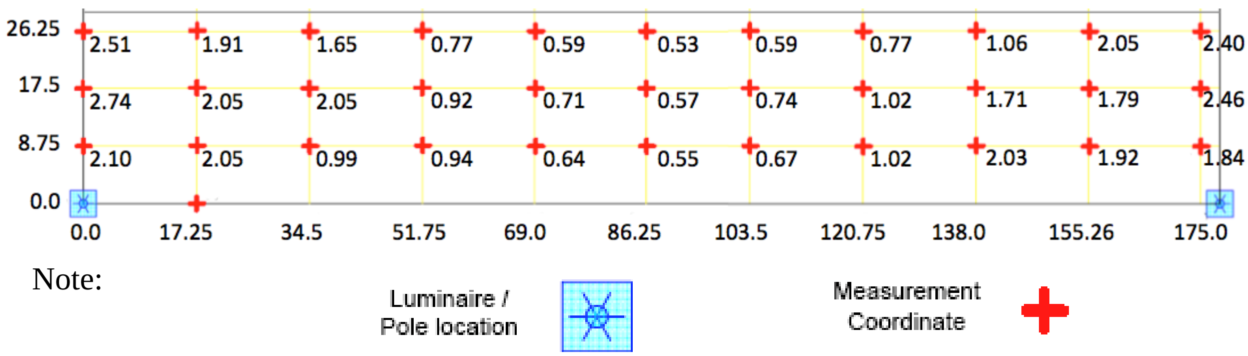


Fig. 30. Illumination measurement (fc) of the LED luminaires at 100% intensity as a function of distance in feet along the street (x-axis) and across the street (y-axis).

Using the recorded illumination measurements as presented above, the illumination plot is as shown in Fig. 31. The illumination level varies from 0.53 fc (blue) to 2.10 fc (red), depending on the distance from the light poles.

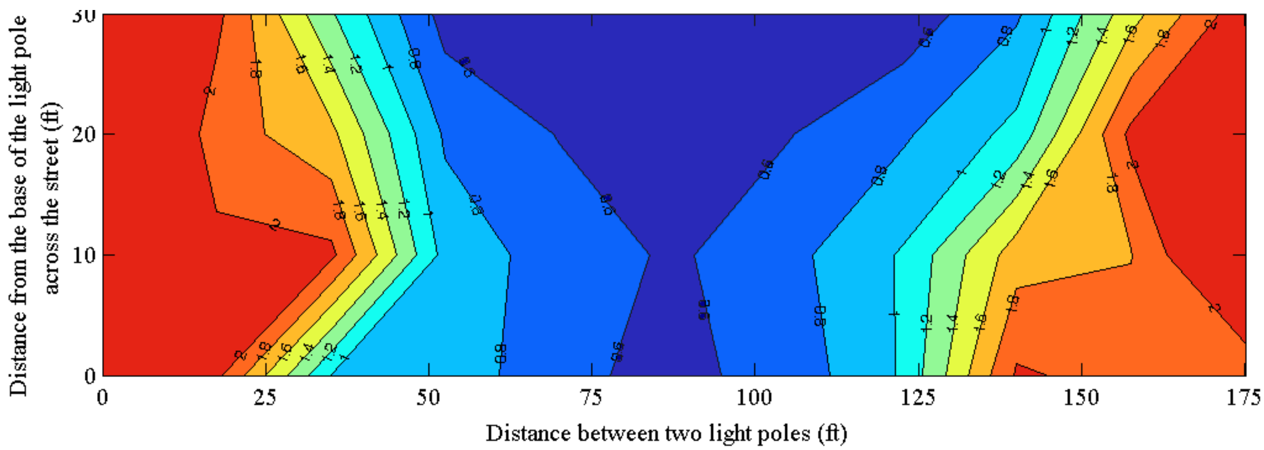


Fig. 31. Illumination (fc) of the LED luminaires at 100% intensity as a function of distance in feet along the street (x-axis) and across the street (y-axis)

The illumination level measurements of the new LED street lighting system at 60% intensity in fc are presented in Fig. 38. These measurements were taken at around 3:30AM on March 5, 2012.

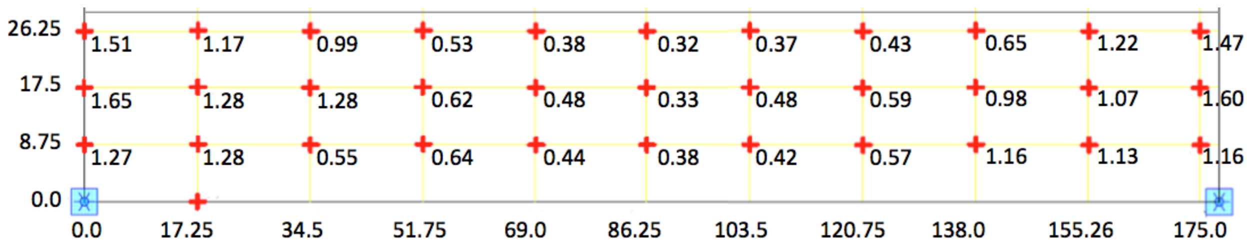


Fig. 32. Illumination measurement (fc) of the LED luminaires at 60% intensity as a function of distance in feet along the street (x-axis) and across the street (y-axis).

Using the recorded illumination measurements, the illumination plot is shown in Fig. 33. The illumination level varies from 0.32 fc (blue) to 1.28 fc (orange), depending on the distance from the light poles.

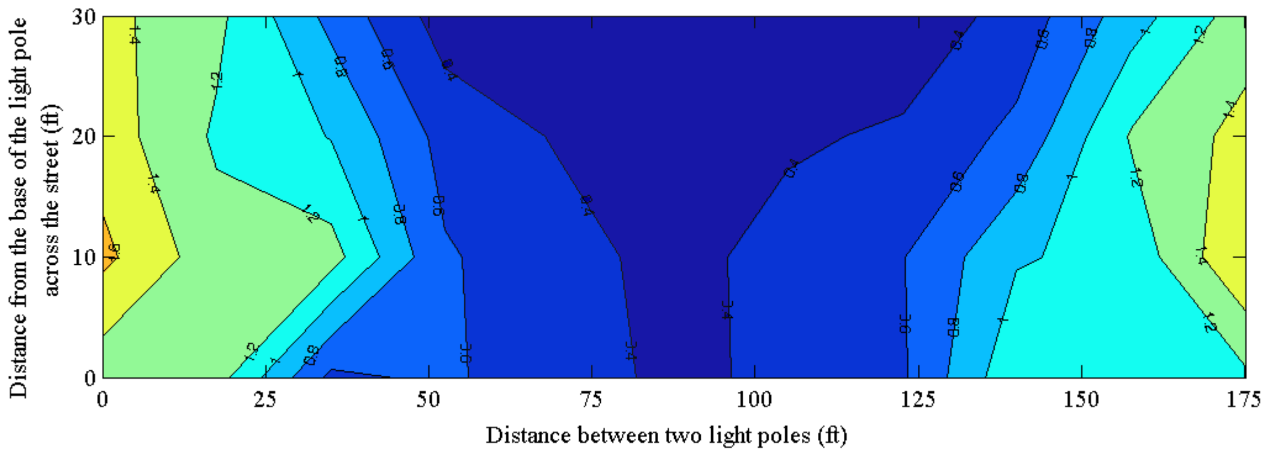


Fig. 33. Illumination (fc) of the LED luminaires at 60% intensity as a function of distance in feet along the street (x-axis) and across the street (y-axis)

3) Color temperature measurements:

The correlated color temperature (CCT) measurements in °K at 100% intensity are presented in Fig. 34.

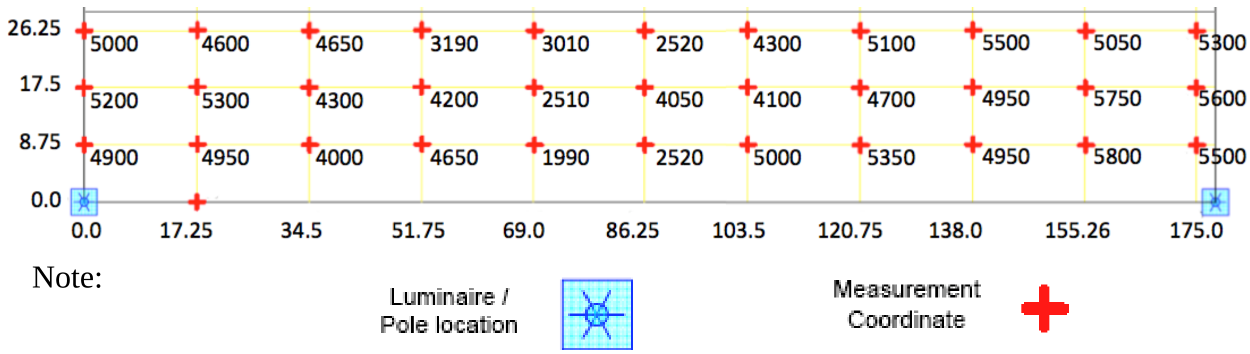


Fig. 34. CCT measurements (°K) of LED luminaires at 100% intensity as a function of distance in feet along the street (x-axis) and across the street (y-axis).

Using the recorded CCT measurements, the illumination plot is shown in Fig. 35. While the areas underneath the light poles appear to have high CCT index (> 4000°K), there are some areas in between the two light poles with the CCT measurements below 3000°K. This is because of the light pollution from the HPS lamp located at Building A. See Fig. 36.

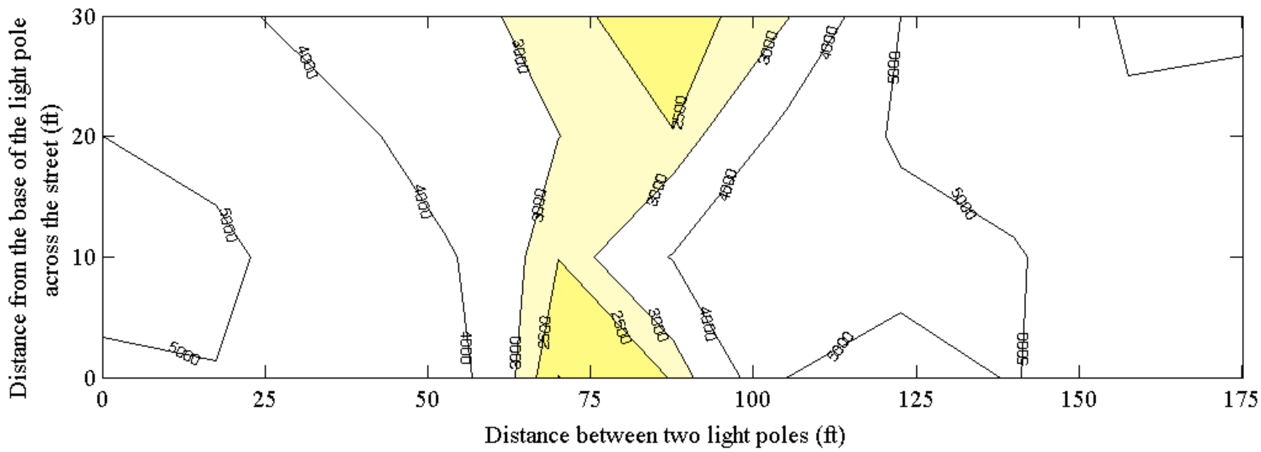


Fig. 35. CCT (°K) of LED luminaires at 100% intensity as a function of distance in feet along the street (x-axis) and across the street (y-axis)

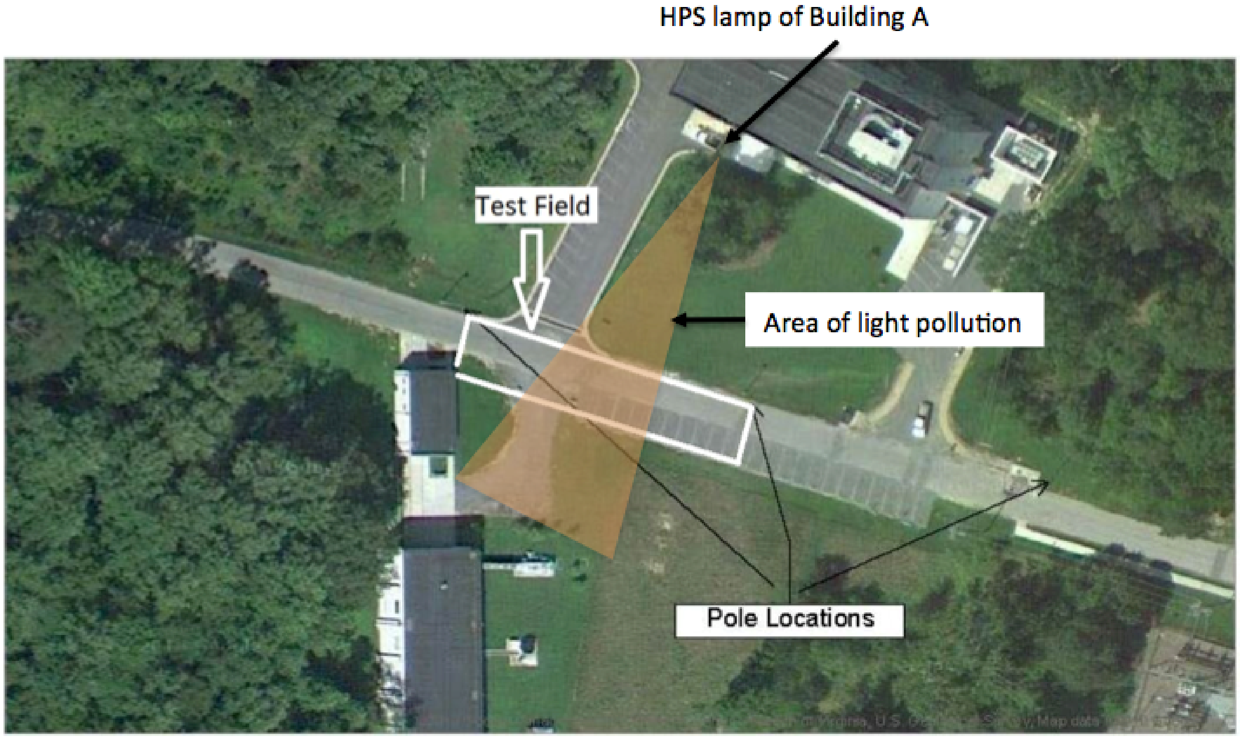


Fig. 36. Aerial view of demonstration site, showing area of light pollution

The correlated color temperature (CCT) measurement in °K between two LED luminaires at 60% illumination intensity is presented in Fig. 37.

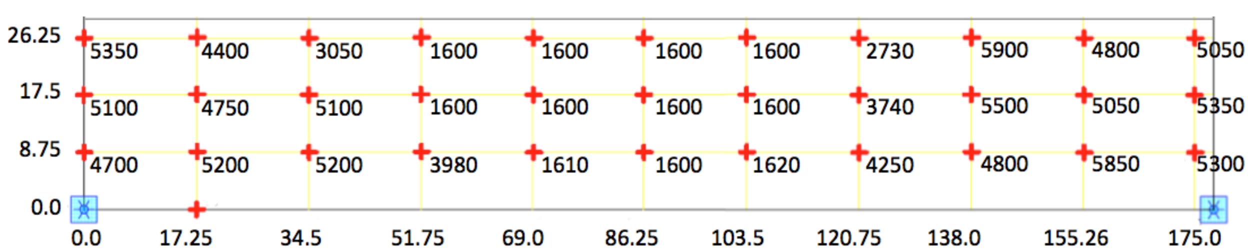


Fig. 37. CCT measurements (°K) of LED luminaires at 60% intensity as a function of distance in feet along the street (x-axis) and across the street (y-axis).

Using the recorded CCT measurements, the illumination plot is as shown in Fig. 38. At the dimmed stage, while the areas underneath the light poles still have high CCT index (> 4000°K), yellowish color light is more prominent in between the two light poles. This is because of the light pollution from the HPS lamps located at Building A. See Fig. 36.

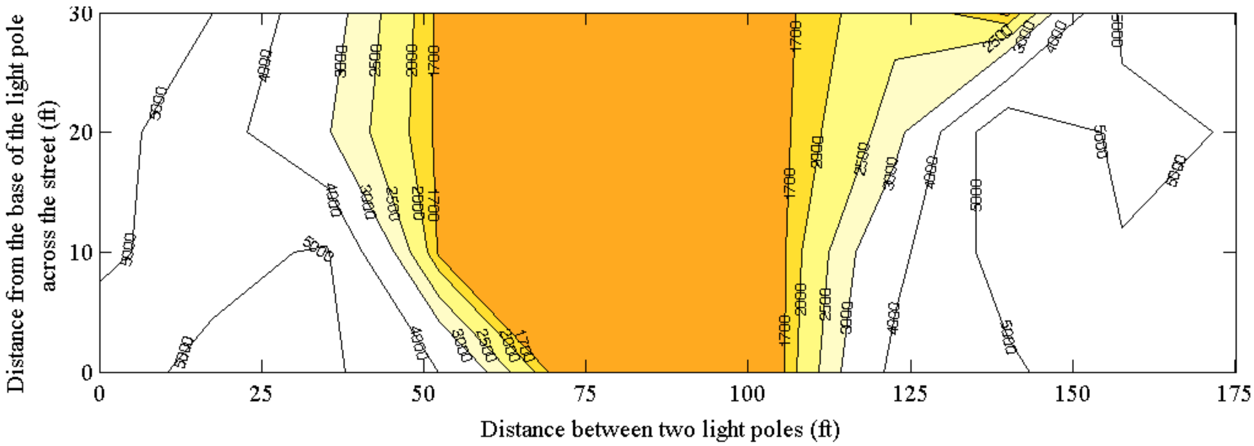


Fig. 38. CCT (°K) of LED luminaires at 60% intensity as a function of distance in feet along the street (x-axis) and across the street (y-axis)

4) Operation of HPS vs LED:

Fig. 39 and Fig. 40 show the daily operation of HPS in comparison with that of LED luminaires in October 2012. Both figures show how motion sensors change the intensity of LED luminaires between 9pm and 4am from dimmed levels to full brightness with the presence of foot/vehicle traffic.

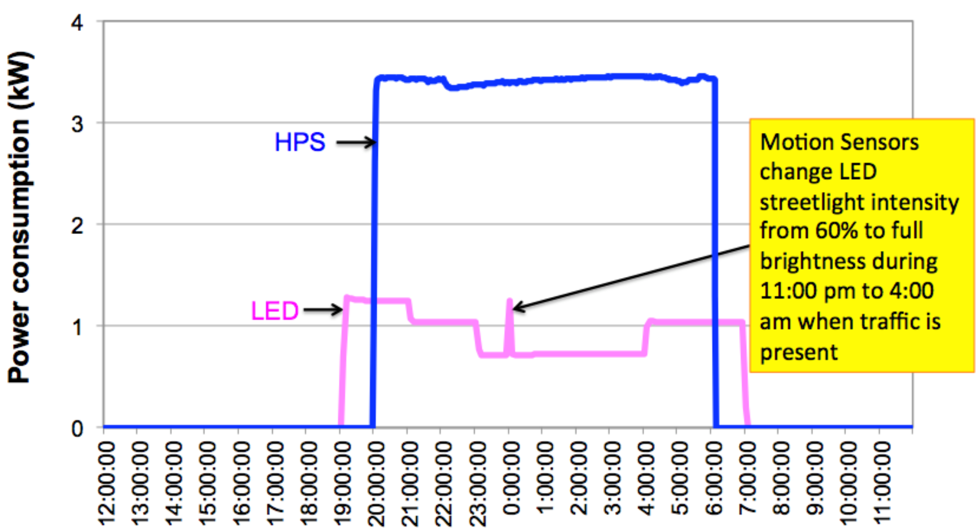


Fig. 39. Daily operation of HPS (2011) vs LED (2012) on 25 August (single traffic detection)

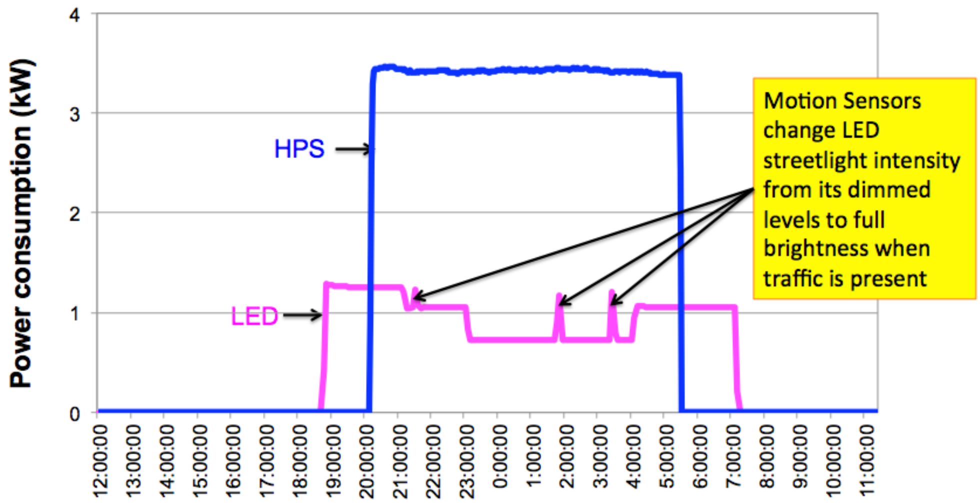


Fig. 40. Daily operation of HPS (2011) vs LED (2012) on 16 October (multiple traffic detections)

5) Light quality:

Fig. 41 to Fig. 48 illustrate the light quality of the newly installed LED lamp, taken at the site on June 11, 2012. These are as opposed to the light quality of the HPS system, shown in Fig. 26.

Fig. 41. Light quality of the LED streetlight, taken at Carderock on June 11, 2012 at 8:51pm (100% intensity)

Fig. 42. Light quality of the LED streetlight, taken at Carderock on June 11, 2012 at 8:53pm (100% intensity)

Fig. 43. Light quality of the LED streetlight, taken at Carderock on June 11, 2012 at 9:12pm (80% intensity)

Fig. 44. Light quality of the LED streetlight, taken at Carderock on June 11, 2012 at 9:14pm (80% intensity)

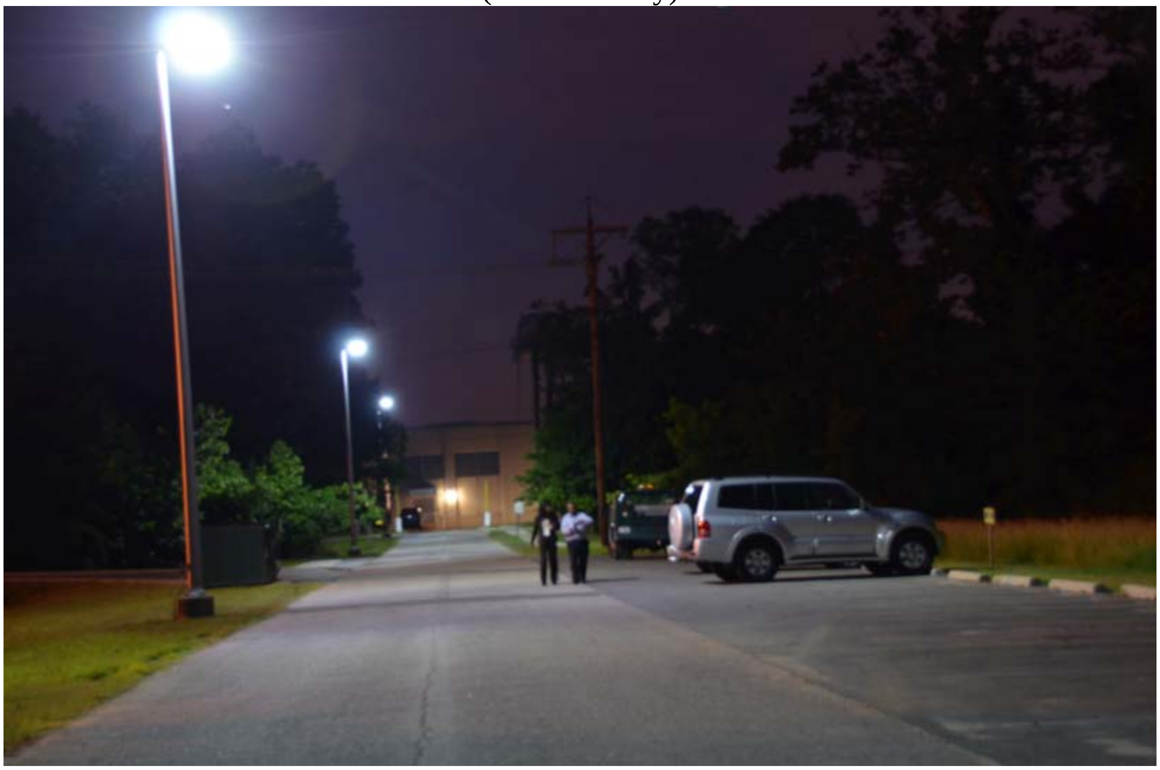


Fig. 45. Light quality of the LED streetlight, taken at Carderock on June 11, 2012 at 9:15pm (80% intensity)

Fig. 46. Light quality of the LED streetlight, taken at Carderock on June 11, 2012 at 9:25pm (80% intensity)

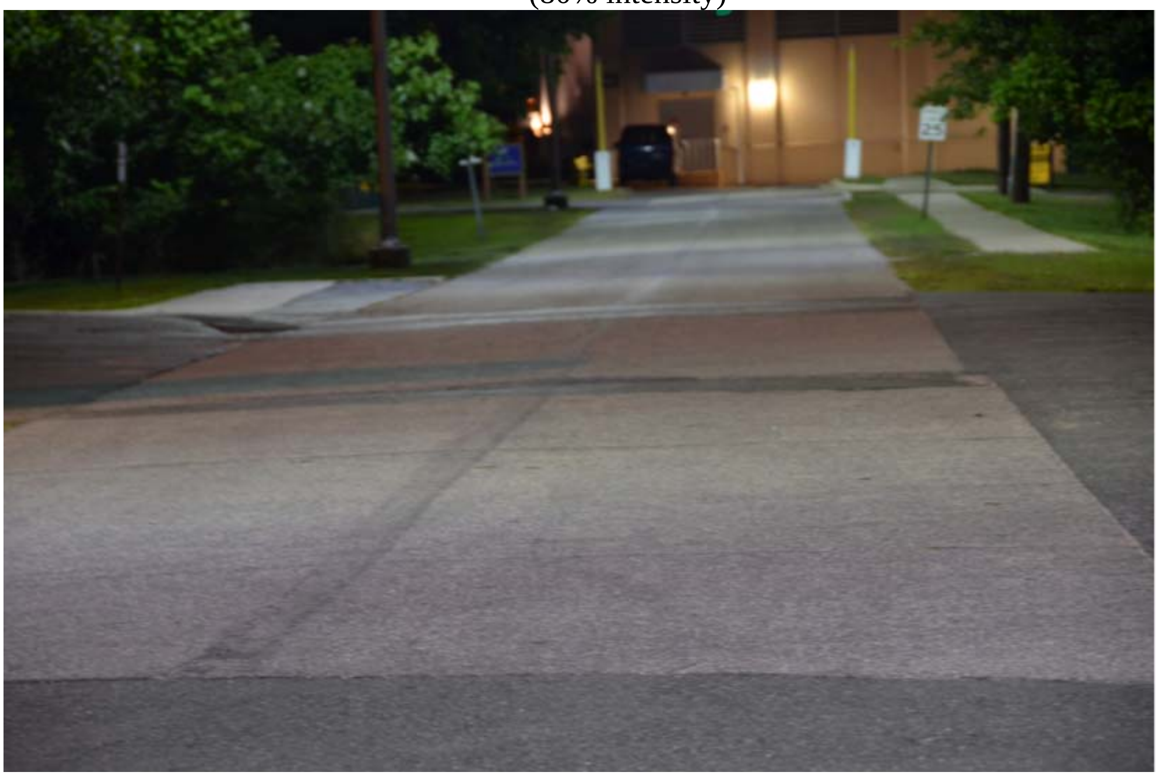


Fig. 47. Light quality of the LED streetlight, taken at Carderock on June 11, 2012 at 9:25pm (80% intensity)

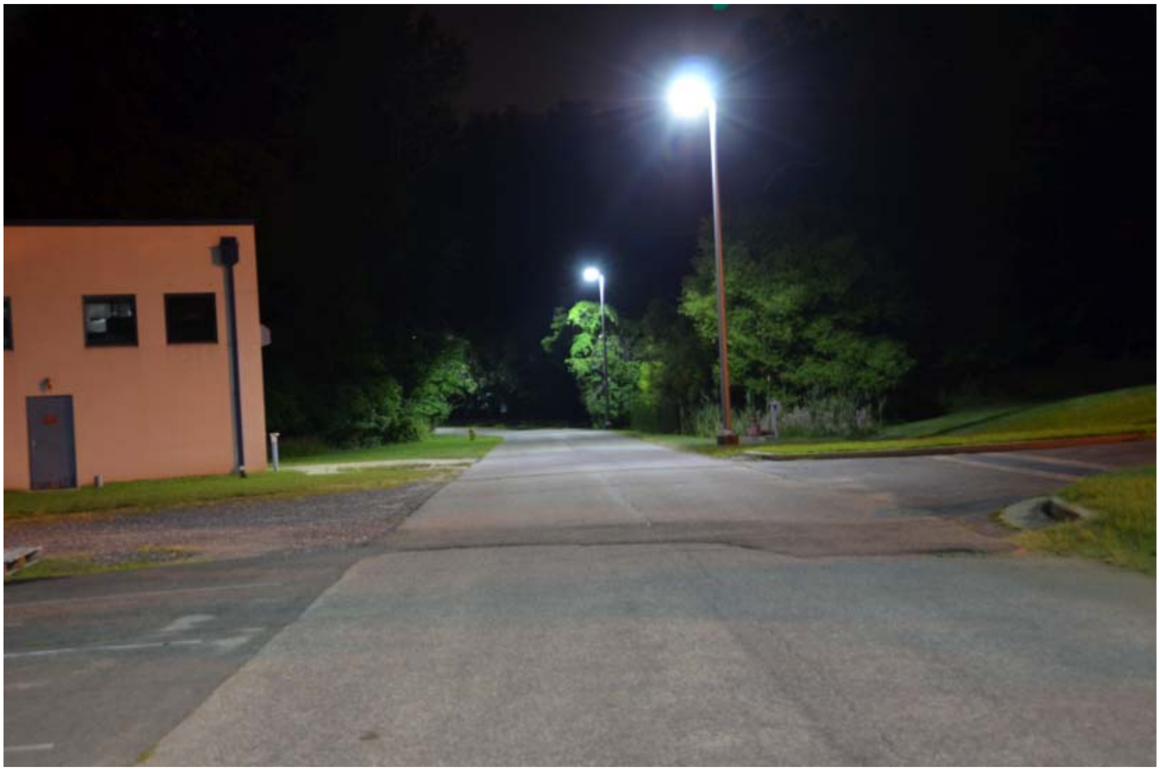


Fig. 48. Light quality of the LED streetlight, taken at Carderock on June 11, 2012 at 9:25pm (80% intensity)

6.0 Performance Assessment

The performance assessment – in terms of electricity usage reduction, carbon footprint reduction, lower cost of ownership over the lifetime, illumination levels, correlated color temperature levels, and mercury waste reduction – was conducted for the system under demonstration. This is presented below according to the performance objectives listed in Table 4.

6.1 Reduction in Electricity Usage (kWh)

The electricity usage reduction can be determined by comparing the electricity consumption of the HPS units and that of the LED units during a one-year period. The table summarizes electricity consumption of HPS and LED luminaires. HPS measurement data were taken from January 2011 to December 2011, while the LED measurement data were taken from January 2012 to December 2012.

Table 10. Electricity consumption of HPS and LED street lighting systems

Month	HPS Electricity Consumption (kWh) in 2011	LED Electricity Consumption (kWh) in 2012
January	1,514	443.9
February	1,290	384.6
March	1,270	319.3
April	1,103	264.2
May	1,030	253.1
June	890	218.3
July	1,034	231.9
August	1,119	274.5
September	1,232	308.7
October	1,431	364.4
November	1,468	396.8
December	1,572	433.1
Total	**14,953**	**3,893**

The measurements indicate annual electricity savings of 14,953 – 3,893 = 11,060kWh. This is equivalent to an average of 74.2% saving during a one-year period. See Table 11. This indicates that the performance objective (i.e., >50% electricity saving) is met for reduction in electricity usage.

6.2 Reduction in Carbon Footprint (lbs)

After deriving the annual energy savings, the carbon footprint reduction (lbs) can be derived by multiplying the CO_2 conversion factor (lbs/kWh) for the area with the annual energy reduction (kWh) achieved. The CO_2 conversion factor for Maryland that available in the NIST's BLCC program is 1.454 lbs/kWh. Thus, the annual CO2 emission reduction is estimated at 16,081 kWh (1.454 lbs/kWh * 11,060kWh/year). This is summarized in Table 11. This indicates that the performance objective (i.e., >50% CO2 emission reduction) is met for reduction in carbon footprint.

Table 11. Comparison of annual electricity consumption and CO2 emissions

	HPS	LED	Annual savings
Annual Electricity Consumption	14,953 kWh	3,893 kWh	11,060 kWh (~74% savings)
Annual CO2 emission	21,742 lbs	5,660 lbs	16,081 lbs (~74% savings)

6.3 Illumination Assessment

To evaluate whether the illumination level of the installed LED luminaires meets the specified criteria, the following recommended values from the Illuminating Engineering Society of North America (IESNA) measurement guideline LM-50-99 is used as a reference:

- Recommended average (AVE) maintained luminance values for collector roads in commercial areas is >= 0.8 fc
- Recommended average-to-minimum (AVE/MIN) value is < 4 to 1
- Recommended maximum-to-minimum (MAX/MIN) value is < 8 to 1

Illumination measurements of the HPS and LED lighting system are compared as shown in Table 12.

Table 12. Illumination measurement in fc of the HPS and LED systems

Illumination measurements in fc	MIN	MAX	AVE	AVE/MIN	MAX/MIN
HPS	0.32	8.5	2.24	7.00	26.6
LED @ 100% intensity	0.53	2.74	1.40	2.64	5.17
LED @ 60% intensity	0.32	1.65	0.86	2.68	5.16

The LED system meets or exceeds the industry standards as described above. Compared with its HPS counter part, LED provides better illumination and luminance uniformity even in its dimmed stage. This indicates that the performance objective is met for illumination measurement.

6.4 Color Temperature Performance

Correlated color temperature (CCT) measurements from the LED units at their full intensity (100%) and dimmed stage (60%) are compared with the baseline values obtained from the existing HPS-based lighting system. These measurements are summarized below:

Table 13. CCT comparison of HPS vs LED

CCT in °K	Maximum CCT	Minimum CCT	CCT range (area with no or low light pollution)
HPS	2140	1600	1600 – 2140
LED @ 100% intensity	5800	2510 (due to light pollution from the HPS unit at Building A)	4300 - 5800
LED @ 60% intensity	5850	1600 (due to light pollution from the HPS unit at Building A)	4700 - 5850

The results indicate that, while the maximum CCT values of LED units are higher than 5000 °K, their minimum CCT values are between 1600 and 2510. The reason behind low CCT values is the light pollution from the HPS lamp located at Building A, as already discussed in Section 5.6. Without the light pollution, e.g., in the area ±25-50 feet from the light poles, the CCT range of LED units range from 4300 °K to 5850 °K. This indicates that the performance objective is met for color temperature performance.

6.5 Reduction in Mercury Waste (mg)

Since LED fixtures do not contain mercury, the reduction in mercury waste can be simply determined by identifying the total number of HPS lamps being replaced over the lifetime of the LED lighting project. In this demonstration project, over a study period of 12 years, the HPS bulbs are to be replaced 4 times or the total of 32 bulbs (for 8 HPS luminaires). As discussed earlier, each HPS bulb at Carderock (model LU400) contains approximately 352-960 mg of mercury. Therefore, the amount of mercury waste reduction is estimated at over the 12-year study period. This is summarized in Table 14, which indicates that the performance objective is met for reduction in Mercury waste.

Table 14. Reduction in mercury waste

	Base case (HPS)	Alternative (LED)	Savings from Alternative
Mercury in each light bulb	11-30 mg	0 mg	11-30 mg/lamp
Number of bulbs to be replaced during the study period of 12 years	8 bulbs every 3 years = 32 bulbs	-	352-960 mg

6.6 User Acceptance and Light Quality

The acceptance level of the street lighting system under demonstration was evaluated by a survey involving the personnel working in the area. The survey was conducted on during the week of April 9-16, 2013. Thirteen (13) individuals responded to the survey. Survey results indicate that everybody either extremely satisfied or very satisfied with the overall performance and visibility improvement offered by the new LED street lighting system. Survey questions and associated results are presented in Appendix I.

Color photographs showing HPS light quality (Fig. 26) and LED light quality (Fig. 41-47) indicate that HPS offers yellowish light, while LED delivers white light – which improves visibility for both pedestrians and surveillance cameras. The result indicates that the performance objective is met for user acceptance and light quality.

6.7 System Availability

The availability of the overall system was derived from the availability of each component of the demonstrated system, including LED luminaires, their outdoor lighting controller (OLC), the SmartServer, traffic sensors and the photocell sensor. Recorded data indicate that all components work as expected, with the following observations:

- There were a couple of electricity outages at the demonstration site when the new LED street lighting system was already installed. The outages caused all voltage/power readings to become zero. These were not counted toward system availability, as they were a site-wide event.
- All system components (LED luminaires, OLCs, SmartServer and traffic/photocell sensors) demonstrated no failure during the 1-year post-installation monitoring period.

This implies 100% system availability during the post-installation monitoring period, thus the performance objective is met for system availability.

6.8 System Reliability

System reliability was measured by the amount of time the system performs as designed. Recorded data indicate that:

- LED luminaires were switched ON at sunset;
- LED luminaires were switched OFF at sunrise;
- LED luminaires were dimmed at pre-selected times;
- LED luminaires increased their intensity to 100% when foot/vehicle traffic was detected; and their intensity was gradually decreased to the previous level after a pre-set time.
- The system was also function as expected during rain and snow.

This implies 100% system reliability, thus the performance objective is met for system reliability.

7.0 Cost Assessment

This section provides summary of cost information for the technology demonstration at the site. It discusses the cost-benefit of the demonstrated technology by comparing the two systems (HPS vs LED), using the following criteria: the net present value (NPV), saving to investment ratio (SIR), payback period and adjusted internal rate of return (AIRR).

7.1 Cost Model

The cost components tracked during the course of the demonstration project include:

(1) Hardware capital costs – These are the costs of LED light fixtures and the associated monitoring and control infrastructure, i.e., SmartServer, outdoor lighting control (OLC) as well as traffic/photocell sensors.

(2) Installation costs – These include actual costs for lamp installation and electrical wiring at the demonstration site.

(3) Operational costs – These depend on the amount of electricity required to run the existing and new systems, as well as the electricity rate at Carderock.

(4) Maintenance costs – The maintenance costs are the costs associated with the number of man-hours required to replace the lamps at the end of their service life. The hardware service life of the LED system was estimated using the life of LED light fixtures (i.e., about 12 years). On the other hand, the service life of the HPS system was estimated based on how often the base replaces its HPS light fixtures. At Carderock, the existing HPS light bulbs are replaced every 3 years and ballasts every 6 years. While there is no maintenance required for the LED system for bulb replacement, small maintenance effort is required related to changing batteries for traffic sensors.

Table 15 summarizes cost model for the demonstrated LED street lighting system.

One area worth discussing is the integration of the intelligent demand-sensitive control feature to the dimmable LED streetlighting system. While the dimmable LED streetlighting system can be programmed to dim according to signals from the photocell sensor, the demand-sensitive dimming control feature allows the LED system to increase its light intensity when foot or vehicle traffic is detected. This feature provides added values to end-users by increasing safety and satisfactory. However, it results in slightly higher investment and operating costs. That is, the system requires additional traffic sensors ($460 one time) and incurs small maintenance fees ($59/year) associated with changing batteries of the traffic sensors.

Without the traffic sensors, the LEDs in dimmed condition cannot be turned back to their full intensity when the vehicle traffic appears. Therefore, without the traffic sensors, electricity consumption of the LED streetlighting system is expected to be less than that of the system with the traffic sensors and the intelligent demand-sensitive control. The electricity consumption of the LED system with and without the demand-sensitive control feature is listed in Table 15. The former is obtained from field measurements (3,893kWh/year), while the latter is obtained by neglecting electricity spikes from field measurements when traffic sensors are activated with foot/vehicle traffics (3,872kWh/year). This small difference is caused by the fact that foot/vehicle traffic is almost negligible on the base late at night, which did not trigger the sensor often.

Table 15. Cost model for the HPS vs LED street lighting systems

Cost element	Data tracked during the demonstration	Costs
Hardware capital costs	Luminaires and OLCs traffic/photocell sensors	HPS hardware capital costs (for new installation) • HPS luminaires = 8*$400/lamp = $3,200 • Photocell sensor = $100
		Hardware capital costs for LED • LED luminaires + OLCs = 8*$1,195/lamp = $10,400 • SmartServer = $750 • Photocell sensor = $100 • Traffic sensors = $460
Installation costs	Lamp installation and electrical wiring	• Lamp installation = $4,900 • Electrical wiring = $6,150 These costs are applicable to both HPS and LED for new installation.
Facility operational costs	Estimate based on electricity consumption during the demonstration	HPS electricity consumption = 14,953 kWh/yr @ 11.83 c/kWh = $1,769/year
		LED electricity consumption w/control = 3,893kWh/yr@11.83c/kWh = $460/year w/o control = 3,872kWh/yr@11.83c/kWh = $458/year
Maintenance cost	Frequency of required maintenance; labor and material per maintenance action	Maintenance cost for HPS • Light bulb: $50 every 3 years; Ballast: $200 every 6 years; Labor: $50/hr Y3: 8 bulb replacement = $400 Labor = 5hrs*$50/hr = $250 Y6: 8 bulb & 8 ballast replacement = $2,000; Labor = 8hrs*$50/hr = $400 Y9: same as Y3
		Maintenance cost for LED • No maintenance required for bulb/ballast replacement • Change batteries for traffic sensors (every year): Battery = $9/4units = $9; Labor = 1hr*$50/hr = $50.
Hardware lifetime	Estimate hardware life time	Lifetime for HPS: 3 yrs for bulbs; 6 yrs for ballasts
		Lifetime for LED: 12 years or more

7.2 Cost Drivers

At the time of the demonstration project, the LED luminaire was acquired at $1,195 each. This cost is expected to come down significantly in the next few years.

Additional hardware capital costs of the LED project included the SmartServer, traffic and photocell sensors. One SmartServer with one set of photocell/traffic sensors can be used to control up to 200 luminaires. Therefore, additional saving can be achieved when the equipment is used to control a large number of luminaires, as opposed to eight luminaires in the demonstration project.

The installation and maintenance costs are site-specific, and can be costly. At Carderock, all electrical work must be performed by State licensed and bonded contractors who have registered with the facility manager. Such contractors are required to have security clearances and access to the base and work under the supervision of the Facilities Division. As a result, for the demonstration project, only one group of electricians was qualified to perform the work, which could drive up costs for installation and electrical wiring at the base.

Electricity rate (c/kWh) also varies significantly by state. The demonstration site is located in Maryland, with the estimated electricity rate of 11.83 c/kWh. The electricity rate could be as high as an average of 33.96 c/kWh in Hawaii (as of March 2013) [17].

These factors had some impact on the life-cycle cost analysis to a certain extent.

7.3 Cost Analysis and Comparison

This section presents an estimated life-cycle cost analysis of the demonstrated technology, focusing on the net present value (NPV), saving to investment ratio (SIR), payback period and adjusted internal rate of return (AIRR).

These factors were determined using the National Institute of Standards and Technology (NIST) Building Life-Cycle Cost (BLCC) Program for MILCON Analysis. Available at: http://www1.eere.energy.gov/femp/information/download_blcc.html #blcc.

A list of assumptions made for the cost analysis is presented below:

- The analysis is for new installation.
- Study period is 12 years.
- Discount rate is 3%.
- Discount and escalation rates are based on real dollars.

The data in Table 15 are used as inputs to the NIST's BLCC program to calculate the Net Present Value (NPV) over the 12-year life for the base case (with HPS lamps) as compared to the alternative based on LED technology. The NPV comparison is presented in two scenarios.

- The first scenario considers the dimmable LED streetlighting units and their intelligent demand-sensitive control system. The NPV comparison under this scenario is presented in Table 16.
- The second scenario considers only the dimmable LED streetlighting units without the intelligent demand-sensitive feature. This is to quantify the LED system benefit without its intelligent control. The NPV comparison under this scenario is presented in Table 17.

Note that all data used as inputs for the NIST's BLCC program are available in Appendix G; and comparative reports from the NIST's BLCC program are available in Appendix H.

Table 16. Net Present Value (NPV) comparison over the 12-year life (HPS vs LED w/ traffic sensors and w/ battery replacement)

	Base case (HPS)	Alternative (LED w/control)	Savings from Alternative
Initial investment cost	$14,350	$21,920	-$7,570
Energy consumption cost	$17,909	$4,663	$13,247
Replacement cost	$3,700	$708	$2,992
Total present value life-cycle cost	**$35,959**	**$27,291**	**$8,669**

These results indicate that the demonstrated LED system with the intelligent demand-sensitive dimming control feature has proven to provide lower cost of ownership than its HPS counterpart over the system lifetime. Even though the LED luminaire with its control system has higher initial cost, it incurs much lower monthly electricity costs and has lower maintenance requirements than the HPS system.

Additional results from NIST's BLCC indicate that:

- The Savings-to-Investment Ratio (SIR) for the LED project is 2.15.
- The Adjusted Internal Rate of Return (AIRR) of the LED project is 9.77%
- The payback period is 6 years.
- Life-cycle electricity saving is 132,690 kWh during the project life of 12 years.
- Life-cycle CO_2 emission saving is 192,955 lbs during the project life of 12 years.

Table 17. Net Present Value (NPV) comparison over the 12-year life (HPS vs LED w/o traffic sensors and w/o battery replacement)

	Base case (HPS)	Alternative (LED)	Savings from Alternative
Initial investment cost	$14,350	$21,460	-$7,110
Energy consumption cost	$17,909	$4,637	$13,272
Replacement cost	$3,700	$0	$3,700
Total present value life-cycle cost	**$35,959**	**$26,097**	**$9,862**

Results from NIST's BLCC indicate that, the LED system w/o the intelligent demand-sensitive dimming control feature has also proven to provide lower cost of ownership than its HPS counterpart over the system lifetime.

In fact, when comparing the two LED alternatives: the LED system w/ and w/o the intelligent demand-sensitive dimming control, the second option without the intelligent control costs about $1,200 less in NPV. This can be expected as there are additional investment costs associated with the traffic sensor plus more maintenance costs associated with changing batteries. The SIR increases slightly from 2.15 to 2.39, and the AIRR increases slightly from 9.77% to 10.75%. Although the LED option w/o the control appears to be more attractive than the one w/ the control, it comes at the expense of the ability to turn up the light intensity to its full brightness when traffic is detected.

The SIR, AIRR, payback period, life-cycle electricity saving and CO2 emission savings for this scenario is summarized below.

- The Savings-to-Investment Ratio (SIR) of the LED project is 2.39.
- The Adjusted Internal Rate of Return (AIRR) of the LED project is 10.75%
- The payback period is 5 years.
- Life-cycle electricity saving is 132,942 kWh during the project life of 12 years.
- Life-cycle CO_2 emission saving is 193,321 lbs during the project life of 12 years.

8.0 Implementation Issues

The following issues were faced during the demonstration:

1) *Restrictions on physical access to the site*

At Carderock, visitors must be escorted in the base at all times. In general, the permit to access the base during working hours is obtainable at the Visitor Center by the gate, upon providing a valid ID and the name of the host/contact person on base. A security person at the Visitor Center then contacts the host to come to the gate and escort the visitor. Typical waiting time is 15-20 minutes.

For access during non-working hours, a request must be submitted to the security at the base at least 2 weeks in advance of the visit by the host/contact person on behalf of visitors. Requests must include names, addresses, reasons and the date of visit. A pass is then issued to the host/contact person and a copy of the pass is sent to the guard entry, who checks the visitors' IDs before admitting.

2) *Restrictions on bringing equipment to the site*

All electrical and electronic tools and equipment including computers must be registered and approved by the security at the base before bringing into Carderock. Visitors must fill out a form indicating the equipment name, model, serial number and intended uses on the base. A minimum of one week is required for approval.

3) *Restrictions on wireless communications*

The facility does allow the operation of some wireless equipment but under very strict conditions. A system data sheet must be completed for each wireless transmitting and receiving component and submitted ahead of time to the Space and Naval Warfare Systems Command (SPAWAR) for approval. Data requested include: location of transmitter, min and max frequencies of operation, operational frequency, peak and average antenna power and gain, etc. The reasons are that RF radiation poses a potential hazard to ordnance/explosives, personnel and gasoline fueling operations.

For the system installed, the only wireless communications required is that of the traffic sensor (based on PIR). The system data sheet was submitted, and we followed the following guidelines very strictly:

- For Hazards of Electromagnetic Radiation to Ordnance (HERO), RF device to be brought in should be used at least 5 feet from ordnance/explosives.
- For, Hazards of Electromagnetic Radiation to Personnel (HERP), HERP Controlled and Action Level Limits are less than 1 foot. Personnel should be instructed not to touch any radiating antenna due to a possible RF shock hazard.
- For Hazards of Electromagnetic Radiation to Fuel (HERF), a minimum safe separation distance of 50 feet is recommended between transmit antennas and nonvolatile fueling/fuel-handling operations.

4) *Restrictions on remote access from outside the base to the equipment*

For security reasons, the Base does not allow direct Ethernet link to the outside world for accessing datalogging devices and the SmartServer. This has prevented us from remote logging to the LED lighting system and undertaking any remote monitoring as well as system updating and troubleshooting tasks. Hence, the Virginia Tech engineer must make once a month trip to the facility to download the electrical measurement data from the data logger and the operation data from the SmartServer.

5) *Restrictions on installation contractors*

All electrical work on the base must be performed by State licensed and bonded contractors who have experience working on the base. Such contractors must have security clearances and work under the supervision of the Facilities Division.

6) *In-rush current*

At the beginning of new LED installation, we noticed that one or two LEDs were left ON at the dimmed stage during the day. After investigating the issue, this was found to be due to the high in-rush current created when the LED driver was switched ON, which caused the contacts of some of the relays to shut at times. The light controllers were upgraded that can sustain the high in-rush current created by the LED driver. Following this design change the LED system operated without a glitch..

Appendix A: Health and Safety Plan (HASP)

- *Applicable local, state and federal health and safety laws and regulations:*

In this demonstration project regarding the installation of the new LED street lighting units at the Naval Surface Warfare Center at Carderock, the project team followed the Federal health and safety regulations - the "Occupational Safety & Health Administration (OSHA)" of the U.S. Department of Labor's Regulations.[4]

In addition, Virginia Tech as a state agency is also required to follow the "Virginia Occupational Safety and Health Program (VOSH)" Administrative Regulations Manual.[5]

This demonstration project also required the removal and recycling of the existing high-pressure sodium streetlights. Relevant guidelines can be found in Federal regulations, Virginia State regulations and National Electricity Code (NEC).

- *Potential for worker exposure to hazardous materials:*

There exists the possibility of electrical workers to be exposed to mercury if the existing high-pressure sodium streetlights are broken during the their removal or the subsequent recycling of the high-pressure sodium streetlights. We followed the "Occupational Safety & Health Administration (OSHA)" of the U.S. Department of Labor, which has regulations regarding this eventuality. [6]

- *Physical requirements expected of workers:*

This light fixture replacement project required up to three technicians to complete the installation. They were required to manage an automated lift to raise the fixtures to 30 feet on top of the light poles. Each light fixture weighed about 45 pounds.

- *Technology's history of breakdowns or accidents:*

The service life of the LED units are estimated at 60,000 operating hours according to the manufacturer.

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[4] Occupational Safety & Health Administration, U.S. Department of Labor. (February 28, 2006) *Regulations (Standards 29 CFR).* Retrieved from: http://osha.gov/pls/oshaweb/owasrch.search_form?p_doc_type=STANDARDS&p_toc_level=1&p_keyvalue=1910

[5] Virginia Department of Labor and Industry. (September 21, 2006) *Administrative Regulations Manual (ARM).* Retrieved from: http://www.doli.virginia.gov/publications/vosh_manuals.html

[6] Occupational Safety & Health Administration, U.S. Department of Labor. (February 28, 2006) *Regulations (Standards 29 Part 1910.H CFR).* Retrieved from:

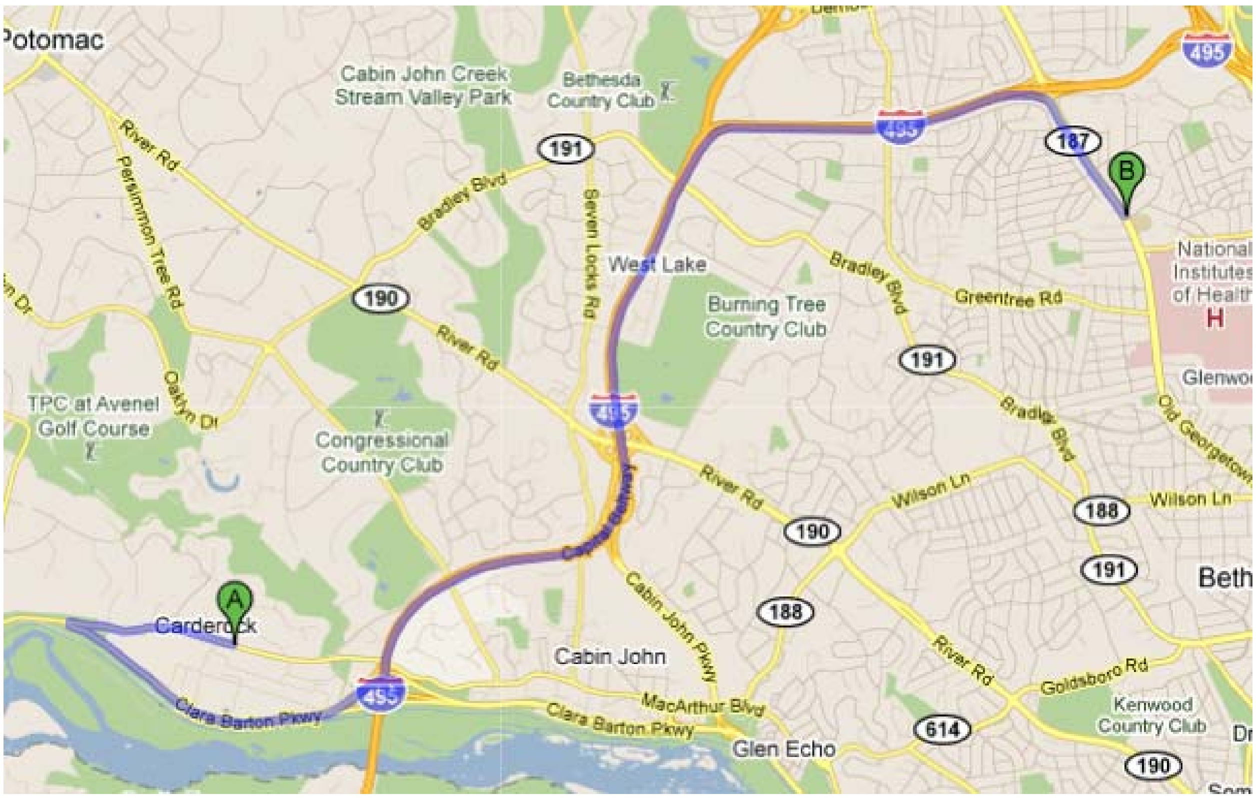
http://osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9765

- *Potential effects from transporting of equipment and impact of this technology on the surrounding environment:*

There are no possible negative effects anticipated for transporting of materials for this project. Overall, the new technology has a positive impact on the surrounding environment. It provides the required lighting needs while consuming less energy, and therefore a lower carbon footprint.

- *Closest medical facility:*

In the event of an accident during the demonstration project, the nearest hospital is Suburban Hospital in Bethesda, Maryland, 8.5 miles away. The figure below shows directions to the Suburban Hospital from Carderock.



Driving direction from Carderock (A) to the Suburban Hospital (B):

1.	Head **west** on **MacArthur Blvd** toward **Anchorage Dr**	.8 mi
2.	Turn left at **Clara Barton Pkwy**	1.4 mi
3.	Take the **I-495** ramp on the left	374 ft
4.	Keep left at the fork and merge onto **I-495 N**	5.3 mi
5.	Take exit **36** to merge onto **MD-187 S/Old Georgetown Rd** toward **Bethesda**	.9 mi
6.	Old Georgetown Rd	0.2 mi

Appendix B: Points of Contact

The important points of contact (POC) involved in the demonstration are listed below.

Table B-1: Points of contact

Name	Organization	Phone/email	Role in the project
Dr. Saifur Rahman	Virginia Tech – Advanced Research Institute (ARI) 900 N. Glebe Road Arlington, VA 22203	571-858-3300 srahman@vt.edu	PI
Dr. Manisa Pipattanasomporn	Virginia Tech – Advanced Research Institute (ARI) 900 N. Glebe Rd, Arlington, VA 22203	571-858-3302 mpipatta@vt.edu	Co-PI
Dr. Isaac Flory	Dept of Eng Technology Old Dominion University 5115 Hampton Blvd Norfork, VA 23529	757-683-6560 iflory@odu.edu	Co-PI
Mr. Greg Cancila	Naval Surface Warfare Center, Carderock Division (NSWC CD) Philadelphia 5001 S. Broad Street Philadelphia, PA 19112	215-897-7607 Gregory.cancila@navy.mil	Point of contact at Carderock

Appendix C: Luminaire Comparison Summary

This Appendix presents the current state of the findings related to the relighting of the test area at the Carderock facility. There are a number of other lighting products and LED equipped luminaires which are available for purchase, but the focus of this project was to recommend lighting products that meet performance requirements with the luminaires maintaining a similar appearance. This constraint rules out a number of lighting products, however the techniques presented can be adapted to different lighting products in varied outdoor lighting applications.

It is noted that lighting simulations as presented in this report are based on a pole height of 30 feet. Also, the electrical power consumption levels presented are all values published by the luminaire manufacturers based upon 277/480V operation. After running photometric simulations using each luminaire, four (4) options are recommended that may meet the project needs. Table C-1 presents individual luminaire operating data for all options that have been evaluated thus far.

Table C-1: Luminaire Operating Data

Luminaire	Manufacturer	Input Power	Lumens (published)	CCT
400W HPS	Unknown	465W (approx..)	50,000	2100°K
ALX2 Type 3	Lithonia	488W (LED Qty. unknown)	28,000	5100° K
Beta STR LWY 2M Type 2 Medium	Beta/Ruud	202W (80 LED)	11,684	6000° K
Beta STR LWY 2M Type 2 Short	Beta/Ruud	202W (80 LED)	11,966	6000° K
Cimarron CL1 90 Type 2	Hubbell	227W (90 LED)	14,343	5000°K
Cimarron CL1 90 Type 3	Hubbell	227W (90 LED)	14,756	5000°K
Cimarron CL1 90 Type 4	Hubbell	227W (90 LED)	14,172	5000°K
Cimarron CL1 60 Type 2	Hubbell	157W (60 LED)	9,871	5000°K
Cimarron CL1 60 Type 3	Hubbell	157W (60 LED)	10,137	5000°K
Cimarron CL1 60 Type 4	Hubbell	157W (60 LED)	9,718	5000°K

Specific data comparing the performance of the options is presented in Table C-2.

Table C-2. Comparison of Projected Performance

Luminaire	Average (fc)	Maximum (fc)	Minimum (fc)	MAX/ MIN	AVE/ MIN
400W HPS	1.08	6.32	0.05 (approx)	126.35	21.65
ALX2 Type 3	1.28	3.85	0.11	36.31	12.07
Beta STR LWY 2M Type 2 Medium	0.86	1.67	0.16	10.19	5.24
Beta STR LWY 2M Type 2 Short	0.88	2.26	0.14	15.7	6.11
Cimarron CL1 90 Type 2	1.09	3.76	0.38	9.84	3.97
Cimarron CL1 90 Type 3	1.13	3.01	0.29	10.44	8.45
Cimarron CL1 90 Type 4	0.76	3.05	0.33	9.17	4.43
Cimarron CL1 60 Type 2	0.75	2.9	0.26	11.03	4.73
Cimarron CL1 60 Type 3	0.75	2.01	0.19	10.44	8.45
Cimarron CL1 60 Type 4	0.51	2.07	0.25	8.32	3.99

If a performance metric is developed based upon average illuminance and individual luminaire power consumption, the performance of each alternative based upon this metric can be ranked. In this particular case, the greater the ratio of average illumination to luminaire input power – the more effective the luminaire in this particular application.

Table C-3. Project Efficacy (new metric)

Luminaire	Average Illumination (fc)	Input Power (per luminaire)	Project Efficacy (avg. fc per luminaire watt)
400W HPS (Basis)	1.08	465W	0.002323
Cimarron CL1 90 Type 3	1.13	227W	0.004978
Cimarron CL1 90 Type 2	1.09	227W	0.004802
Cimarron CL1 60 Type 3	0.75	157W	0.004777
Cimarron CL1 60 Type 2	0.75	157W	0.004777
Beta STR LWY 2M Type 2 Short	0.88	202W	0.004356
Beta STR LWY 2M Type 2 Medium	0.86	202W	0.004257
Cimarron CL1 90 Type 4	0.76	227W	0.003348
Cimarron CL1 60 Type 4	0.51	157W	0.003248
ALX2 Type 3	1.28	488W	0.002623

If the “Average/Minimum” uniformity metric is also employed as a performance metric, the alternatives can be presented in a ranked fashion as shown in Table C-4.

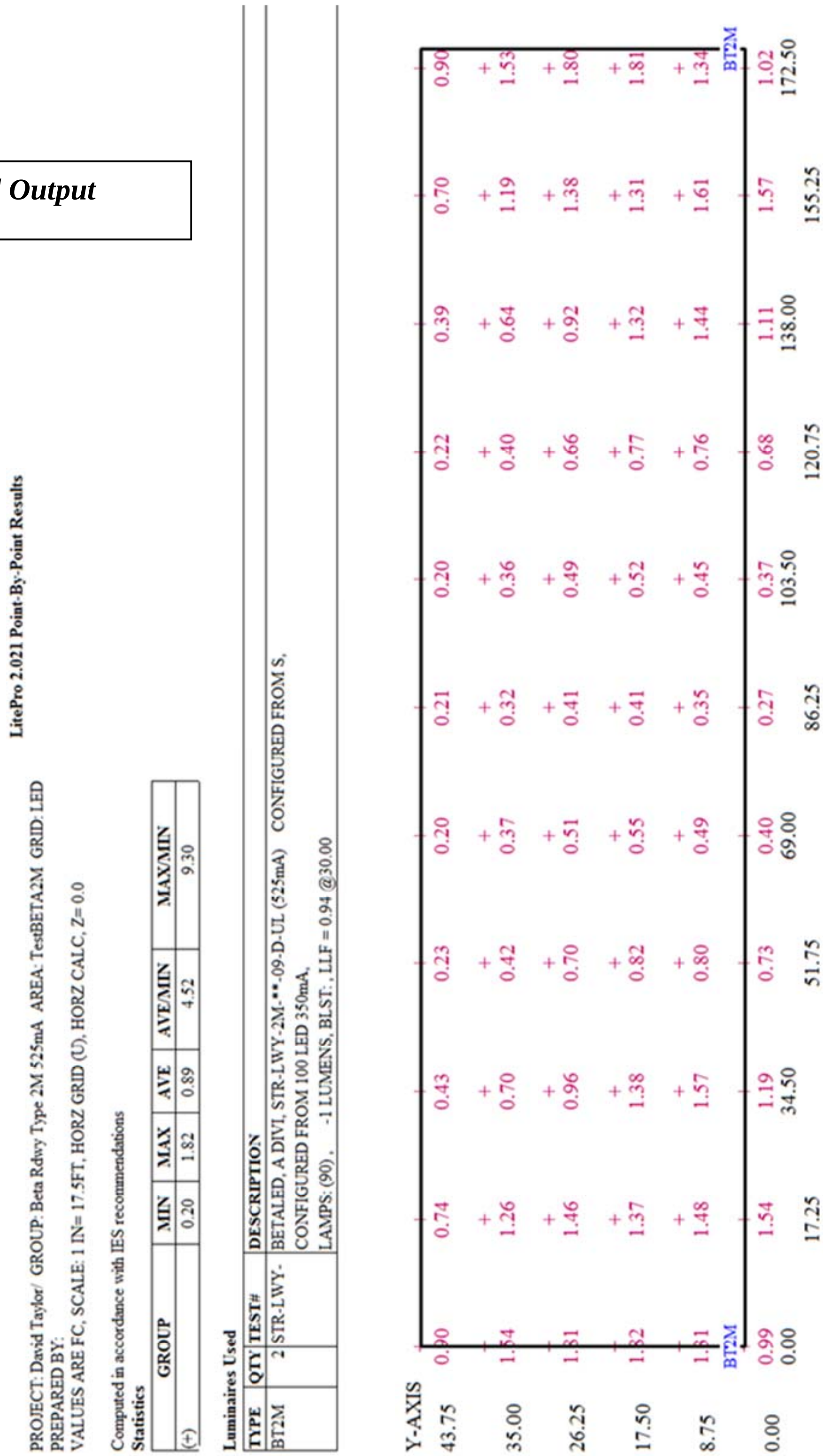
Table C-4. Uniformity to Power Ratio (new metric)

Luminaire	Avg/Min (Uniformity)
400W HPS (Basis)	*21.65*
Cimarron CL1 90 Type 2	3.97
Cimarron CL1 60 Type 4	3.99
Cimarron CL1 90 Type 4	4.43
Cimarron CL1 60 Type 2	4.73
Beta STR LWY 2M Type 2 Medium	5.24
Beta STR LWY 2M Type 2 Short	6.11
Cimarron CL1 90 Type 3	8.45
Cimarron CL1 60 Type 3	8.45
ALX2 Type 3	12.07

Based upon simulation results, the Hubbell Cimarron LED luminaire with Type 2 distribution offers superior efficacy and uniformity. However, later on it was determined that the “cobra-head” style roadway luminaires should be employed due to aesthetic compatibility with other lighting on the site. As Hubbell Lighting Inc., was unable to offer a unit that would meet that requirement, the unit selected is manufactured by Beta Lighting, Inc. – model #STR-LWY-2M-HT.

Fig. C-1 and C-2 present illumination simulation using the selected luminaire (i.e., Beta Lighting #STR-LWY-2M-HT) at its full intensity and dimmed stage, respectively.

Full Output



LitePro 2.021 Point-By-Point Results

PROJECT: David Taylor/ GROUP: Beta Rdwy Type 2M 525mA AREA: TestBETA2M GRID: LED
PREPARED BY:
VALUES ARE FC, SCALE: 1 IN= 17.5FT, HORZ GRID (U), HORZ CALC, Z= 0.0

Computed in accordance with IES recommendations

Statistics

GROUP	MIN	MAX	AVE	AVE/MIN	MAX/MIN
(+)	0.20	1.82	0.89	4.52	9.30

Luminaires Used

TYPE	QTY	TEST#	DESCRIPTION
BT2M	2	STR-LWY-	BETALED, A DIVI, STR-LWY-2M-**-09-D-UL (525mA) CONFIGURED FROM S, CONFIGURED FROM 100 LED 350mA, LAMPS: (90) , -1 LUMENS, BLST: , LLF = 0.94 @30.00

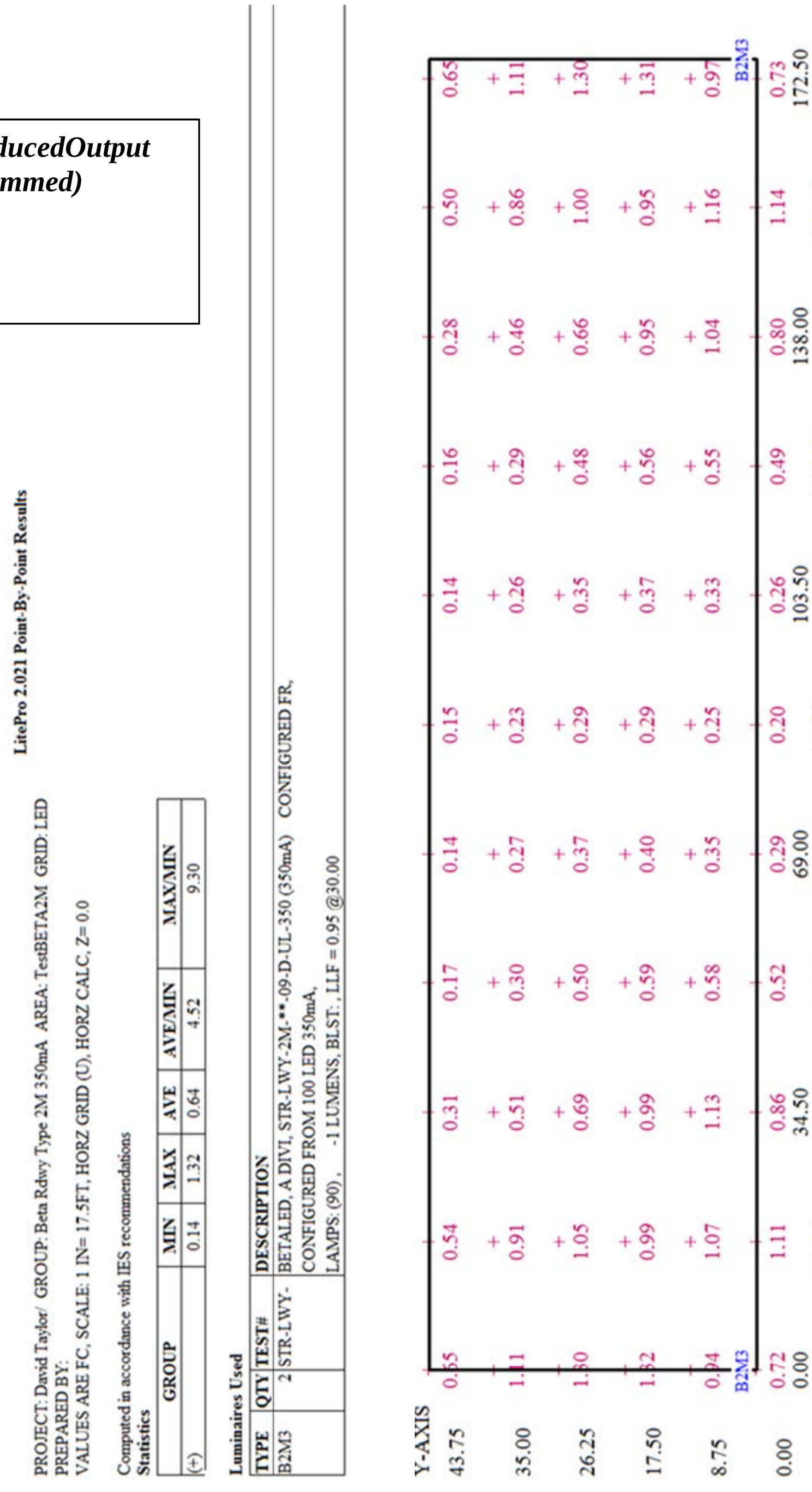
Y-AXIS	0.00	17.25	34.50	51.75	69.00	86.25	103.50	120.75	138.00	155.25	172.50
43.75	0.90	0.74	0.43	0.23	0.20	0.21	0.20	0.22	0.39	0.70	0.90
35.00	1.54	1.26	0.70	0.42	0.37	0.32	0.36	0.40	0.64	1.19	1.53
26.25	1.81	1.46	0.96	0.70	0.51	0.41	0.49	0.66	0.92	1.38	1.80
17.50	1.82	1.37	1.38	0.82	0.55	0.41	0.52	0.77	1.32	1.31	1.81
8.75	1.81	1.48	1.57	0.80	0.49	0.35	0.45	0.76	1.44	1.61	1.34
0.00	0.99	1.54	1.19	0.73	0.40	0.27	0.37	0.68	1.11	1.57	1.02

BT2M (at 0.00 and 172.50)

X-AXIS

Fig. C-1. Illumination simulation of Beta Lighting #STR-LWY-2M-HT at pole height of 30 feet (100% illumination level)

ReducedOutput (Dimmed)



LitePro 2.021 Point-By-Point Results

PROJECT: David Taylor/ GROUP: Beta Rdwy Type 2M 350mA AREA: TestBETA2M GRID: LED
PREPARED BY:
VALUES ARE FC, SCALE: 1 IN= 17.5FT, HORZ GRID (U), HORZ CALC, Z= 0.0

Computed in accordance with IES recommendations
Statistics

GROUP	MIN	MAX	AVE	AVE/MIN	MAX/MIN
(+)	0.14	1.32	0.64	4.52	9.30

Luminaires Used

TYPE	QTY	TEST#	DESCRIPTION
B2M3	2	STR-LWY-	BETALED, A DIVI, STR-LWY-2M-**-09-D-UL-350 (350mA) CONFIGURED FR, CONFIGURED FROM 100 LED 350mA, LAMPS: (90) , -1 LUMENS, BLST: , LLF = 0.95 @30.00

Y-AXIS \ X-AXIS	0.00	17.25	34.50	51.75	69.00	86.25	103.50	120.75	138.00	155.25	172.50
43.75	0.65	0.54	0.31	0.17	0.14	0.15	0.14	0.16	0.28	0.50	0.65
35.00	1.11	0.91	0.51	0.30	0.27	0.23	0.26	0.29	0.46	0.86	1.11
26.25	1.30	1.05	0.69	0.50	0.37	0.29	0.35	0.48	0.66	1.00	1.30
17.50	1.32	0.99	0.99	0.59	0.40	0.29	0.37	0.56	0.95	0.95	1.31
8.75	0.94	1.07	1.13	0.58	0.35	0.25	0.33	0.55	1.04	1.16	0.97
0.00	0.72	1.11	0.86	0.52	0.29	0.20	0.26	0.49	0.80	1.14	0.73

Fig. C-2. Illumination simulation of Beta Lighting #STR-LWY-2M-HT at pole height of 30 feet (60% illumination level)

Appendix D – HPS Electrical Measurement Data

Table D-1: Electrical Measurement Data of HPS Luminaires in January 2011

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Jan-2011	278.2	3.44	14.3	49.2
2-Jan-2011	278.0	3.42	14.7	50.2
3-Jan-2011	282.3	3.49	15.2	52.9
4-Jan-2011	277.7	3.44	14.3	49.2
5-Jan-2011	276.9	3.42	14.5	49.4
6-Jan-2011	277.4	3.44	14.4	49.4
7-Jan-2011	277.7	3.43	14.4	49.4
8-Jan-2011	278.0	3.43	14.5	49.7
9-Jan-2011	277.1	3.42	14.7	50.3
10-Jan-2011	276.3	3.42	14.3	48.9
11-Jan-2011	276.8	3.43	14.4	49.3
12-Jan-2011	277.2	3.43	14.2	49.1
13-Jan-2011	275.7	3.44	14.2	48.8
14-Jan-2011	276.3	3.42	14.0	48.0
15-Jan-2011	275.7	3.41	14.2	48.3
16-Jan-2011	275.8	3.4	14.5	49.2
17-Jan-2011	276.1	3.41	14.3	48.8
18-Jan-2011	276.6	3.41	14.6	49.6
19-Jan-2011	277.3	3.44	14.5	49.8
20-Jan-2011	277.2	3.42	14.2	48.5
21-Jan-2011	277.0	3.43	14.1	48.5
22-Jan-2011	277.5	3.44	14.0	48.2
23-Jan-2011	276.6	3.43	14.0	48.0
24-Jan-2011	277.2	3.43	13.9	47.9
25-Jan-2011	277.3	3.44	13.9	47.9
26-Jan-2011	278.5	3.44	14.1	48.5
27-Jan-2011	277.4	3.43	14.9	51.2
28-Jan-2011	276.4	3.41	13.7	46.7
29-Jan-2011	276.9	3.42	13.7	46.9
30-Jan-2011	277.1	3.43	13.6	46.5
31-Jan-2011	277.1	3.41	13.6	46.3
TOTAL kWh				1,514.2

Table D-2: Electrical Measurement Data of HPS Luminaires in February 2011

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Feb-2011	276.9	3.43	13.6	46.8
2-Feb-2011	278.4	3.44	13.8	47.4
3-Feb-2011	278.8	3.43	13.8	47.2
4-Feb-2011	278.1	3.45	15.7	54.1
5-Feb-2011	278.0	3.44	13.4	46.2
6-Feb-2011	277.3	3.43	13.7	47.0
7-Feb-2011	278.9	3.44	13.4	46.0
8-Feb-2011	277.8	3.44	13.8	47.4
9-Feb-2011	277.9	3.48	13.7	47.1
10-Feb-2011	278.2	3.44	13.6	46.7
11-Feb-2011	278.2	3.44	13.2	45.5
12-Feb-2011	277.9	3.43	13.3	45.5
13-Feb-2011	277.7	3.44	13.1	45.2
14-Feb-2011	277.9	3.45	13.3	45.8
15-Feb-2011	278.8	3.44	13.1	45.1
16-Feb-2011	278.3	3.45	13.1	45.1
17-Feb-2011	277.8	3.43	13.0	44.6
18-Feb-2011	278.7	3.45	13.0	44.9
19-Feb-2011	279.5	3.46	13.3	46.0
20-Feb-2011	281.4	3.48	12.8	44.7
21-Feb-2011	279.1	3.45	13.5	46.6
22-Feb-2011	278.1	3.43	13.7	47.1
23-Feb-2011	278.9	3.48	13.0	46.5
24-Feb-2011	278.1	3.44	12.8	44.0
25-Feb-2011	279.4	3.47	12.9	44.8
26-Feb-2011	280.2	3.44	13.4	46.2
27-Feb-2011	279.1	3.44	12.7	43.7
28-Feb-2011	278.1	3.45	12.7	43.9
TOTAL kWh				1,289.5

Table D-3: Electrical Measurement Data of HPS Luminaires in March 2011

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Mar-2011	279.4	3.45	13.1	45.1
2-Mar-2011	278.7	3.43	12.5	42.9
3-Mar-2011	277.3	3.41	12.5	42.5
4-Mar-2011	277.1	3.43	12.5	42.8
5-Mar-2011	277.3	3.44	12.5	43.0
6-Mar-2011	278.4	3.44	12.6	43.4
7-Mar-2011	278.6	3.47	12.9	44.7
8-Mar-2011	276.2	3.43	12.4	42.4
9-Mar-2011	277.7	3.43	7.5	25.7
10-Mar-2011	278.8	3.45	12.7	43.7
11-Mar-2011	280.1	3.45	13.1	45.3
12-Mar-2011	278.4	3.45	12.2	42.1
13-Mar-2011	277.1	3.41	12.1	41.3
14-Mar-2011	278.2	3.42	12.1	41.4
15-Mar-2011	277.4	3.42	12.0	41.1
16-Mar-2011	278.9	3.43	12.4	42.5
17-Mar-2011	278.8	3.45	11.9	41.2
18-Mar-2011	279.6	3.46	11.9	41.1
19-Mar-2011	280.8	3.49	11.9	41.5
20-Mar-2011	281.5	3.50	11.8	41.4
21-Mar-2011	281.0	3.50	11.8	41.4
22-Mar-2011	279.9	3.48	12.3	42.8
23-Mar-2011	282.6	3.53	7.2	25.5
24-Mar-2011	282.1	3.51	12.0	42.1
25-Mar-2011	282.9	3.52	11.9	42.0
26-Mar-2011	281.6	3.51	11.6	40.6
27-Mar-2011	282.3	3.49	11.5	40.2
28-Mar-2011	281.3	3.49	11.7	40.9
29-Mar-2011	281.8	3.48	11.4	39.6
30-Mar-2011	277.7	3.43	11.4	39.2
31-Mar-2011	278.8	3.45	11.8	40.8
TOTAL kWh				1,270.2

Table D-4: Electrical Measurement Data of HPS Luminaires in April 2011

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Apr-2011	281.9	3.52	12.0	42.4
2-Apr-2011	282.8	3.53	11.5	40.5
3-Apr-2011	275.5	3.41	11.2	38.3
4-Apr-2011	276.6	3.42	11.3	38.7
5-Apr-2011	276.7	3.42	11.3	38.7
6-Apr-2011	276.0	3.43	11.3	38.7
7-Apr-2011	278.8	3.40	11.0	37.5
8-Apr-2011	278.3	3.42	11.1	37.8
9-Apr-2011	278.2	3.41	11.7	39.9
10-Apr-2011	277.3	3.42	11.3	38.6
11-Apr-2011	278.8	3.45	10.9	37.7
12-Apr-2011	277.0	3.44	11.0	37.8
13-Apr-2011	277.3	3.43	11.1	38.2
14-Apr-2011	276.6	3.44	11.5	39.5
15-Apr-2011	275.0	3.37	10.7	35.9
16-Apr-2011	277.7	3.41	10.7	36.3
17-Apr-2011	279.3	3.38	11.2	38.0
18-Apr-2011	278.9	3.44	10.6	36.5
19-Apr-2011	278.4	3.44	10.6	36.4
20-Apr-2011	277.9	3.44	4.3	14.8
21-Apr-2011	278.7	3.43	10.6	36.5
22-Apr-2011	281.6	3.50	10.6	37.1
23-Apr-2011	279.1	3.43	10.7	36.9
24-Apr-2011	278.6	3.43	10.6	36.5
25-Apr-2011	276.3	3.42	10.4	35.5
26-Apr-2011	276.0	3.39	10.3	35.0
27-Apr-2011	275.7	3.42	10.3	35.2
28-Apr-2011	280.3	3.46	10.6	36.7
29-Apr-2011	278.1	3.46	10.4	36.0
30-Apr-2011	279.4	3.46	10.3	35.6
TOTAL kWh				1,103.1

Table D-5: Electrical Measurement Data of HPS Luminaires in May 2011

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-May-2011	282.8	3.39	10.0	33.9
2-May-2011	280.5	3.41	10.2	34.9
3-May-2011	278.6	3.45	10.3	35.5
4-May-2011	278.6	3.43	10.0	34.3
5-May-2011	281.4	3.46	10.1	34.8
6-May-2011	278.1	3.40	9.8	33.3
7-May-2011	281.3	3.47	9.9	34.4
8-May-2011	279.5	3.48	10.0	34.7
9-May-2011	279.9	3.49	9.8	34.2
10-May-2011	278.8	3.45	9.7	33.5
11-May-2011	278.9	3.39	9.6	32.6
12-May-2011	276.9	3.40	9.8	33.4
13-May-2011	277.2	3.43	9.7	33.2
14-May-2011	278.9	3.45	10.3	35.4
15-May-2011	279.7	3.45	10.3	35.4
16-May-2011	278.1	3.36	9.8	32.9
17-May-2011	278.8	3.43	9.7	33.4
18-May-2011	281.8	3.50	10.0	34.9
19-May-2011	279.6	3.50	9.8	34.4
20-May-2011	279.5	3.47	9.6	33.3
21-May-2011	277.4	3.44	9.3	32.1
22-May-2011	279.5	3.43	9.4	32.2
23-May-2011	277.8	3.41	9.3	31.8
24-May-2011	275.9	3.40	9.4	31.9
25-May-2011	276.3	3.37	9.6	32.3
26-May-2011	276.3	3.35	9.2	30.7
27-May-2011	275	3.40	9.2	31.4
28-May-2011	273.8	3.35	9.8	32.8
29-May-2011	275.8	3.40	9.2	31.3
30-May-2011	275.6	3.31	9.2	30.4
31-May 2011	276.4	3.36	9.2	30.8
TOTAL kWh				1,029.9

Table D-6: Electrical Measurement Data of HPS Luminaires in June 2011

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Jun-2011	274.7	3.34	9.2	30.6
2-Jun-2011	274.1	3.37	9.1	30.5
3-Jun-2011	275.6	3.39	9.1	30.8
4-Jun-2011	276.7	3.37	9.1	30.7
5-Jun-2011	277.4	3.39	9.1	30.9
6-Jun-2011	277.6	3.32	9.4	31.1
7-Jun-2011	276.7	3.39	9.2	31.2
8-Jun-2011	276.6	3.36	9.0	30.3
9-Jun-2011	274.8	3.37	9.0	30.3
10-Jun-2011	274.6	3.40	9.6	32.5
11-Jun-2011	275.9	3.45	9.1	31.5
12-Jun-2011	278.1	3.45	8.9	30.8
13-Jun-2011	275.1	3.25	8.9	28.8
14-Jun-2011	273.9	3.22	8.8	28.3
15-Jun-2011	276.2	3.05	9.0	27.4
16-Jun-2011	277.0	3.22	8.9	28.7
17-Jun-2011	276.0	3.26	9.1	29.7
18-Jun-2011	275.2	3.29	9.1	30.0
19-Jun-2011	277.8	3.39	9.2	31.2
20-Jun-2011	279.2	3.25	9.1	29.7
21-Jun-2011	277.9	3.27	9.4	30.7
22-Jun-2011	276.5	3.35	9.3	31.3
23-Jun-2011	275.2	3.09	8.1	25.1
24-Jun-2011	275.3	3.39	9.1	30.7
25-Jun-2011	276.0	3.08	8.1	25.1
26-Jun-2011	276.1	2.96	8.0	23.7
27-Jun-2011	276.4	2.58	4.2	10.9
28-Jun-2011*	277.5	0	0	0
29-Jun-2011*	276.2	0	0	0
30-Jun-2011	275.4	3.11	2.4	7.4
TOTAL kWh				890.4

* The photocell sensor switch used to control current to the streetlights was defective. The defective photocell sensor was changed on July 12, 2011. Thus, the streetlights were inoperative, and the data logger showed voltage readings indicating no power outage.

Table D-7: Electrical Measurement Data of HPS Luminaires in July 2011

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Jul-2011	276.9	3.36	8.4	28.1
2-Jul-2011	276.6	3.42	8.2	28.1
3-Jul-2011	278.1	3.41	8.4	28.7
4-Jul-2011	276.9	3.44	6.1	21.1
5-Jul-2011*	277.9	0	0	0
6-Jul-2011*	276.6	0	0	0
7-Jul-2011*	276.1	0	0	0
8-Jul-2011*	275.3	0	0	0
9-Jul-2011*	276.4	0	0	0
10-Jul-2011*	278.4	0	0	0
11-Jul-2011*	277.0	0	0	0
12-Jul-2011	275.0	3.11	2.6	8.2
13-Jul-2011	217.6	2.94	3.5	10.4
14-Jul-2011	275.0	3.38	5.9	19.8
15-Jul-2011	277.0	3.28	3.7	12.0
16-Jul-2011	279.3	3.46	9.5	32.9
17-Jul-2011	278.5	3.43	9.6	32.8
18-Jul-2011	277.2	3.41	9.6	32.7
19-Jul-2011	275.5	3.41	9.7	32.9
20-Jul-2011	275.6	3.39	9.7	33.0
21-Jul-2011	275.3	3.40	9.7	33.0
22-Jul-2011	274.5	3.38	9.7	32.9
23-Jul-2011	274.8	3.39	9.8	33.2
24-Jul-2011	275.3	3.39	9.8	33.4
25-Jul-2011	275.6	3.39	9.9	33.5
26-Jul-2011	274.8	3.39	9.8	33.2
27-Jul-2011	274.4	3.39	9.9	33.6
28-Jul-2011	276.1	3.42	9.9	33.8
29-Jul-2011	274.6	3.39	10.1	34.3
30-Jul-2011	273.4	3.38	10.2	34.6
31-Jul-2011	275.5	3.38	10.0	33.9
TOTAL kWh				1033.8

* The photocell sensor switch used to control current to the streetlights was defective. The defective photocell sensor was changed on July 12, 2011. Thus, the streetlights were inoperative, and the data logger showed voltage readings indicating no power outage.

Table D-8: Electrical Measurement Data of HPS Luminaires in August 2011

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Aug-2011	275.8	3.38	10.0	33.9
2-Aug-2011	274.5	3.39	10.0	33.8
3-Aug-2011	273.9	3.37	10.2	34.3
4-Aug-2011	274.8	3.37	10.9	36.6
5-Aug-2011	274.2	3.37	10.2	34.5
6-Aug-2011	275.0	3.38	10.1	34.3
7-Aug-2011	276.2	3.38	10.2	34.6
8-Aug-2011	275.9	3.38	10.4	35.1
9-Aug-2011	275.6	3.39	10.3	34.9
10-Aug-2011	274.7	3.39	10.3	34.8
11-Aug-2011	274.7	3.39	10.3	34.9
12-Aug-2011	275.1	3.39	10.3	35.1
13-Aug-2011	275.5	3.41	10.4	35.6
14-Aug-2011	276.7	3.39	10.8	36.5
15-Aug-2011	276.7	3.40	11.1	37.7
16-Aug-2011	277.4	3.40	10.6	36.2
17-Aug-2011	276.2	3.39	10.5	35.7
18-Aug-2011	278.1	3.43	10.6	36.4
19-Aug-2011	278.5	3.43	11.0	37.7
20-Aug-2011	276.6	3.39	11.0	37.3
21-Aug-2011	275.8	3.39	10.7	36.4
22-Aug-2011	276.2	3.38	11.0	37.2
23-Aug-2011	276.1	3.40	10.7	36.5
24-Aug-2011	276.8	3.40	10.7	36.4
25-Aug-2011	276.7	3.41	10.7	36.3
26-Aug-2011	275.6	3.37	10.8	36.3
27-Aug-2011	276.2	3.39	10.8	36.8
28-Aug-2011	276.6	3.38	12.2	41.3
29-Aug-2011	275.0	3.38	11.0	37.3
30-Aug-2011	275.5	3.39	11.1	37.6
31-Aug-2011	275.2	3.40	11.0	37.4
TOTAL kWh				1119.5

Table D-9: Electrical Measurement Data of HPS Luminaires in September 2011

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Sep-2011	275.7	3.39	10.9	37.0
2-Sep-2011	275.1	3.37	11.2	37.8
3-Sep-2011	275.7	3.37	11.3	38.2
4-Sep-2011	276.6	3.41	11.3	38.6
5-Sep-2011	279.8	3.46	11.8	40.7
6-Sep-2011	282.3	3.49	12.5	43.6
7-Sep-2011	280.4	3.43	11.6	39.9
8-Sep-2011	279.2	3.40	12.5	42.3
9-Sep-2011	278.1	3.41	11.9	40.4
10-Sep-2011	277.9	3.42	11.5	39.2
11-Sep-2011	278.0	3.43	11.5	39.6
12-Sep-2011	278.1	3.40	11.5	39.2
13-Sep-2011	277.0	3.40	11.6	39.5
14-Sep-2011	276.9	3.41	11.8	40.3
15-Sep-2011	279.7	3.46	11.9	41.2
16-Sep-2011	278.6	3.43	11.8	40.3
17-Sep-2011	280.0	3.44	12.4	42.8
18-Sep-2011	279.3	3.44	11.9	40.8
19-Sep-2011	278.0	3.42	12.1	41.3
20-Sep-2011	281.5	3.44	12.2	41.9
21-Sep-2011	275.6	3.37	12.7	42.9
22-Sep-2011	276.8	3.38	12.5	42.2
23-Sep-2011	279.5	3.41	12.7	43.2
24-Sep-2011	278.5	3.42	12.1	41.3
25-Sep-2011	278.1	3.41	12.3	41.9
26-Sep-2011	276.3	3.38	12.3	41.4
27-Sep-2011	276.1	3.41	12.6	42.9
28-Sep-2011	276.4	3.39	13.2	44.8
29-Sep-2011	276.9	3.43	12.7	43.7
30-Sep-2011	281.8	3.49	12.4	43.4
TOTAL kWh				1232.2

Table D-10: Electrical Measurement Data of HPS Luminaires in October 2011

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Oct-2011	280.5	3.46	13.7	47.5
2-Oct-2011	281.7	3.51	12.7	44.6
3-Oct-2011	279.1	3.44	12.8	44.0
4-Oct-2011	278.7	3.43	12.5	42.7
5-Oct-2011	281.9	3.47	12.5	43.3
6-Oct-2011	283.1	3.50	12.5	43.8
7-Oct-2011	282.9	3.48	12.6	43.8
8-Oct-2011	279.9	3.47	12.6	43.8
9-Oct-2011	280.1	3.46	14.1	48.9
10-Oct-2011	280.7	3.45	15.2	52.5
11-Oct-2011	280.3	3.42	13.0	44.5
12-Oct-2011	280.7	3.43	13.8	47.2
13-Oct-2011	278.1	3.41	14.7	50.1
14-Oct-2011	278.5	3.40	13.3	45.3
15-Oct-2011	278.7	3.41	12.9	44.1
16-Oct-2011	278.6	3.42	13.0	44.3
17-Oct-2011	276.6	3.40	13.4	45.7
18-Oct-2011	277.4	3.39	13.1	44.4
19-Oct-2011	274.2	3.38	14.0	47.4
20-Oct-2011	274.7	3.37	13.2	44.5
21-Oct-2011	276.3	3.39	13.4	45.6
22-Oct-2011	278.9	3.41	13.3	45.3
23-Oct-2011	277.3	3.42	13.4	45.7
24-Oct-2011	282.2	3.48	13.3	46.4
25-Oct-2011	281.9	3.47	13.3	46.1
26-Oct-2011	283.0	3.49	13.4	46.7
27-Oct-2011	282.9	3.46	14.6	50.5
28-Oct-2011	278.5	3.43	13.8	47.5
29-Oct-2011	277.6	3.42	15.1	51.7
30-Oct-2011	279.4	3.44	13.5	46.5
31-Oct-2011	280.1	3.45	13.6	46.9
TOTAL kWh				1431.1

Table D-11: Electrical Measurement Data of HPS Luminaires in November 2011

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Nov-2011	280.6	3.42	13.6	46.4
2-Nov-2011	280.2	3.40	13.7	46.7
3-Nov-2011	280.7	3.42	13.7	46.7
4-Nov-2011	282.5	3.44	14.0	48.1
5-Nov-2011	278.6	3.38	13.7	46.4
6-Nov-2011	277.7	3.40	13.8	46.8
7-Nov-2011	280.7	3.42	13.8	47.3
8-Nov-2011	277.9	3.38	13.8	46.8
9-Nov-2011	280.5	3.43	14.0	48.0
10-Nov-2011	277.8	3.39	14.7	49.8
11-Nov-2011	278.4	3.40	13.9	47.4
12-Nov-2011	279.2	3.39	14.0	47.5
13-Nov-2011	280.5	3.40	14.0	47.7
14-Nov-2011	281.5	3.42	14.2	48.7
15-Nov-2011	278.8	3.40	15.1	51.2
16-Nov-2011	278.9	3.38	14.9	50.2
17-Nov-2011	279.2	3.42	14.8	50.7
18-Nov-2011	280.0	3.38	14.1	47.7
19-Nov-2011	280.1	3.39	14.3	48.5
20-Nov-2011	277.8	3.38	14.6	49.2
21-Nov-2011	280.6	3.42	15.7	53.7
22-Nov-2011	279.6	3.42	16.0	54.7
23-Nov-2011	277.9	3.39	15.4	52.4
24-Nov-2011	278.1	3.39	14.3	48.5
25-Nov-2011	276.9	3.38	14.4	48.6
26-Nov-2011	264.1	3.37	14.8	49.9
27-Nov-2011	277.3	3.39	14.5	49.1
28-Nov-2011	281.1	3.43	14.6	49.9
29-Nov-2011	280.8	3.42	14.5	49.4
30-Nov-2011	278.8	3.41	14.8	50.3
TOTAL kWh				1468.1

Table D-12: Electrical Measurement Data of HPS Luminaires in December 2011

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Dec-2011	279.3	3.39	14.5	49.1
2-Dec-2011	277.6	3.41	14.5	49.5
3-Dec-2011	277.6	3.38	15.2	51.4
4-Dec-2011	276.2	3.38	14.7	49.5
5-Dec-2011	278.2	3.39	14.7	49.7
6-Dec-2011	279.3	3.42	15.8	54.2
7-Dec-2011	279.0	3.42	16.1	54.9
8-Dec-2011	278.1	3.41	14.7	50.0
9-Dec-2011	277.4	3.39	14.7	49.7
10-Dec-2011	277.4	3.38	14.8	49.9
11-Dec-2011	276.7	3.39	14.7	49.8
12-Dec-2011	275.5	3.37	14.8	49.7
13-Dec-2011	275.7	3.37	14.7	49.4
14-Dec-2011	276.1	3.37	15.1	50.9
15-Dec-2011	274.4	3.36	14.7	49.4
16-Dec-2011	274.7	3.37	15.0	50.4
17-Dec-2011	276.2	3.38	15.1	50.9
18-Dec-2011	276.0	3.38	15.3	51.7
19-Dec-2011	279.1	3.40	15.0	51.1
20-Dec-2011	279.4	3.43	15.3	52.6
21-Dec-2011	281.6	3.45	15.8	54.7
22-Dec-2011	278.9	3.42	14.8	50.7
23-Dec-2011	277.9	3.41	15.3	52.0
24-Dec-2011	278.1	3.39	14.8	50.0
25-Dec-2011	278.4	3.40	14.7	49.8
26-Dec-2011	277.9	3.41	14.6	49.8
27-Dec-2011	277.0	3.36	15.6	52.3
28-Dec-2011	277.7	3.44	14.9	51.1
29-Dec-2011	277.5	3.42	14.5	49.5
30-Dec-2011	277.0	3.42	14.4	49.2
31-Dec-2011	278.2	3.44	14.3	49.2
TOTAL kWh				1572.2

Appendix E – Test Results of the LED Control System

Sunset and sunrise are determined by an astronomical clock. For the purpose of this evaluation sunrise is scheduled for 07:04:02 and sunset is scheduled for 19:30:53.

Table E-1. Test results of the LED control system

Time	Photocontrol Status	Luminaire Status	Intensity
Before Sunset (17:43:00)	Light Dark	Off Off	N/A N/A
After Sunset (19:35:00)	Light Dark Light (after dark and luminaire operating) Dark (after luminaire is off)	Off On Off On	N/A 100% N/A 100%
Just Prior to 9:00 PM (20:50:15)	Light Dark	On On	100% 100%
Just After 9:00 PM (21:05:00)	Light Dark	On On	80% 80%
Just Prior to 11:00 PM (22:50:00)	Light Dark	On On	80% 80%
Just After 11:00 PM (23:10:00)	Light Dark	On On	60% (motion sensor brings to 100% for 5 minutes) 60% (motion sensor brings to 100% for 5 minutes)
Just Prior to 4:00 AM (03:50:00)	Light Dark	On On	60% (motion sensor brings to 100% for 5 minutes) 60% (motion sensor brings to 100% for 5 minutes)
Just After 4:00 AM (04:10:00)	Light Dark	On On	100% 100%
Just Prior to Sunrise (07:00:00)	Dark Light (after dark and luminaire operating) Dark (after luminaire is off)	On Off On	100% N/A 100%
Just After Sunrise (07:10:00)	Dark Light (after dark and luminaire operating) Dark (after luminaire is off)	On Off On	100% N/A 100%

Table E-2. Photocontrol short circuit test result

Time	Photocontrol Status	Luminaire Status	Intensity
Before Sunset (16:40:00)	Replaced with short circuit	Off	N/A
After Sunset (19:29:00)	Replaced with short circuit	On	100%

Table E-3. Photocontrol open circuit test results

Time	Photocontrol Status	Luminaire Status	Intensity
Before Sunset (17:34:00)	Replaced with open circuit	Off	N/A
After Sunset (19:28:00)	Replaced with open circuit	Off	N/A
After Sunset (19:30:55)	Replaced with open circuit	Off	N/A
After Sunset (19:40:55)	Replaced with open circuit	Off	N/A
After Sunset (19:50:55)	Replaced with open circuit	Off	N/A
After Sunset (20:20:53)	Replaced with open circuit	Off	N/A
After Sunset (20:30:53)	Replaced with open circuit	On	100%
Skip to AM Time Period			
Before Sunrise (06:03:00)	Replaced with open circuit	On	100%
Before Sunrise (06:04:00)	Replaced with open circuit	On	100%
Before Sunrise (06:14:00)	Replaced with open circuit	On Off On	100% N/A 100%
Before Sunrise (06:24:00)	Replaced with open circuit	On Off On	100% N/A 100%
After Sunrise (07:05:00)	Replaced with open circuit	Off	N/A

Appendix F – LED Electrical Measurement Data

Table F-1: Electrical Measurement Data of LED Luminaires in January 2012

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Jan-2012	282.3	0.96	24.0	23.1
2-Jan-2012	281.0	0.98	24.0	23.4
3-Jan-2012	281.4	0.99	24.0	23.6
4-Jan-2012	284.8	0.99	23.7	23.5
5-Jan-2012	283.4	1.34	7.1	9.5
6-Jan-2012	284.8	0.83	13.8	11.4
7-Jan-2012	283.9	0.83	13.7	11.3
8-Jan-2012	283.9	0.82	13.8	11.3
9-Jan-2012	283.8	0.82	13.8	11.4
10-Jan-2012	282.9	0.83	14.1	11.7
11-Jan-2012	282.6	0.83	13.7	11.4
12-Jan-2012	281.6	0.86	14.0	12.1
13-Jan-2012	283.1	0.96	13.7	13.1
14-Jan-2012	216.9	0.95	13.0	12.4
15-Jan-2012	223.2	0.95	13.7	13.1
16-Jan-2012	280.8	0.94	13.5	12.8
17-Jan-2012	283.6	0.94	13.7	13.0
18-Jan-2012	283.3	0.94	13.6	12.8
19-Jan-2012	281.2	0.92	15.1	14.0
20-Jan-2012	283.2	1.06	13.6	14.5
21-Jan-2012	280.5	1.07	13.8	14.7
22-Jan-2012	282.5	1.06	13.5	14.3
23-Jan-2012	282.0	1.05	13.6	14.3
24-Jan-2012	281.9	1.05	13.7	14.3
25-Jan-2012	281.6	1.04	13.3	13.8
26-Jan-2012	281.6	1.04	13.5	14.1
27-Jan-2012	283.2	1.03	13.7	14.2
28-Jan-2012	282.6	1.04	13.2	13.8
29-Jan-2012	280.0	1.05	13.3	14.0
30-Jan-2012	279.5	1.05	13.2	13.8
31-Jan-2012	279.8	1.03	13.2	13.6
TOTAL kWh				443.9

Table F-2: Electrical Measurement Data of LED Luminaires in February 2012

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Feb-2012	279.7	1.02	13.2	13.5
2-Feb-2012	280.3	1.03	13.2	13.6
3-Feb-2012	280.1	1.06	13.0	13.8
4-Feb-2012	280.8	1.05	13.1	13.7
5-Feb-2012	281.9	1.05	13.3	14.0
6-Feb-2012	279.3	1.05	12.9	13.5
7-Feb-2012	280.5	1.05	12.9	13.5
8-Feb-2012	279.6	1.04	12.9	13.5
9-Feb-2012	280.5	1.06	13.0	13.7
10-Feb-2012	281.4	1.04	12.8	13.4
11-Feb-2012	283.4	1.05	13.0	13.7
12-Feb-2012	279.3	1.09	12.9	14.0
13-Feb-2012	280.1	1.08	12.7	13.7
14-Feb-2012	281.0	1.05	12.9	13.5
15-Feb-2012	280.8	1.03	12.8	13.1
16-Feb-2012	279.0	1.04	12.7	13.2
17-Feb-2012	279.6	1.04	12.6	13.1
18-Feb-2012	279.8	1.04	12.5	13.0
19-Feb-2012	277.7	1.04	12.6	13.2
20-Feb-2012	279.0	1.05	12.6	13.2
21-Feb-2012	279.7	1.04	12.4	12.9
22-Feb-2012	282.9	1.04	12.4	12.9
23-Feb-2012	284.3	1.04	12.4	12.9
24-Feb-2012	284.9	1.03	12.4	12.7
25-Feb-2012	285.6	1.05	12.3	12.9
26-Feb-2012	285.8	1.05	12.2	12.8
27-Feb-2012	284.4	1.03	12.1	12.5
28-Feb-2012	283.4	1.03	12.0	12.5
29-Feb-2012	282.2	1.03	12.2	12.5
TOTAL kWh				384.6

Table F-3: Electrical Measurement Data of LED Luminaires in March 2012

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Mar-2012	282.5	1.03	12.3	12.6
2-Mar-2012	282.0	1.03	12.0	12.3
3-Mar-2012	282.9	1.04	12.5	13.0
4-Mar-2012	283.2	1.03	12.0	12.3
5-Mar-2012	283.1	1.04	11.9	12.4
6-Mar-2012	281.2	0.98	11.8	11.6
7-Mar-2012	279.9	0.92	11.8	10.8
8-Mar-2012	280.9	0.92	11.8	10.8
9-Mar-2012	278.9	0.92	11.9	11.0
10-Mar-2012	277.9	0.9	11.7	10.6
11-Mar-2012	279.6	0.94	11.6	10.9
12-Mar-2012	280.5	0.94	11.6	10.9
13-Mar-2012	282.1	0.94	11.7	10.9
14-Mar-2012	281.7	0.92	11.5	10.6
15-Mar-2012	279.3	0.93	11.5	10.7
16-Mar-2012	278.3	0.82	11.7	9.5
17-Mar-2012	280.8	0.8	11.3	9.1
18-Mar-2012	282.5	0.79	11.4	9.0
19-Mar-2012	279.0	0.79	11.2	8.9
20-Mar-2012	277.4	0.81	11.4	9.2
21-Mar-2012	278.3	0.83	11.3	9.3
22-Mar-2012	281.0	0.83	11.2	9.3
23-Mar-2012	281.2	0.84	11.1	9.3
24-Mar-2012	280.3	0.84	11.2	9.4
25-Mar-2012	281.1	0.84	11.4	9.6
26-Mar-2012	279.0	0.85	11.0	9.3
27-Mar-2012	278.2	0.88	10.9	9.6
28-Mar-2012	279.5	0.86	10.8	9.3
29-Mar-2012	278.7	0.83	10.8	9.0
30-Mar-2012	279.0	0.83	10.8	9.0
31-Mar-2012	280.0	0.83	10.8	9.0
TOTAL kWh				319.3

Table F-4: Electrical Measurement Data of LED Luminaires in April 2012

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Apr-2012	282.1	0.83	10.8	9.0
2-Apr-2012	280.6	0.85	10.8	9.1
3-Apr-2012	278.8	0.86	10.5	9.0
4-Apr-2012	278.2	0.84	10.7	9.0
5-Apr-2012	279.7	0.84	10.6	8.9
6-Apr-2012	278.5	0.86	10.4	9.0
7-Apr-2012	279.1	0.85	10.4	8.9
8-Apr-2012	279.1	0.85	10.4	8.8
9-Apr-2012	279.0	0.85	10.4	8.9
10-Apr-2012	282.3	0.86	10.4	9.0
11-Apr-2012	282.5	0.86	10.3	8.8
12-Apr-2012	284.0	0.85	10.3	8.8
13-Apr-2012	284.7	0.86	10.3	8.8
14-Apr-2012	286.8	0.87	10.3	8.9
15-Apr-2012	288.9	0.83	10.3	8.5
16-Apr-2012	283.7	0.84	10.2	8.5
17-Apr-2012	283.0	0.85	10.0	8.5
18-Apr-2012	284.8	0.84	10.2	8.6
19-Apr-2012	285.8	0.86	10.2	8.7
20-Apr-2012	283.7	0.86	9.9	8.6
21-Apr-2012	280.8	0.84	9.9	8.3
22-Apr-2012	284.4	0.85	10.3	8.7
23-Apr-2012	279.8	0.86	10.2	8.8
24-Apr-2012	278.6	0.85	9.9	8.5
25-Apr-2012	279.3	0.88	10.8	9.5
26-Apr-2012	280.2	0.91	10.1	9.2
27-Apr-2012	281.4	0.91	9.8	8.9
28-Apr-2012	280.1	0.91	9.7	8.8
29-Apr-2012	280.8	0.91	9.8	8.9
30-Apr-2012	281.1	0.90	9.6	8.6
TOTAL kWh				264.2

Table F-5: Electrical Measurement Data of LED Luminaires in May 2012

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-May-2012	279.6	0.9	10.0	9.0
2-May-2012	276.4	0.89	9.8	8.8
3-May-2012	276.4	0.9	9.7	8.7
4-May-2012	276.7	0.88	9.5	8.4
5-May-2012	279.2	0.88	9.6	8.4
6-May-2012	280.2	0.89	9.6	8.5
7-May-2012	279.1	0.89	9.4	8.4
8-May-2012	280.1	0.89	9.4	8.4
9-May-2012	279.1	0.9	9.5	8.6
10-May-2012	280.3	0.9	9.6	8.6
11-May-2012	282.2	0.9	9.3	8.3
12-May-2012	284.4	0.88	9.2	8.1
13-May-2012	286.8	0.87	9.3	8.1
14-May-2012	284.4	0.88	9.6	8.5
15-May-2012	283.1	0.88	9.7	8.5
16-May-2012	279.5	0.89	9.5	8.4
17-May-2012	277.4	0.87	9.1	7.9
18-May-2012	277.1	0.87	9.1	7.9
19-May-2012	280.2	0.87	9.0	7.9
20-May-2012	281.2	0.87	9.0	7.8
21-May-2012	279.6	0.88	9.3	8.2
22-May-2012	278.3	0.88	9.1	8.0
23-May-2012	279.3	0.87	8.9	7.8
24-May-2012	279.2	0.87	9.2	8.0
25-May-2012	279.0	0.87	9.3	8.1
26-May-2012	279.4	0.86	8.8	7.6
27-May-2012	280.6	0.86	8.9	7.7
28-May-2012	278.0	0.87	8.8	7.7
29-May-2012	275.7	0.85	8.8	7.4
30-May-2012	277.1	0.89	9.5	8.4
31-May 2012	279.4	0.86	8.7	7.4
TOTAL kWh				253.1

Table F-6: Electrical Measurement Data of LED Luminaires in June 2012

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Jun-2012	277.8	0.86	8.8	7.6
2-Jun-2012	278.4	0.87	9.0	7.9
3-Jun-2012	280.0	0.86	8.7	7.5
4-Jun-2012	278.6	0.87	8.6	7.4
5-Jun-2012	279.6	0.87	8.7	7.5
6-Jun-2012	279.3	0.88	8.6	7.6
7-Jun-2012	278.3	0.87	8.6	7.4
8-Jun-2012	278.8	0.87	8.5	7.4
9-Jun-2012	279.4	0.86	8.5	7.4
10-Jun-2012	279.3	0.86	8.5	7.3
11-Jun-2012	278.3	0.86	8.5	7.3
12-Jun-2012	278.4	0.87	8.9	7.8
13-Jun-2012	278.6	0.86	8.5	7.3
14-Jun-2012	278.6	0.86	8.5	7.3
15-Jun-2012	278.9	0.87	8.6	7.5
16-Jun-2012	279.1	0.86	8.5	7.3
17-Jun-2012	279.7	0.86	8.5	7.3
18-Jun-2012	279.1	0.87	8.8	7.6
19-Jun-2012	278.8	0.86	8.8	7.5
20-Jun-2012	278.1	0.86	8.4	7.2
21-Jun-2012	277.5	0.86	8.4	7.2
22-Jun-2012	277.4	0.84	8.6	7.2
23-Jun-2012	212.9	0.82	4.4	3.6
24-Jun-2012	278.7	0.85	8.5	7.3
25-Jun-2012	278.2	0.87	8.6	7.5
26-Jun-2012	278.5	0.87	8.4	7.3
27-Jun-2012	279.7	0.86	8.5	7.3
28-Jun-2012	278.3	0.86	8.5	7.3
29-Jun-2012	277.8	0.85	8.6	7.3
30-Jun-2012*	122.5	1.03	1.7	1.7
TOTAL kWh				218.3**

* Carderock had electric power outage for about 13 hours on June 30. This outage continued to July 2, 2012.

** Calculated for 30 days, using average electricity consumption from June 1 – June 29 to represent electricity consumption on June 30.

Table F-7: Electrical Measurement Data of LED Luminaires in July 2012

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Jul-2012*	0	0	0	0
2-Jul-2012*	174.8	0.88	8.8	7.7
3-Jul-2012	273.0	0.86	8.7	7.4
4-Jul-2012	274.2	0.87	9.1	7.9
5-Jul-2012	273.1	0.84	8.7	7.3
6-Jul-2012	273.2	0.84	8.7	7.3
7-Jul-2012	277.6	0.83	8.7	7.2
8-Jul-2012	277.7	0.82	8.8	7.2
9-Jul-2012	277.6	0.86	9.0	7.7
10-Jul-2012	278.4	0.86	8.8	7.5
11-Jul-2012	278.0	0.86	8.9	7.7
12-Jul-2012	278.1	0.88	8.7	7.6
13-Jul-2012	278.3	0.87	8.9	7.7
14-Jul-2012	278.7	0.87	9.2	8.0
15-Jul-2012	278.6	0.86	8.9	7.6
16-Jul-2012	278.0	0.86	8.8	7.6
17-Jul-2012	277.6	0.86	8.8	7.6
18-Jul-2012	277.3	0.87	8.8	7.7
19-Jul-2012	277.6	0.87	9.0	7.8
20-Jul-2012	277.5	0.87	9.1	7.9
21-Jul-2012	279.0	0.9	9.6	8.6
22-Jul-2012	279.4	0.87	9.1	7.9
23-Jul-2012	278.6	0.86	9.0	7.8
24-Jul-2012	277.9	0.87	8.9	7.7
25-Jul-2012	278.3	0.86	9.0	7.8
26-Jul-2012	278.2	0.87	9.1	7.9
27-Jul-2012	277.2	0.86	9.2	7.9
28-Jul-2012	278.1	0.86	9.2	7.9
29-Jul-2012	278.7	0.87	9.1	7.9
30-Jul-2012	278.2	0.88	9.1	8.0
31-Jul-2012	277.7	0.87	9.3	8.0
TOTAL kWh				231.9**

* Carderock had electric power outage from June 30 to July 2.

** Calculated for 31 days, using average electricity consumption from July 2 – July 31 to represent electricity consumption on July 1.

Table F-8: Electrical Measurement Data of LED Luminaires in August 2012

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Aug-2012	278.0	0.89	9.6	8.5
2-Aug-2012	277.9	0.87	9.3	8.0
3-Aug-2012	277.6	0.86	9.3	8.1
4-Aug-2012	278.0	0.86	9.3	8.0
5-Aug-2012	278.2	0.84	9.3	7.9
6-Aug-2012	277.9	0.88	9.7	8.5
7-Aug-2012	277.5	0.89	9.5	8.4
8-Aug-2012	277.5	0.88	9.6	8.4
9-Aug-2012	277.6	0.88	9.5	8.4
10-Aug-2012	277.4	0.89	10.1	9.0
11-Aug-2012	278.4	0.89	9.6	8.5
12-Aug-2012	278.9	0.89	9.8	8.7
13-Aug-2012	278.5	0.90	9.7	8.7
14-Aug-2012	277.8	0.90	10.0	9.0
15-Aug-2012	277.8	0.90	9.8	8.9
16-Aug-2012	277.0	0.90	9.8	8.8
17-Aug-2012	277.9	0.90	9.8	8.9
18-Aug-2012	278.4	0.91	10.0	9.1
19-Aug-2012	279.1	0.89	10.0	8.9
20-Aug-2012	278.9	0.90	10.2	9.1
21-Aug-2012	278.6	0.91	10.1	9.2
22-Aug-2012	278.3	0.90	10.0	9.0
23-Aug-2012	277.8	0.94	10.2	9.5
24-Aug-2012	277.7	0.93	10.1	9.4
25-Aug-2012	278.5	0.91	10.3	9.3
26-Aug-2012	279.1	0.91	10.3	9.3
27-Aug-2012	278.5	0.91	10.3	9.3
28-Aug-2012	277.6	0.91	10.4	9.5
29-Aug-2012	278.0	0.91	10.3	9.3
30-Aug-2012	278.1	0.91	10.3	9.3
31-Aug-2012	278.0	0.92	10.3	9.5
TOTAL kWh				274.5

Table F-9: Electrical Measurement Data of LED Luminaires in September 2012

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Sep-2012	278.4	0.90	10.5	9.4
2-Sep-2012	278.7	0.91	10.6	9.6
3-Sep-2012	278.7	0.92	10.6	9.7
4-Sep-2012	278.1	0.91	10.6	9.7
5-Sep-2012	277.4	0.90	10.7	9.7
6-Sep-2012	277.4	0.91	10.8	9.7
7-Sep-2012	277.8	0.92	10.6	9.7
8-Sep-2012	278.4	0.91	10.7	9.7
9-Sep-2012	279.2	0.93	10.9	10.1
10-Sep-2012	279.3	0.93	10.8	10.0
11-Sep-2012	279.4	0.94	10.8	10.1
12-Sep-2012	279.6	0.94	10.8	10.2
13-Sep-2012	279.9	0.93	10.8	10.1
14-Sep-2012	280.0	0.93	10.9	10.2
15-Sep-2012	280.6	0.92	11.0	10.2
16-Sep-2012	283.9	0.93	11.0	10.3
17-Sep-2012	282.8	0.96	11.0	10.5
18-Sep-2012	280.7	0.94	11.3	10.7
19-Sep-2012	281.1	0.95	11.3	10.8
20-Sep-2012	281.2	0.94	11.2	10.5
21-Sep-2012	280.7	0.93	11.3	10.5
22-Sep-2012	280.6	0.94	11.3	10.5
23-Sep-2012	282.2	0.94	11.3	10.7
24-Sep-2012	282.9	0.96	11.3	10.8
25-Sep-2012	282.2	0.96	11.3	10.9
26-Sep-2012	280.7	0.95	11.6	11.1
27-Sep-2012	279.3	0.94	11.5	10.8
28-Sep-2012	279.3	0.94	11.7	10.9
29-Sep-2012	282.3	0.95	11.6	11.0
30-Sep-2012	283.6	0.94	11.5	10.9
TOTAL kWh				308.7

Table F-10: Electrical Measurement Data of LED Luminaires in October 2012

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Oct-2012	283.0	0.95	11.8	11.3
2-Oct-2012	280.8	0.95	12.0	11.4
3-Oct-2012	279.5	0.94	11.8	11.1
4-Oct-2012	278.8	0.94	12.0	11.3
5-Oct-2012	280.3	0.94	11.8	11.1
6-Oct-2012	280.6	0.95	11.8	11.1
7-Oct-2012	282.4	0.95	12.0	11.4
8-Oct-2012	282.2	0.96	12.1	11.6
9-Oct-2012	281.8	0.97	12.2	11.8
10-Oct-2012	282.3	0.95	12.0	11.4
11-Oct-2012	282.1	0.97	12.0	11.6
12-Oct-2012	280.9	0.97	12.0	11.6
13-Oct-2012	280.5	0.98	12.0	11.7
14-Oct-2012	281.6	0.97	12.2	11.8
15-Oct-2012	280.9	0.96	12.3	11.7
16-Oct-2012	281.2	0.97	12.3	11.9
17-Oct-2012	279.9	0.97	12.2	11.8
18-Oct-2012	279.5	0.96	12.3	11.7
19-Oct-2012	279.9	0.96	12.8	12.4
20-Oct-2012	283.1	0.96	12.3	11.9
21-Oct-2012	283.8	0.96	12.3	11.9
22-Oct-2012	281.7	0.98	12.3	12.0
23-Oct-2012	282.6	0.96	12.5	12.0
24-Oct-2012	282.3	0.96	12.5	12.0
25-Oct-2012	281.3	0.95	12.6	12.0
26-Oct-2012	280.7	0.96	12.7	12.2
27-Oct-2012	281.8	0.95	12.7	12.0
28-Oct-2012	282.0	0.96	12.8	12.3
29-Oct-2012	281.0	0.99	13.3	13.1
30-Oct-2012*	100.8	1.34	2.2	2.9
31-Oct-2012*	171.7	0.92	10.1	9.2
TOTAL kWh				364.4**

* Carderock had electric power outage on October 30-31, 2012.

** Monthly electricity consumption is calculated for 31 days, using average electricity consumption from Oct 1 – Oct 29 to represent electricity consumption on July Oct 30 and Oct 31.

Table F-11: Electrical Measurement Data of LED Luminaires in November 2012

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Nov-2012	279.5	0.98	13.0	12.7
2-Nov-2012	279.1	0.97	12.9	12.6
3-Nov-2012	279.4	0.99	13.1	12.9
4-Nov-2012	279.1	0.96	12.9	12.4
5-Nov-2012	278.9	0.99	12.9	12.9
6-Nov-2012	278.2	1.00	13.0	12.9
7-Nov-2012	277.8	1.00	13.2	13.1
8-Nov-2012	279.0	1.01	13.1	13.2
9-Nov-2012	279.6	1.00	13.0	13.0
10-Nov-2012	282.2	0.99	13.0	12.9
11-Nov-2012	284.2	0.99	13.0	12.9
12-Nov-2012	282.7	0.98	13.1	12.9
13-Nov-2012	281.9	1.00	13.4	13.4
14-Nov-2012	280.1	1.01	13.2	13.3
15-Nov-2012	280.0	1.00	13.3	13.3
16-Nov-2012	281.7	0.99	13.4	13.3
17-Nov-2012	280.4	1.00	13.2	13.2
18-Nov-2012	279.7	1.00	13.3	13.3
19-Nov-2012	281.1	0.99	13.4	13.3
20-Nov-2012	281.5	1.00	13.3	13.3
21-Nov-2012	283.2	0.99	13.5	13.4
22-Nov-2012	282.5	1.00	13.4	13.4
23-Nov-2012	282.8	1.00	13.4	13.4
24-Nov-2012	281.9	1.01	13.6	13.7
25-Nov-2012	280.9	1.02	13.5	13.8
26-Nov-2012	282.0	1.01	13.5	13.6
27-Nov-2012	283.0	1.00	13.7	13.7
28-Nov-2012	281.7	1.01	13.7	13.8
29-Nov-2012	281.4	1.01	13.5	13.6
30-Nov-2012	281.3	1.01	13.6	13.7
TOTAL kWh				396.8

Table F-12: Electrical Measurement Data of LED Luminaires in December 2012

Date	Average voltage (Volts)	Total power consumption for per 8 lamps (kW)	Hours ON (hours)	Electricity consumption (kWh)
1-Dec-2012	280.0	1.00	13.6	13.6
2-Dec-2012	280.6	1.00	13.7	13.7
3-Dec-2012	281.2	0.99	13.8	13.7
4-Dec-2012	281.2	0.99	13.8	13.6
5-Dec-2012	281.1	0.99	13.9	13.8
6-Dec-2012	280.8	1.01	13.7	13.8
7-Dec-2012	279.9	1.00	13.9	14.0
8-Dec-2012	280.4	1.00	13.9	13.9
9-Dec-2012	280.6	0.99	14.0	13.9
10-Dec-2012	280.2	1.00	14.2	14.1
11-Dec-2012	280.6	1.00	14.0	14.0
12-Dec-2012	280.2	1.00	13.8	13.8
13-Dec-2012	280.2	1.01	13.9	14.0
14-Dec-2012	279.3	1.01	13.7	13.8
15-Dec-2012	279.5	1.01	13.8	14.0
16-Dec-2012	280.4	1.00	14.0	14.0
17-Dec-2012	280.2	1.00	14.1	14.1
18-Dec-2012	279.8	1.00	14.1	14.1
19-Dec-2012	279.8	1.00	13.8	13.8
20-Dec-2012	279.7	1.01	13.8	13.9
21-Dec-2012	281.0	1.02	14.2	14.4
22-Dec-2012	280.4	1.02	14.0	14.3
23-Dec-2012	279.9	1.01	13.7	13.8
24-Dec-2012	280.4	1.01	13.8	13.9
25-Dec-2012	279.8	1.01	14.1	14.3
26-Dec-2012	279.8	1.01	14.1	14.3
27-Dec-2012	279.5	1.03	14.0	14.4
28-Dec-2012	279.6	1.02	13.9	14.2
29-Dec-2012	280.6	1.00	13.9	14.0
30-Dec-2012	280.2	1.02	13.9	14.2
31-Dec-2012	279.8	1.01	13.8	13.9
TOTAL kWh				433.1

Appendix G – NIST's BLCC Input Report

NIST BLCC 5.3-10: Input Data Listing

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

General Information

File Name:	/Users/pmanisa/Desktop/LED2.xml
Date of Study:	Thu Oct 17 09:37:43 EDT 2013
Analysis Type:	MILCON Analysis, Energy Project
Project Name:	LED Street Lighting System
Project Location:	Maryland
Analyst:	Manisa
Comment:	This project compares economic performance of the existing HPS street lighting system vs the new LED street lighting system (to be installed).
Base Date:	January 1, 2011
Beneficial Occupancy Date:	January 1, 2011
Study Period:	12 years 0 months (January 1, 2011 through December 31, 2022)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Discount and Escalation Rates are REAL (exclusive of general inflation)

Alternative: HPS

Comment: Existing HPS units

Energy: Electricity

Annual Consumption:	14,953.0 kWh
Price per Unit:	$0.11830
Demand Charge:	$0

Utility Rebate:	$0
Location:	Maryland
Rate Schedule:	Commercial
State:	Maryland

Usage Indices

From Date	Duration	Usage Index
January 1, 2011	**Remaining**	100%

Escalation Rates

From Date	Duration	Escalation
April 1, 2010	**1 year 0 months**	-6.07%
April 1, 2011	**1 year 0 months**	1.32%
April 1, 2012	**1 year 0 months**	1.27%
April 1, 2013	**1 year 0 months**	-0.69%
April 1, 2014	**1 year 0 months**	-0.24%
April 1, 2015	**1 year 0 months**	1.02%
April 1, 2016	**1 year 0 months**	1.09%
April 1, 2017	**1 year 0 months**	0.32%
April 1, 2018	**1 year 0 months**	-0.28%
April 1, 2019	**1 year 0 months**	0.48%
April 1, 2020	**1 year 0 months**	0.63%
April 1, 2021	**1 year 0 months**	0.32%
April 1, 2022	**1 year 0 months**	0.47%
April 1, 2023	**1 year 0 months**	0.82%
April 1, 2024	**1 year 0 months**	0.39%
April 1, 2025	**1 year 0 months**	0.46%
April 1, 2026	**1 year 0 months**	0.73%
April 1, 2027	**1 year 0 months**	0.8%
April 1, 2028	**1 year 0 months**	1.55%
April 1, 2029	**1 year 0 months**	1.49%
April 1, 2030	**1 year 0 months**	1.47%

April 1, 2031	**1 year 0 months**	1.41%
April 1, 2032	**1 year 0 months**	0.82%
April 1, 2033	**1 year 0 months**	0.81%
April 1, 2034	**1 year 0 months**	0.77%
April 1, 2035	**1 year 0 months**	0.87%
April 1, 2036	**1 year 0 months**	0.86%
April 1, 2037	**1 year 0 months**	0.86%
April 1, 2038	**1 year 0 months**	0.88%
April 1, 2039	**1 year 0 months**	0.84%
April 1, 2040	**Remaining**	0.86%

Component: HPS

Initial Investment

Initial Cost (base-year $):	$14,350
Annual Rate of Increase:	3%
Expected Asset Life:	3 years 0 months
Residual Value Factor:	0%

Cost-Phasing

Cost Adjustment Factor: 0%

Years/Months (from Date)	Date	Portion
0 years 0 months	**January 1, 2011**	100%

Routine Non-Recurring OM&R: Bulb replacement - Year 3

Years/Months:	3 years 0 months
Amount:	$650
Annual Rate of Increase:	3%

Routine Non-Recurring OM&R: Bulb replacement - Year 6

Years/Months:	6 years 0 months
Amount:	$2,400
Annual Rate of Increase:	3%

Routine Non-Recurring OM&R: Bulb replacement - Year 9

Years/Months:	9 years 0 months
Amount:	$650
Annual Rate of Increase:	3%

Alternative: LED w/ control

Energy: Electricity

Annual Consumption:	3,893.0 kWh
Price per Unit:	$0.11830
Demand Charge:	$0
Utility Rebate:	$0
Location:	Maryland
Rate Schedule:	Commercial
State:	Maryland

Usage Indices

From Date	Duration	Usage Index
January 1, 2011	**Remaining**	100%

Escalation Rates

From Date	Duration	Escalation
April 1, 2010	**1 year 0 months**	-6.07%
April 1, 2011	**1 year 0 months**	1.32%
April 1, 2012	**1 year 0 months**	1.27%

April 1, 2013	**1 year 0 months**	-0.69%
April 1, 2014	**1 year 0 months**	-0.24%
April 1, 2015	**1 year 0 months**	1.02%
April 1, 2016	**1 year 0 months**	1.09%
April 1, 2017	**1 year 0 months**	0.32%
April 1, 2018	**1 year 0 months**	-0.28%
April 1, 2019	**1 year 0 months**	0.48%
April 1, 2020	**1 year 0 months**	0.63%
April 1, 2021	**1 year 0 months**	0.32%
April 1, 2022	**1 year 0 months**	0.47%
April 1, 2023	**1 year 0 months**	0.82%
April 1, 2024	**1 year 0 months**	0.39%
April 1, 2025	**1 year 0 months**	0.46%
April 1, 2026	**1 year 0 months**	0.73%
April 1, 2027	**1 year 0 months**	0.8%
April 1, 2028	**1 year 0 months**	1.55%
April 1, 2029	**1 year 0 months**	1.49%
April 1, 2030	**1 year 0 months**	1.47%
April 1, 2031	**1 year 0 months**	1.41%
April 1, 2032	**1 year 0 months**	0.82%
April 1, 2033	**1 year 0 months**	0.81%
April 1, 2034	**1 year 0 months**	0.77%
April 1, 2035	**1 year 0 months**	0.87%
April 1, 2036	**1 year 0 months**	0.86%
April 1, 2037	**1 year 0 months**	0.86%
April 1, 2038	**1 year 0 months**	0.88%
April 1, 2039	**1 year 0 months**	0.84%
April 1, 2040	**Remaining**	0.86%

Component:

Initial Investment

Initial Cost (base-year $):	$21,920
Annual Rate of Increase:	3%
Expected Asset Life:	12 years 0 months
Residual Value Factor:	0%

Cost-Phasing

Cost Adjustment Factor: 0%

Years/Months (from Date)	Date	Portion
0 years 0 months	**January 1, 2011**	100%

Routine Recurring OM&R: Changing batteries

Amount:	$59
Annual Rate of Increase:	3%

Usage Indices

From Date	Duration	Factor
January 1, 2011	**Remaining**	100%

Alternative: LED w/o control

Energy: Electricity

Annual Consumption:	3,872.0 kWh
Price per Unit:	$0.11830
Demand Charge:	$0
Utility Rebate:	$0
Location:	Maryland
Rate Schedule:	Commercial
State:	Maryland

Usage Indices

From Date	Duration	Usage Index
January 1, 2011	**Remaining**	100%

Escalation Rates

From Date	Duration	Escalation
April 1, 2010	**1 year 0 months**	-6.07%
April 1, 2011	**1 year 0 months**	1.32%
April 1, 2012	**1 year 0 months**	1.27%
April 1, 2013	**1 year 0 months**	-0.69%
April 1, 2014	**1 year 0 months**	-0.24%
April 1, 2015	**1 year 0 months**	1.02%
April 1, 2016	**1 year 0 months**	1.09%
April 1, 2017	**1 year 0 months**	0.32%
April 1, 2018	**1 year 0 months**	-0.28%
April 1, 2019	**1 year 0 months**	0.48%
April 1, 2020	**1 year 0 months**	0.63%
April 1, 2021	**1 year 0 months**	0.32%
April 1, 2022	**1 year 0 months**	0.47%
April 1, 2023	**1 year 0 months**	0.82%
April 1, 2024	**1 year 0 months**	0.39%
April 1, 2025	**1 year 0 months**	0.46%
April 1, 2026	**1 year 0 months**	0.73%
April 1, 2027	**1 year 0 months**	0.8%
April 1, 2028	**1 year 0 months**	1.55%
April 1, 2029	**1 year 0 months**	1.49%
April 1, 2030	**1 year 0 months**	1.47%
April 1, 2031	**1 year 0 months**	1.41%
April 1, 2032	**1 year 0 months**	0.82%
April 1, 2033	**1 year 0 months**	0.81%
April 1, 2034	**1 year 0 months**	0.77%
April 1, 2035	**1 year 0 months**	0.87%

April 1, 2036	**1 year 0 months**	0.86%
April 1, 2037	**1 year 0 months**	0.86%
April 1, 2038	**1 year 0 months**	0.88%
April 1, 2039	**1 year 0 months**	0.84%
April 1, 2040	**Remaining**	0.86%

Component:

Initial Investment

Initial Cost (base-year $):	$21,460
Annual Rate of Increase:	3%
Expected Asset Life:	12 years 0 months
Residual Value Factor:	0%

Cost-Phasing

Cost Adjustment Factor: 0%

Years/Months (from Date)	Date	Portion
0 years 0 months	**January 1, 2011**	100%

Routine Recurring OM&R: Copy of: Changing batteries

Amount:	$0
Annual Rate of Increase:	3%

Usage Indices

From Date	Duration	Factor
January 1, 2011	**Remaining**	100%

Appendix H – Comparative Analysis Report from NIST's BLCC

Case 1: HPS vs LED w/ demand-sensitive dimming control

NIST BLCC 5.3-10: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: HPS

Alternative: LED w/ control

General Information

File Name:	/Users/pmanisa/Desktop/LED2.xml
Date of Study:	Thu Oct 17 09:52:36 EDT 2013
Project Name:	LED Street Lighting System
Project Location:	Maryland
Analysis Type:	MILCON Analysis, Energy Project
Analyst:	Manisa
Comment	This project compares economic performance of the existing HPS street lighting system vs the new LED street lighting system (to be installed).
Base Date:	January 1, 2011
Beneficial Occupancy Date:	January 1, 2011
Study Period:	12 years 0 months(January 1, 2011 through December 31, 2022)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative

Initial Investment Costs:			
Capital Requirements as of Base Date	$14,350	$21,920	-$7,570
Future Costs:			
Energy Consumption Costs	$17,909	$4,663	$13,247
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Routine Recurring and Non-Recurring OM&R Costs	$3,700	$708	$2,992
Major Repair and Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	$0	$0
	------------	------------	------------
Subtotal (for Future Cost Items)	$21,609	$5,371	$16,239
	------------	------------	------------
Total PV Life-Cycle Cost	$35,959	$27,291	$8,669

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$16,239
- Increased Total Investment	$7,570

Net Savings	$8,669

Savings-to-Investment Ratio (SIR)

SIR = 2.15

Adjusted Internal Rate of Return

AIRR = 9.77%

Payback Period

Estimated Years to Payback (from beginning of Beneficial Occupancy Period)

Simple Payback occurs in year 6

Discounted Payback occurs in year 7

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	14,953.0 kWh	3,893.0 kWh	11,060.0 kWh	132,689.7 kWh

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	51.0 MBtu	13.3 MBtu	37.7 MBtu	452.8 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO_2	9,863.08 kg	2,567.84 kg	7,295.24 kg	87,522.89 kg
SO_2	79.31 kg	20.65 kg	58.66 kg	703.79 kg
NOx	17.88 kg	4.65 kg	13.22 kg	158.63 kg
Total:				
CO_2	9,863.08 kg	2,567.84 kg	7,295.24 kg	87,522.89 kg
SO_2	79.31 kg	20.65 kg	58.66 kg	703.79 kg
NOx	17.88 kg	4.65 kg	13.22 kg	158.63 kg

Case 2: HPS vs LED w/o demand-sensitive dimming control

NIST BLCC 5.3-10: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: HPS

Alternative: LED w/o control

General Information

File Name:	/Users/pmanisa/Desktop/LED2.xml
Date of Study:	Thu Oct 17 09:54:47 EDT 2013
Project Name:	LED Street Lighting System
Project Location:	Maryland
Analysis Type:	MILCON Analysis, Energy Project
Analyst:	Manisa
Comment	This project compares economic performance of the existing HPS street lighting system vs the new LED street lighting system (to be installed).
Base Date:	January 1, 2011
Beneficial Occupancy Date:	January 1, 2011
Study Period:	12 years 0 months(January 1, 2011 through December 31, 2022)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$14,350	$21,460	-$7,110
Future Costs:			

Energy Consumption Costs	$17,909	$4,637	$13,272
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Routine Recurring and Non-Recurring OM&R Costs	$3,700	$0	$3,700
Major Repair and Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	$0	$0
	------------	------------	------------
Subtotal (for Future Cost Items)	$21,609	$4,637	$16,972
	------------	------------	------------
Total PV Life-Cycle Cost	$35,959	$26,097	$9,862

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$16,972
- Increased Total Investment	$7,110

Net Savings	$9,862

Savings-to-Investment Ratio (SIR)

SIR = 2.39

Adjusted Internal Rate of Return

AIRR = 10.75%

Payback Period

Estimated Years to Payback (from beginning of Beneficial Occupancy Period)

Simple Payback occurs in year	5
Discounted Payback occurs in year	6

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	14,953.0 kWh	3,872.0 kWh	11,081.0 kWh	132,941.7 kWh

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	51.0 MBtu	13.2 MBtu	37.8 MBtu	453.6 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO2	9,863.08 kg	2,553.99 kg	7,309.09 kg	87,689.08 kg
SO2	79.31 kg	20.54 kg	58.77 kg	705.12 kg
NOx	17.88 kg	4.63 kg	13.25 kg	158.93 kg
Total:				
CO2	9,863.08 kg	2,553.99 kg	7,309.09 kg	87,689.08 kg
SO2	79.31 kg	20.54 kg	58.77 kg	705.12 kg
NOx	17.88 kg	4.63 kg	13.25 kg	158.93 kg

Appendix I – Survey Questions

LED Satisfaction Survey

This survey is conducted in conjunction with the "*Bi-level demand-sensitive LED street lighting system*" project sponsored by the Department of Defense under Environmental Security Technology Certification Program (ESTCP). The objective of this survey is to evaluate user satisfaction and acceptance in light quality of the newly installed LED street lighting system at the Naval Surface Warfare Center (NSWC) – Carderock Division in West Bethesda, MD.

Please check appropriate boxes to answer our short questions below:

1) How satisfied are you with the overall performance of LED lighting?

	Extremely atis ied
	Very satisfied
	Mode ately satisfied
	Slightly satisfie
	Not at ll satisfied

2) How satisfied are you with the visibility improvement offered by the LED streetlights for you as a driver?

	Ex emely satisfied
	Very satisf d
	Modera ely atisfi d
	Slightly satisfie
	Not at all satisfied

3) How satisfied are you with the visibility improvement offered by the LED streetlights for you as a pedestrian?

	Extremely satisfied
	Very satisf d
	Moderately satisfied
	S htly satisf ed
	Not at all satisfied

4) Do you feel that the new streetlights give off the right amount of light, or are they too bright or too dim?

	Right amount of ligh
	Too rig t
	Too dim

Survey results associated with each question are presented below.

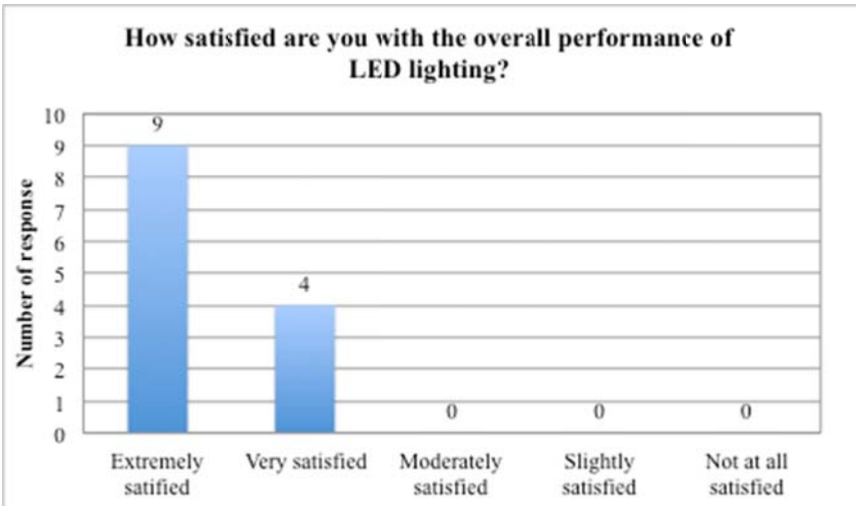


Fig. I-1. Survey results for Question 1 “How satisfied are you with the overall performance of LED lighting?”

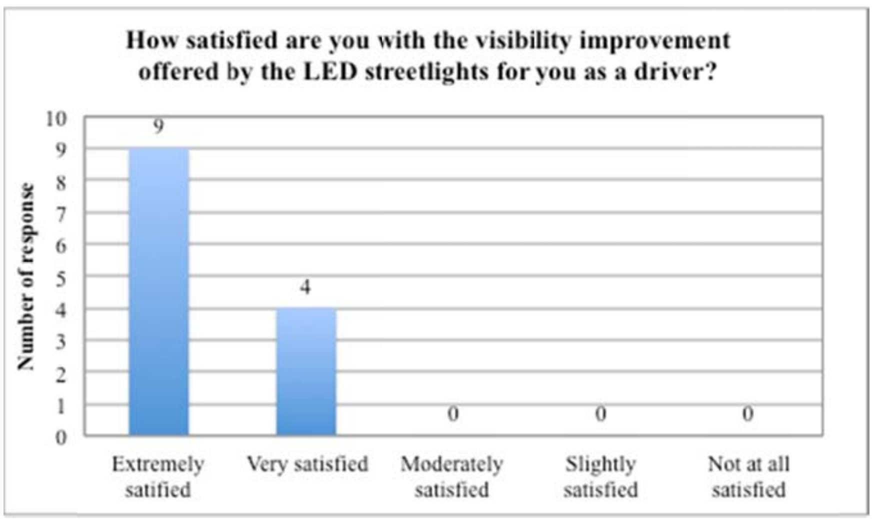


Fig. I-2. Survey results for Question 2 “How satisfied are you with the visibility improvement offered by the LED streetlights for you as a driver?”

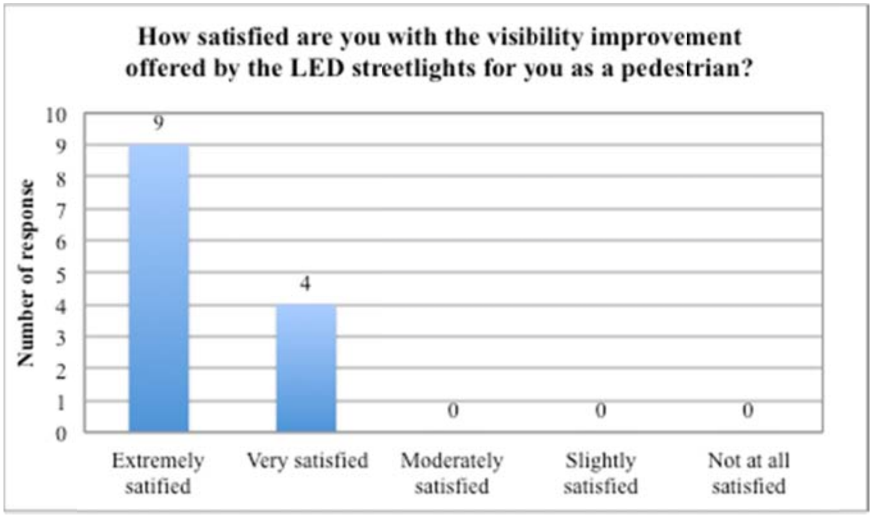


Fig. I-3. Survey results for Question 3 “How satisfied are you with the visibility improvement offered by the LED streetlights for you as a pedestrian?”

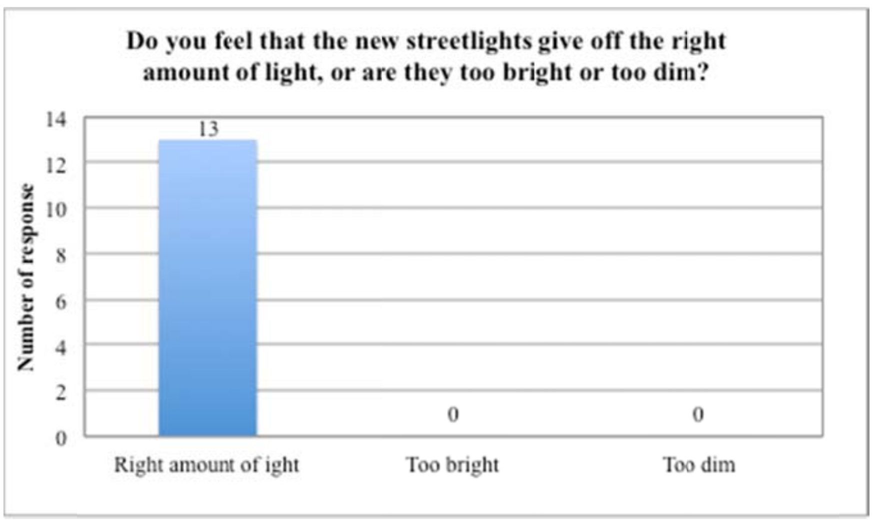


Fig. I-4. Survey results for Question 4 “Do you feel that the new streetlights give off the right amount of light, or are they too bright or too dim?”

References

[1] DOE Commercially Available LED Product Evaluation and Reporting (CALiPER) program [Online]. Available: http://www1.eere.energy.gov/buildings/ssl/caliper.html. Retrieved: May 2013

[2] DOE Solid-State Lighting GATEWAY Demonstrations [Online]. Available: http://www1.eere.energy.gov/buildings/ssl/gatewaydemos.html. Retrieved: May 2013.

[3] DOE Solid-State Lighting GATEWAY Demonstration Results [Online]. Available: http://www1.eere.energy.gov/buildings/ssl/gatewaydemos_results.html. Retrieved: May 2013.

[4] DOE, Demonstration Assessment of LED Parking Struture Lighting, March 2013 [Online]. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2013_gateway_dept-labor.pdf. Retrieved: May 2013.

[5] DOE, Use of Occupancy Sensors in LED Parking Lot and Garage Applications: Early Experience, October 2012 [Online]. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_gateway_sensors.pdf. Retrieved: May 2013.

[6] DOE, Demonstration Assessment of LED Roadway Lighting, September 2012 [Online]. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_gateway-msslc_philadelphia.pdf. Retrieved: May 2013.

[7] DOE, SSL Demonstration: Central Park, New York City, November 2012 [Online]. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/central-park_brief.pdf. Retrieved: May 2013.

[8] NEMA, Guidelines on the Application of Dimming to High Intensity Discharge Lamps, LSD 14-2002.

[9] Yunfen Ji and Robert Wolsey, Lighting Answers: Dimming Systems for High-Intensity Discharge Lamps, Vol 1, No. 4, September 1994, ISSN: 1069-0050.

[10] California Lighting Technology Center, Bi-Level Smart Parking Garage Fixture [Online]. Available: http://cltc.ucdavis.edu/content/view/668/355. Retrieved: May 2013.

[11] Ali Kriscenski, Ann Arbor Lighting Up with 100% LEDs, January 26, 2008 [Online]. Available: http://www.inhabitat.com/2008/01/26/ann-arbor-lighting-up-with-100-leds/. Retrieved: May 2013.

[12] Michael Keating, California Municipality Shifting to Energy-Saving LED Streetlights, May 2009 [Online]. Available: http://govpro.com/public_works/highways/content/LED_San_Jose_0518/. Retrieved: May 2013.

[13] Mark Halverson, "Current DoD Policies and Directives on Energy Conservation" [Online]. Available: http://www.wbdg.org/pdfs/usace_ewcdr_dod_policies.pdf. Retrieved: May 2013.

[14] The Institution of Lighting Engineers, "The Outdoor Lighting Guide", Taylor & Francis, 2005. ISBN: 0415370078.

[15] Virginia Driver's Manual [Online]. Available: http://www.dmv.state.va.us/webdoc/pdf/dmv39.pdf. Retrieved: May 2013.

[16] Data published by Green Purchasing Institute, Berkeley, CA [Online]. Available http://www.zeromercury.org/EU_developments/AnnexIVMercury_inHPS_LampsEU_Recs.pdf. Retrieved: August 2009.

[17] EIA, Electric Power Monthly [Online]. Available: http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a. Retrieved May 2013.