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LED Street Lighting and Network Controls
San Francisco, CA

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Preface

Energy Solutions provided monitoring, data collection, and data analysis services for this Light-Emitting Diode Street Lighting and Network Controls Assessment Project under contract to the Emerging Technologies Program of Pacific Gas and Electric Company (PG&E). The project was carried out in collaboration with the San Francisco Public Utilities Commission (SFPUC). This project evaluated the replacement of 400W and 200W nominal high-pressure sodium streetlights with networked LED streetlights in the SFPUC pilot location. This project also included functional testing and energy performance assessment of the streetlight network controls technology.

The LED streetlight model chosen by the SFPUC to replace 400W HPS streetlights for this evaluation was the BetaLED LEDway™ 120-LED Type III luminaire rated at 222W, hereinafter referred to as LED streetlight A. The LED streetlight model chosen by the SFPUC to replace 200W HPS streetlights for this evaluation was the LED Roadway Satellite Series 96-LED Type II LED luminaire rated at 88W, hereinafter referred to as LED streetlight B.

Acknowledgements

This project was funded by the Emerging Technologies Program of PG&E. Energy Solutions would like to gratefully acknowledge the participation and assistance of the SFPUC, and cooperation from BetaLED, LED Roadway, and ROAM / Acuity.

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Executive Summary

This report summarizes an assessment project conducted to study the performance of light-emitting diode (LED) luminaires with network controls in two different street lighting applications. The project included installation of LED streetlights with network controls on public roadways in San Francisco Public Utilities Commission (SFPUC) service territory in San Francisco, California. Quantitative light and electrical power measurements as well as surface-level photographs and overhead photographs from a maintenance bucket truck were taken to compare base case high-pressure sodium (HPS) performance with that of the LED replacement luminaires. Network controls functionality and monitoring capabilities were also tested and qualitative satisfaction with the system was gauged through a user survey. Estimated economic performance of the LED streetlights and network controls was compared to that of the incumbent HPS streetlights.

This pilot project consisted of two unique street lighting applications. In the first, 20 400W nominal HPS luminaires were replaced with Type III LED luminaires rated at 222W (LED streetlight A). In the second application, 32 200W nominal HPS luminaires were replaced with Type II LED luminaires from a different manufacturer rated at 88W (LED streetlight B). The SFPUC selected, procured and installed the retrofit LED luminaires. The LED street lighting pilot location chosen by the SFPUC was the Tenderloin District of San Francisco in an area bounded by Leavenworth Street, Eddy Street, Mason Street, and Market Street. Within the pilot area, a block of Leavenworth Street and a block of Turk Street were chosen as specific test locations where comparative lighting and energy performance data was collected. The dimensions of these test locations were also used for computer modeling of HPS and LED streetlight performance.

The street lighting network controls technology deployed for this demonstration was the ROAM (Remote Operation Asset Management) system, a remote streetlight monitoring and management system designed to improve street lighting service by identifying streetlight malfunctions, reducing outage durations, and minimizing system costs. The technology consists of wireless transceiver-equipped ROAM photocell nodes compatible with streetlight twist-lock receptacles, one or more ROAM gateway devices that manage network nodes through a wireless mesh network and connect the network to the internet through cellular uplink (Ethernet or other wireless uplink options are also available), a Network Operation Center (NOC) that collects and manages network data, and a secure ROAM internet portal for system access and management. Along with detecting and recording asset malfunctions, the ROAM system can be used to turn streetlights on and off manually or by issuing scheduled on/off operation, and the system logs power draw and energy information for connected streetlights. The piloted ROAM system did not allow for dimming, which limited its energy savings potential, but the company has developed a version of the streetlight controls product that includes Dimming Control Modules (DCM) mounted inside the luminaire that are compatible with 0-10v dimming ballasts and drivers. This product is scheduled for full launch in summer of 2010, though prototypes have already shipped to several ROAM customers.

Energy Performance

Energy savings potential from the replacement of the streetlights was a key performance consideration for this study. The network controls also allowed for operation schedule changes with energy savings implications, but the SFPUC did not desire to reduce streetlight runtime in the pilot location so no runtime savings were assumed. A summary of measured electric power results for the base case HPS luminaires and for LED luminaires is presented in Table I below. It was assumed that the base case HPS and LED retrofit streetlights operate 4,100 hours annually.[1] Energy costs are based on the SFPUC rates for streetlight electricity. PG&E electric rates for street lighting are higher, which would improve the economic outlook for LED street lighting projects; economic calculations were also run with PG&E rates for comparison (see Streetlight and Network Controls Economic Performance).

Table I: Average System Power per Luminaire and Estimated Savings

Street Lighting Scenarios	Power[I] (W)	Power Savings (W)	% Power Savings over HPS	Estimated Annual Energy Savings (kWh)	Annual Energy Cost Savings per Streetlight
400W HPS	481.1	-	-	-	-
LED A	224.1	257.0	53.4%	1,054	$105
200W HPS	227.1	-	-	-	-
LED B	93.6	133.5	58.8%	547	$55

I. Power includes measured luminaire wattage plus weighted controls wattage for the networked LEDs

This study estimates that if the nationwide stock of installed HPS and other HID roadway luminaires, which together account for almost 85% of roadway lighting electricity, were replaced with LED luminaires at 50% power savings, over 12,900 GWh of total annual electric energy savings could be achieved. This corresponds to avoiding around 10 million metric tons of CO_2 emissions or the equivalent of saving 22 million barrels of oil (See Potential Savings).

Lighting Performance

It should be emphasized that this report includes analysis of two unique applications: 1) base case 400W HPS cobraheads replaced by LED streetlight A from one manufacturer, on a roadway with unique luminaire spacings, and 2) base case 200W HPS cobraheads replaced by LED streetlight B from a different manufacturer, on a different roadway with unique luminaire spacing. For both of these applications, the report analyzes the performance of the LED streetlight as compared to the base case HPS streetlight. However, it is not appropriate to compare the performance results of the two demonstrated LED options to each other.

Limited photopic and scotopic illuminance measurements were taken in the field to evaluate HPS and LED streetlight performance on Leavenworth and Turk Streets. Field illuminance measurements did not cover the entire roadways, so averages of the measured points would not be indicative of overall performance. However, comparison of the high, mid, and low-range measured levels before and after LED retrofit does provide some indication of changes in illuminance levels. For more thorough characterizations of lighting performance, a computer model was used to generate illuminance levels over simulated measurement grids covering roadways with the same dimensions as the actual locations on each street. Comparative metrics calculated from modeled data included average, maximum, and minimum illuminance and uniformity values (coefficient of

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[1] Based on PG&E LS-2 Rate Schedule for Customer Owned Streetlights; see Appendix E.

variation, average-to-minimum uniformity ratio, and maximum-to-minimum uniformity ratio). Due to uncertainties as to performance changes over time, particularly in the case of the LED luminaires, for which there is no standard method for estimating long term light source depreciation, only initial streetlight performance for the HPS and LED sources was computer modeled (no light loss factors assumed).

For the demonstration roadways, classified as high pedestrian-conflict collectors, the Illuminating Engineering Society of North America (IESNA) RP-8-00 lighting standard calls for minimum average illuminance of 1.2 fc (pavement reflectance class R2-R3) and average-to-minimum uniformity (AMU) of 4.0. For the 400W and 200W HPS base cases, the modeled HPS and LED sources met the average illuminance requirement initially (rounded to the tenths place). However, the RP-8-00 standard is written for maintained illuminance over the light source lifetime, which would be lower due to various depreciation factors (lamp depreciation, dirt and weathering, etc.). For both of the LED streetlight models evaluated, maintained illuminance in the demonstration layouts would likely fall below RP-8-00's minimum recommendation. To assure minimum maintained illuminance levels, slightly higher output would be required from the LED streetlights, either by adjusting drive current settings for higher output or installing different luminaire models.

For both evaluated applications (400W and 200W base cases), the HPS and LED light sources fell well within the AMU requirement. Lighting uniformity changed little from the HPS sources to the LED sources, though there was a slight decrease in uniformity from the 200W HPS to the LEDs.

Table II: Summary Modeled Photopic Illuminance Results

Luminaire	Average Illuminance (fc)	Coefficient of Variation	Average-to-Minimum Uniformity	Maximum-to-Minimum Uniformity
400W HPS	3.38	0.53	2.42	5.93
LED A	1.15	0.53	2.30	5.60
200W HPS	2.24	0.33	2.03	3.36
LED B	1.30	0.39	2.61	4.60

Table III: Summary Measured Photopic Illuminance Results

Luminaire	High Range Illuminance (fc)	Mid Range Illuminance (fc)	Low Range Illuminance (fc)
400W HPS	6.47	2.30	0.98
LED A	2.63	1.25	0.50
% Change	-59.4%	-45.7%	-49.0%
200W HPS	3.33	1.93	1.85
LED B	2.57	1.36	0.90
% Change	-22.8%	-29.5%	-51.4%

Based on computer modeled average illuminance results for the incumbent 400W and 200W HPS streetlights, it is evident that both locations were originally lit well above the IESNA minimum recommendation. The reason for this lighting design is the high level of night time activity typical for the area. Computer modeled results showed significant reductions in average photopic illuminance for the LED streetlights as compared to the modeled performance of the HPS streetlights. A significant decrease in the photopic illuminance levels measured in the field was also observed. However, even with lower photopic light levels under the replacement LED streetlights, qualitatively the SFPUC host site contact reported that the LED streetlights were an improvement over the HPS streetlights. Responding to a short questionnaire on street lighting performance at the demonstration locations, the host contact reported satisfactory or improved driver and pedestrian visibility, location appearance, and safety for both LED streetlight installations.

While results showed lower photopic output for the LED options, it is important to recognize the differences in scotopic performance of the HPS and LED sources. HPS is a narrower spectrum light source that emits energy mostly in wavelengths of 550 to 650 nm. This falls within the range of the photopic visual efficiency function, which peaks between 560 to 600 nm and is driven only by the eye's cone photoreceptors. LEDs and other broad spectrum sources also emit in short wavelengths that excite the rod photoreceptors and are more heavily weighted by scotopic and mesopic visual efficiency functions (see Mesopic Illuminance Discussion). Illuminance levels under nighttime roadway conditions typically fall in the mesopic range of visual perception where both cone and rod photoreceptors are active. Research on the relative importance of mesopic performance and other broad spectrum light benefits is ongoing to determine if precisely equivalent photopic illuminance levels are necessary to provide adequate performance with LED improvements in mesopic output, color rendering, and luminous intensity distribution. Evaluating and demonstrating these possible benefits was one of the motivations for carrying out the street lighting pilot.

In both applications the field-measured LED illuminance levels in the scotopic range were higher than photopic levels, while the HPS scotopic illuminance levels were significantly lower than photopic output. In fact, LED scotopic illuminance levels were on average higher than those for the HPS. Ratios of scotopic-to-photopic output (S/P ratios) based on field illuminance measurements are listed below.

Table IV: Measured S/P Ratios

Luminaire	S / P Ratio
400W HPS	0.58
LED A	1.84

Luminaire	S / P Ratio
200W HPS	0.63
LED B	1.62

These light source S/P ratios were used to scale from computer modeled photopic illuminance levels to scotopic levels. Mesopic illuminance levels were then calculated based on several models (see Mesopic Illuminance section). There was little or no difference between photopic illuminance and mesopic illuminance for the HPS sources, while mesopic illuminance levels were higher than photopic illuminance levels for the LED luminaires.

Table V: Average Illuminance Results from Mesopic Models

Luminaire	Modeled Photopic Values	MOVE Model	Unified Luminance Method	LEM Method
400W HPS	3.38	3.14	3.34	3.38
LED A	1.15	1.39	1.35	1.99
200W HPS	2.24	2.06	2.16	2.24
LED B	1.30	1.50	1.46	2.24

Network Controls Performance

A test plan to evaluate the network controls system was prepared to collect information on system design, set-up, and use from the manufacturer and SFPUC personnel, and from hands-on experience. This plan included four evaluation categories:

1. Technology overview and equipment description: network components, features, management system, and vendor specifications for performance, precision, durability, energy usage
2. User survey and interviews: user feedback on control technology's installation and use, advantages and drawbacks, including satisfaction scales and qualitative comments
3. System functional testing: operation of web interface and network functions; observe input of scheduling and dimming commands; data queries; report production; streetlight mapping; etc. including field observations of system response and logged power data
4. System economics: cost estimates from manufacturer and potential cost savings due to system installation to provide system payback and present value analysis

Results from the network controls testing activities are summarized below. In general, the pilot demonstrated that web-based control, monitoring, and management of street lighting inventories through network controls is possible and that RF mesh networking with photocell-adapted streetlight nodes represents a simple, effective solution requiring little additional infrastructure. The ROAM system was found to be easy to install and commission, as the controls were compatible with standard photocell receptacles and the nodes networked themselves after installation. Programming network attribute data for each installed node and other system set-up steps required minimal training for operators, and the web-based management tool provided useful benefits for system operation. Successful luminaire control, grouping, and outage detection from the user interface was observed during testing. Customer support was also easily available during system testing to address questions. However, some difficulties arose with luminaire scheduling features, as actual activation of saved schedules appeared to lag by one day from settings. This issue was mitigated after customer support was contacted to activate same-day event scheduling. The controls were also not compatible with dimmable streetlights for the demonstration, though future ROAM controls will reportedly include an integrated Dimming Control Module (DCM) compatible with 0-10v dimming drivers.

Energy monitoring and metering is one of the key potential benefits of advanced street lighting controls. The ROAM system as demonstrated was able to measure luminaire power with on-board circuitry and log average readings at hourly intervals. The system was also able to generate exportable files with hourly data and would be customizable to provide information for desired periods of times and aggregations of assets. Luminaire-level power measurements were not viewable in real-time however; they had to be queried at least one day after logging.

In order to maintain network communication, system components drew some power whether the streetlights were on or off, though spread over the entire street lighting inventory, the on-state weighted load per streetlight was quite small (around 3W). ROAM power measurement accuracy varies over the controlled-load range, from -10% to +5% for loads of 40 – 1000W. Reported accuracy at a load of 100W is 2.7%, while at a higher load of 400W the reported accuracy improves to 0.5%. Next generation ROAM controls will reportedly improve on power metering accuracy.

Table VI: Network Controls Performance Summary

Network Controls System Feature	Advantages	Drawbacks	Survey Ranking Most Satisfied 1 – 5 Least Satisfied
System Design and Compatibility	Simple product design … luminaire control system utilized NEMA twist lock receptacle, minimal training required		1
System Installation	The initial installation of the ROAM system was extremely simple system; arrived pre-programmed		1
System Commissioning	Custom activation manual made entering attribute information extremely easy, node coordinates updated through web …took only minutes	GPS communication during installation was an issue due to interference from buildings; nodes took 2-3 days (quiet period) to establish in network	2
System Energy Benefits	Scheduled reductions in run-time possible with controls (not tested in pilot)	Low overall energy benefit, would be improved with dimming. Controls add some minimal continuous load	4
Web-based System Interface	"…found the interface and its functions to be almost intuitive"	Some difficulty with scheduling feature; problems activating schedule timely for test event (one-day lag)	2
Energy Metering	Reporting of avg. power, energy enabled for single streetlights; capable of exporting averages to .csv, .pdf files for analysis; fixture burn hours and KWh reports available by day, month	Does not display power in real time; reporting lags by one day. System-wide power totals not available but could be programmed by ROAM	N / A
Outage Detection, Maintenance Planning	Reports operation status daily, "Completely value added … enables proactive maintenance. Identified outage during testing"		1
Customer Support	"Customer support provided immediately at each request; called support during scheduling exercise to work out questions"		1

Economic Performance

Though still an emerging technology, LED streetlights are beginning to experience greater market adoption as costs decline and consumers become more familiar with the technology and more confident in performance and energy savings benefits. Recent announcements of LED street lighting plans by cities like Los Angeles, CA (4,000 shipped and up to 140,000 planned installations) and Pittsburgh, PA (proposal to replace 40,000+) demonstrate that LED streetlights are being taken seriously. Even so, this technology currently accounts for only a small fraction of the national installed base.

Networked streetlights are more rare; these control options represent a major shift from the traditional model of photocell controlled lights with no operator feedback. Network controls can provide operators various lighting and energy management benefits such as reduced runtimes and detection of outages and "day-burners," and controls with dimming capabilities that enable adaptive street lighting strategies to reduce lighting power as conditions change (i.e. periods of lower traffic or pedestrian volume). A few products are starting to make inroads in the U.S. street lighting market; the City of Glendale, AZ has just networked 18,500 streetlights with wireless controls, and Los Angeles has announced similar plans. San Jose, CA has announced that it is installing a pilot of 155 ROAM-enabled LED streetlights with dimming controls in 2010. San Jose also recently installed a pilot 120 streetlight system of dimmable LEDs networked by power-line carrier technology. European cities have demonstrated these types of network controls as well, such as Oslo, Norway's deployment of over 15,000 power-line carrier controlled "smart streetlights."

In this evaluation, calculations of simple payback period and net present value were made for LED streetlight installations with and without ROAM network controls, based on estimated energy and maintenance savings compared to incumbent HPS streetlights. For broader applicability, the estimated system costs used in economic calculations were for larger-scale installations than those of the pilot. Retrofit scenarios and replacement at end-of-useful life / new construction scenarios were both evaluated. Retrofit economics consider the total cost of the LED luminaire and controls, including installation labor costs. Replacement at end-of-useful life / new construction economics only include the incremental cost of the LED luminaire and controls above the HPS luminaire cost and do not include labor costs, which would be roughly equal regardless of technology choice.

Economic estimates are sensitive to site-specific variables such as maintenance and energy costs, and to LED luminaire and network controls costs. Results are also predicated on assumed maintenance savings from longer lasting LEDs and controls benefits. Results presented here are only meant to characterize economic performance at the equipment, energy, and maintenance costs assumed for this evaluation. Both LED streetlight manufacturers whose streetlights were evaluated offer various other LED streetlight models at different price points and outputs that may be more appropriate for other 400W and 200W HPS replacement projects, depending on location variables (pole spacing, road width, vehicle and pedestrian traffic, etc.). Readers are advised to use cost estimates and equipment lifetime assumptions appropriate for their own location and project specific analyses.

Three economic scenarios were developed for the two streetlight retrofit applications evaluated in this report:

1. Non-networked LEDs
2. Networked LEDs (higher cost, additional maintenance savings)
3. Hypothetical Adaptive Networked LEDs dimmed to 50% power for half of each night (highest initial cost and highest energy savings)

The outlined adaptive scenario is purely hypothetical and would not be feasible for the SFPUC pilot location because the LED streetlights and controls did not include dimming options. The example is meant only to illustrate what might be possible with dimmable networked LED streetlights, especially in light of ROAM's introduction of prototype dimming network controls.

There is typically a direct correlation between LED price and light output for a given manufacturer's product line. However, as noted previously, LED streetlights from two different manufacturers were used in the two applications evaluated here. For the SFPUC pilot, the LED luminaires selected to replace the 200W HPS streetlights had a higher relative cost per lumen of light output than the LED luminaires selected to replace the 400W HPS streetlights, resulting in the specific economic conclusions shown here. These economic conclusions should not be used to generalize for all cases.

Table VII: Summary Economics Results

Scenario			End-of-Useful Life / New Construction			Retrofit		
Base Case	LED Case	Annual Savings	Initial Investment	Simple Payback (Years)	15-Year NPV	Initial Investment	Simple Payback (Years)	15-Year NPV
400W HPS	Non-networked	$168	$706	5.8	$926	$1,056	8.7	$576
	Networked	$196	$775	6.1	$919	$1,125	8.9	$570
	Networked, Adaptive	$216	$830	5.6	$1,167	$1,180	7.9	$818
200W HPS	Non-networked	$64	$574	8.0	$381	$903	12.7	$52
	Networked	$67	$643	8.5	$374	$972	12.8	$45
	Networked, Adaptive	$76	$698	8.2	$443	$1,026	12.0	$114

Using SFPUC electricity rates and average estimated maintenance costs from 2008 data for the SFPUC streetlight inventory ($30 per streetlight per year), results from this study showed retrofit paybacks of 8 to 12 years for the replacement of the HPS streetlights with networked or non-networked LEDs and net present values (NPV) in the $50 to $800 range. Simple payback and NPV improved for end-of-useful life / new construction scenarios due to lower incremental project costs. For the 400W and 200W HPS base cases, the difference in simple payback for non-networked, networked, and adaptive networked options was small as estimated annual savings were always higher for the more expensive options.

When maintenance cost data from 2008 was differentiated according to HPS streetlight wattage (rather than using inventory-average maintenance costs), 400W HPS streetlight maintenance costs were found to be almost four times the SFPUC inventory average due to unusually frequent maintenance visits for lamp replacements (See Estimated Installation and Maintenance Costs). Economic calculations using these higher baseline maintenance costs, and consequently higher assumed savings, resulted in paybacks as low as 5.2 years for 400W HPS retrofits (See Retrofit Economics).

Using inventory-average maintenance costs and savings, but applying the PG&E streetlight electricity rates for energy savings estimates and including an available incentive level of $150 per streetlight for these types of LED installations (400W and 200W replacements) in PG&E service territory, the economic performance of the LED options improved for both HPS base cases. For the 400W HPS base case, retrofit paybacks improved to around 7 years and NPV increased to $800 to $1,100. For the 200W HPS base case, the increase in energy savings and decrease in initial project cost brought the retrofit payback periods down to around 9 years and NPV to $400 to $500. (See Streetlight and Network Controls Economic Performance).

This study shows that energy savings potential from available LED streetlights is significant. The network controls system demonstrated by SFPUC also showed that streetlight networking through existing twist-lock receptacles and wireless technology is possible and relatively simple to implement. Controls that allow operators to more proactively and efficiently manage street lighting assets should provide cost savings, but expected energy impacts of non-dimming controls are limited. Dimming controls that give operators the ability to adjust lighting power to meet minimum performance criteria based on changing conditions would offer even more energy savings potential. Scheduled trimming of streetlight run time would also provide additional energy savings, though this was not tested in the demonstration.

In addition to lighting and energy performance, the cost/benefit analysis for networked LED street lighting investments will be a key evaluation criterion for municipalities and utilities considering these technologies. Project economics are subject to location specifics such as costs of equipment, labor, and maintenance and the longevity of the installed controls and luminaire components. The higher initial cost of LED streetlights and advanced controls is a challenge but the energy and maintenance savings can provide real long term value.

The energy cost savings estimated in this study assume that street lighting electricity is billed based on actual energy usage, whereas typically streetlights are not metered but are billed at flat rates that assume monthly runtime and energy use. For customers wishing to use network controls to alter street lighting schedules in any way, including enacting adaptive dimming strategies, cost savings will only be realized if applicable metered utility rate schedules are available. Network controls products with metering functions can facilitate this option, but they will need to be able to provide metered energy data in a useful format and at a level of accuracy acceptable to utilities.

Project Background

Project Overview

This LED street lighting and network controls assessment project studied the viability of networked LED luminaires as replacements for existing HPS streetlights. Project partners included the SFPUC and PG&E. HPS luminaires of 400W and 200W nominal rating located in the Tenderloin District in San Francisco, CA were replaced with new LED luminaires. The LED luminaires were evaluated for lighting and energy performance and economic metrics such as simple payback and net present value (NPV). This project also included functional testing and evaluation of streetlight network controls. The assessment was conducted as part of the Emerging Technologies Program of PG&E. The Emerging Technologies program "is an information-only program that seeks to accelerate the introduction of innovative energy efficient technologies, applications and analytical tools that are not widely adopted in California… [The] information includes verified energy savings and demand reductions, market potential and market barriers, incremental cost, and the technology's life expectancy."[2]

Streetlight Technology and Market Overview

The most prevalent roadway lighting technology today is high-intensity discharge (HID), most commonly HPS, and less frequently metal halide and mercury vapor. These light sources account for almost 85% of the estimated 31 TWh electricity used annually for roadway lighting.[3] HPS is the most common source primarily because of its long rated life, low cost, and relatively high efficiency. An HPS drawback is low color rendition (typical CRI of 22) due to narrow spectral distribution.[4]

Market penetration of LED streetlights is still relatively low, though the technology is continuing to attract attention for potential energy and maintenance savings and lighting performance benefits such as more uniform lighting distribution and enhanced nighttime visibility. The City of Los Angeles, CA has announced large scale LED conversion plans, with 4,000 streetlights shipped, and up to 140,000 planned for retrofit.[5] The City estimates that LEDs will reduce street lighting energy usage by 40% and save $10 million annually in combined maintenance and energy costs. Other locations leading the transition to LED street lighting include Pittsburgh, PA which has proposed replacing its streetlights (over 40,000) with LEDs for energy, environmental, and economic benefits ($2.5 million annual savings estimated)[6] and Anchorage, AK, which is installing 16,000 LED streetlights city-wide.

Municipal interest in LED streetlight conversions has grown to the point that the DOE in fall 2009 announced the planned establishment of a Municipal Solid-State Street Lighting Consortium to "collect, analyze, and share technical information and experiences related to LED street lighting

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[2] Pacific Gas and Electric Company (2006). Program Descriptions, Market Integrated Demand Side Management, Emerging Technologies.

[3] Navigant Consulting, Inc. (2002). "US Lighting Market Characterization, Volume I." Tables 5-7, 5-17, 5-20, and 8-7. http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lmc_report_tables.pdf

[4] High-Intensity Discharge Lamps Analysis of Potential Energy Savings Docket #: EE-DET-03-001 USDOE Technical Support Document: Energy Efficiency Program for Commercial and Industrial Equipment. December 2004

[5] See LEDs Magazine article *BetaLED streetlights included in Los Angeles retrofit program*. Sept 22, 2009 http://www.ledsmagazine.com/news/6/9/22

[6] LEDs Magazine article Pittsburgh councilman releases plan to convert city streetlights to LEDs. Dec. 17, 2008: http://www.ledsmagazine.com/news/5/12/12

demonstrations" to leverage project results and information, particularly as American Reinvestment and Recovery Act of 2009 (ARRA) funding has become available to support efficient streetlight conversions.[7]

Recent PG&E Emerging Technologies studies have demonstrated energy savings for viable LED street lighting technologies of 50% to 70% over incumbent HPS technologies and have documented significant LED luminaire cost reductions.[8] The U.S. Department of Energy (DOE) has also been evaluating a variety of outdoor LED field demonstrations through its GATEWAY Demonstration program and lab testing LED products through its CALiPER program.[9]

DEMONSTRATION STREETLIGHT INFORMATION

In the pilot demonstration location in San Francisco, two different applications were evaluated. In the first, 20 400W nominal HPS luminaires were replaced with Type III LED luminaires rated at 222W (LED A). In the second, 32 200W nominal HPS luminaires were replaced with Type II LED luminaires rated at 88W (LED B). Within the pilot location, five 400W nominal HPS luminaires were also replaced with the same 88W LED model (this replacement option was not evaluated here). ROAM photocell-adapted RF transceiver nodes were installed on the demonstration luminaires to establish a mesh network for streetlight control and a ROAM system gateway was installed on a local utility pole to bridge the networked streetlights to the internet via cellular uplink. The pilot network controls system allows for advanced control options such as remote scheduling, outage identification and energy metering. This assessment of the piloted technology is only meant to characterize performance of the specific LED luminaire models and network controls evaluated under the demonstration conditions. Performance may be different in other locations and for future generations of these products. HPS and LED luminaire and lamp performance metrics as reported in manufacturer product cut sheets and .ies files are summarized below:

Table VIII: Listed HPS and LED Luminaire Performance

Luminaire	Luminaire Power	Initial Lamp Lumens	Luminaire Lumens/W	CRI
400W HPS	468	51,000	78	22%
LED A	222	13,320	60	75%
200W HPS	250	20,000	62	21%
LED B	88	6,851	78	72%

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[7] See Program web page: http://www1.eere.energy.gov/buildings/ssl/gatewaydemos_consortium.html

[8] - Cook, et al. "PG&E Emerging Technologies Program Application Assessment Report #0726: LED Street Lighting, Phase III Continuation; Oakland, CA." November 2008.
- Cook, et al. "PG&E Emerging Technologies Program Application Assessment Report #0727: LED Street Lighting, San Francisco, CA." December 2008.
Available online through the Emerging Technologies Coordinating Council at http://www.etcc-ca.com and through the DOE at http://www.netl.doe.gov/ssl/techdemos.htm

[9] DOE's GATEWAY Demonstration Programs support demonstrations of high-performance LED products to develop field data and experience for applications that save energy, are cost effective, and maintain or improve light levels. See http://www.netl.doe.gov/ssl/techdemos.htm.
DOE's Commercially Available LED Product Evaluation and Reporting (CALiPER) program supports testing of a wide array of SSL products available for general illumination. DOE allows its test results to be distributed in the public interest for noncommercial, educational purposes only. See http://www.netl.doe.gov/ssl/comm_testing.htm.

Manufacturer information listed the HPS rated lamp life as 18,000 hours, or roughly 4.4 years (at an assumed 4,100 hours of operation per year), for the 400W lamps and 24,000 hours, or roughly 5.9 years (at an assumed 4,1000 hours of operation per year), for the 200W HPS lamps. The manufacturers of the LED streetlights assessed in this study both publish predicted lives of 80,000+ hours, or over 20 years, for the LEDs used in the luminaires. The manufacturer of LED streetlight A provides a 5-year warranty for the 222W LED luminaire and the manufacturer of LED streetlight B provides a 6-year warranty for the 88W LED luminaire. As an LED luminaire consists of multiple components (LEDs, driver, housing, coating, etc.), the expected useful life of the luminaire may not be the same as that of the LEDs, and standard methods to test and predict LED streetlight lifetimes are still in development.[10]

Network Controls Technology and Market Overview

Use of streetlight network controls is a major shift from the traditional approach of photocell-controlled lights with no feedback to the operator. A networked system provides city-wide management and monitoring of streetlight assets from a remote location. Network controls, especially those with the ability to dim streetlights, can also provide adaptive street lighting options for enhanced energy benefits, such as reducing lighting power as conditions change (i.e. lower traffic or pedestrian volume), along with benefits such as reduced runtimes and detection of outages and "day-burners" – malfunctioning luminaires that operate during daylight conditions.

Like LED streetlights, networked streetlights represent a very small fraction of the installed inventory, though a few products are making their way into the U.S. market at the pilot to mid-scale level. From April to December of 2008, the City of Glendale, AZ deployed a network for 18,500 of its HPS streetlights using photocell-adapted ROAM wireless RF transceivers such as those demonstrated in the SFPUC pilot. The system recorded and monitored individual streetlight activity and reportedly helped achieve system-wide maintenance benefits for the City.[11] The City of Los Angeles, CA has also previously demonstrated wireless network controls benefits for its street lighting system, deploying several 1,000 networked streetlights several years ago as part of a system trail for GE StreetSmarts,[12] now Tyco Lumawise. In conjunction with its current roll out of LED streetlights, the City is planning on installing network controls on all new streetlights to allow the LA Bureau of Street Lighting to monitor system performance in real time, verifying LED energy savings and optimizing maintenance.[13] European cities have experimented with streetlight networking as well. Oslo, Norway began installation in 2006 of a system of 15,000 "smart streetlights" with Echelon power-line carrier controls.[14] Oslo has achieved 62% energy savings on retrofitted lights; two thirds due to changing over to electronic ballasts and the balance due to using the controls to reduce lamp burn hours.

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[10] IESNA's LM 80 LED Lumen Maintenance Approved Test Method for LED chips does not provide guidance or make any recommendations regarding predictive estimations or extrapolation for lumen maintenance beyond that determined from actual measurement (6,000 hrs). IESNA's TM-21 is being developed to set a standard method for forecasting LED chip depreciation to L70 lifetimes based on heat management, drive currents, etc., but this may still not address total luminaire life.

[11] LD+A, the magazine of the IESNA, Jan. 2009. Michael Sills-Trauch. http://www.roamservices.net/pdf/LDA_Article_ROAM_Glendale.pdf).

[12] www.geconsumerproducts.com/pressroom/press_releases/lighting/commercial_lighting/streetsmarts.htm

[13] City of Los Angeles Led Street Lighting Case Study. CCI, Feb, 2009. http://www.mwcog.org/environment/streetlights/downloads/CCI%20Case%20Study%20Los%20Angeles%20LED%20Retrofit.pdf

[14] Oslo Street Lighting System Slashes Energy Use with LonWorks® Technology: http://www.echelon.com/solutions/unique/appstories/Oslo.htm

DEMONSTRATION NETWORK CONTROLS SYSTEM INFORMATION

The street lighting network controls solution deployed for this demonstration was the ROAM system, a remote streetlight monitoring and management system designed to improve street lighting service by reducing outages and malfunctions and minimizing system costs. ROAM is a subsidiary of Acuity Brand Controls, owned and operated by Acuity Brands, Inc. The ROAM mesh wireless network is self-configuring and begins to communicate immediately upon installation. The network is also self-healing in that it is programmed to re-establish automatically after any communication disruptions. Along with detecting and recording asset malfunctions, the ROAM system can be used to turn streetlights on and off manually or by issuing scheduled on/off operation. The system also logs power draw and energy information for connected streetlights.

The technology consists of wireless transceiver-equipped ROAM photocells, or nodes, at the luminaire level that insert into standard twist-lock receptacles. These intercommunicate through a wireless mesh network and report to one or more ROAM gateway devices. The gateway serves as the central collection point for multiple nodes. The gateway and nodes operate at 2.4 GHz using IEEE 802.15.4 standard protocols, forming a Wide Area Network (WAN); each node communicates with other nodes in order to deliver data to the gateway. The gateway connects the network with a Network Operation Center (NOC) through the internet (via Ethernet, cellular uplink, or wireless) in order to collect and manage network data. A secure web-based ROAM portal is used by operators for system access and management and can be accessed from any desktop or laptop with an internet connection.

The ROAM node, with diagnostic and wireless technology, locks on top of the fixture and replaces a traditional on/off photocell, and can be used with light sources from 45 to 1,000W. The nodes are compatible with a variety of light sources including HID, LED, CFL, induction, and incandescent. The ROAM node photocell uses a filtered silicon light sensor. In the event of a cellular network problem at the gateway, or if the ROAM mesh network goes down, the ROAM photocells revert to default photocell operation.

Each ROAM node detects and reports the following conditions: Fully Operational; Fixture Malfunction, No Communication; Unspecified Malfunction; Partial Report; Unregistered; No Power at Activation; Low Wattage; Operational with Issues. Each node also collects and reports hourly averaged power use and maximum and minimum line voltage. The power measurement accuracy is reportedly -10% to +5% over a load range of 40W to 1,000W. At a load of 100W the reported accuracy is 2.7%, while at a higher load of 400W the reported accuracy improves to 0.5%. The load from each ROAM photocontrol on average is 1.6W.

Figure 1: ROAM Node[15]

The ROAM gateway serves as the central collection point for multiple ROAM nodes in a given vicinity and transmits information between the nodes within the network and the NOC, where the

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[15] ROAM 2.0 User Guide, Version 1.2

data is optimized for viewing and made available to authorized users via a secure web portal. One gateway can manage up to 2,000 nodes, depending on local topology. The ROAM gateway's average power draw is 5.5W. Communications between the gateway and ROAM NOC are encrypted using AES algorithms. Historical data is kept on the portal for 1 to 3 years; older data is stored on an alternative media. ROAM system components currently come with a 3-year product warranty and 8-year design life.

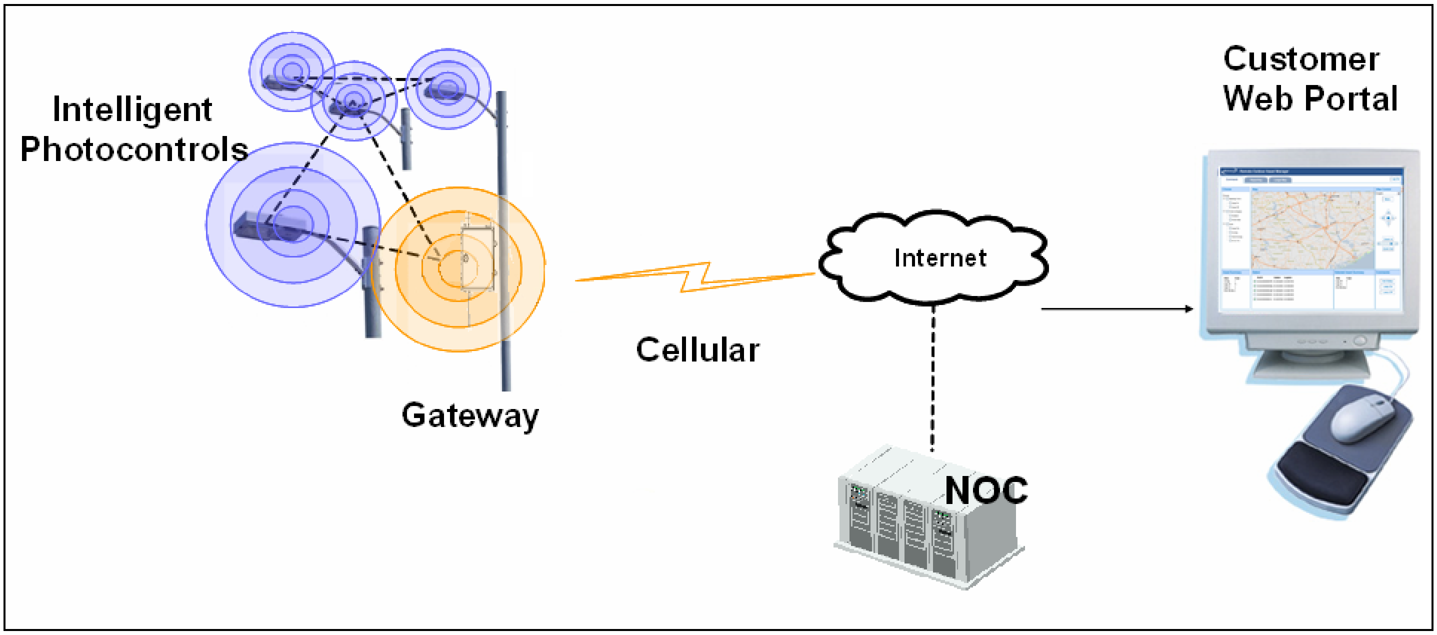

Figure 2: Basic System Architecture Diagram for SFPUC ROAM Pilot

The demonstrated ROAM technology is not compatible with dimming luminaires, though the ROAM system provides the needed architecture to convey dimming commands to ROAM-enabled streetlights. ROAM is currently working with several fixture manufacturers to develop solutions that will allow networked streetlights to execute dimming commands[16] and has shipped Dimming Control Modules (DCMs) to several customers. This option requires an integrated dimmable electronic ballast or driver and a ROAM DCM integrated into the fixture, ideally during manufacturing. The ROAM DCM will reportedly be compatible with any fixture that has a 0-10v dimmable ballast or driver. A bi-level dimming control will reportedly also be available for streetlights with non-continuous dimming drivers. The DCM option is expected to be available in volume product in early summer 2010, although demonstration samples are already being installed in pilot locations.

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[16] ROAM FAQs: http://www.roamservices.net/pdf/ROAM_FAQs.pdf

Project Objectives

The objectives of this study were to examine energy, lighting, and economic performance of networked LED luminaires as compared to incumbent 400W and 200W HPS luminaires. In addition, the project included functional testing of the piloted streetlight network controls technology. Potential electrical demand and energy savings were measured in terms of average wattage and estimated annual kWh usage. Lighting performance was assessed primarily through computer modeling of photopic illuminance. Limited photopic and scotopic illuminance measurements were also made in the field and mesopic illuminance was calculated based on measured scotopic-to-photopic illuminance ratios (S/P ratios) and modeled photopic results. Correlated color temperature (in Kelvin) was also measured, and before and after photographs were taken for qualitative indication of performance. Finally, economic performance was evaluated through simple payback period and net present value analyses for substitution of HPS streetlights with networked and non-networked LED luminaires in new installation and retrofit scenarios.

Methodology

Host site information

The demonstration LED luminaires were installed in the Tenderloin District of San Francisco, CA. The LED pilot area was bounded by Leavenworth, Eddy, Mason, and Market Streets. Twenty 400W nominal HPS streetlights on Leavenworth and Jones Streets were replaced with ROAM-networked 222W nominal LED streetlights (LED streetlight A). Thirty two 200W nominal HPS streetlights were replaced on Eddy and Turk Streets with ROAM-networked 88W nominal LED luminaires (LED streetlight B). Five 400W nominal HPS streetlights on Golden Gate Avenue were also replaced with LED streetlight B, though these were not studied for this evaluation. The SFPUC selected the demonstration locations and selected, procured and installed the retrofit LED luminaires.

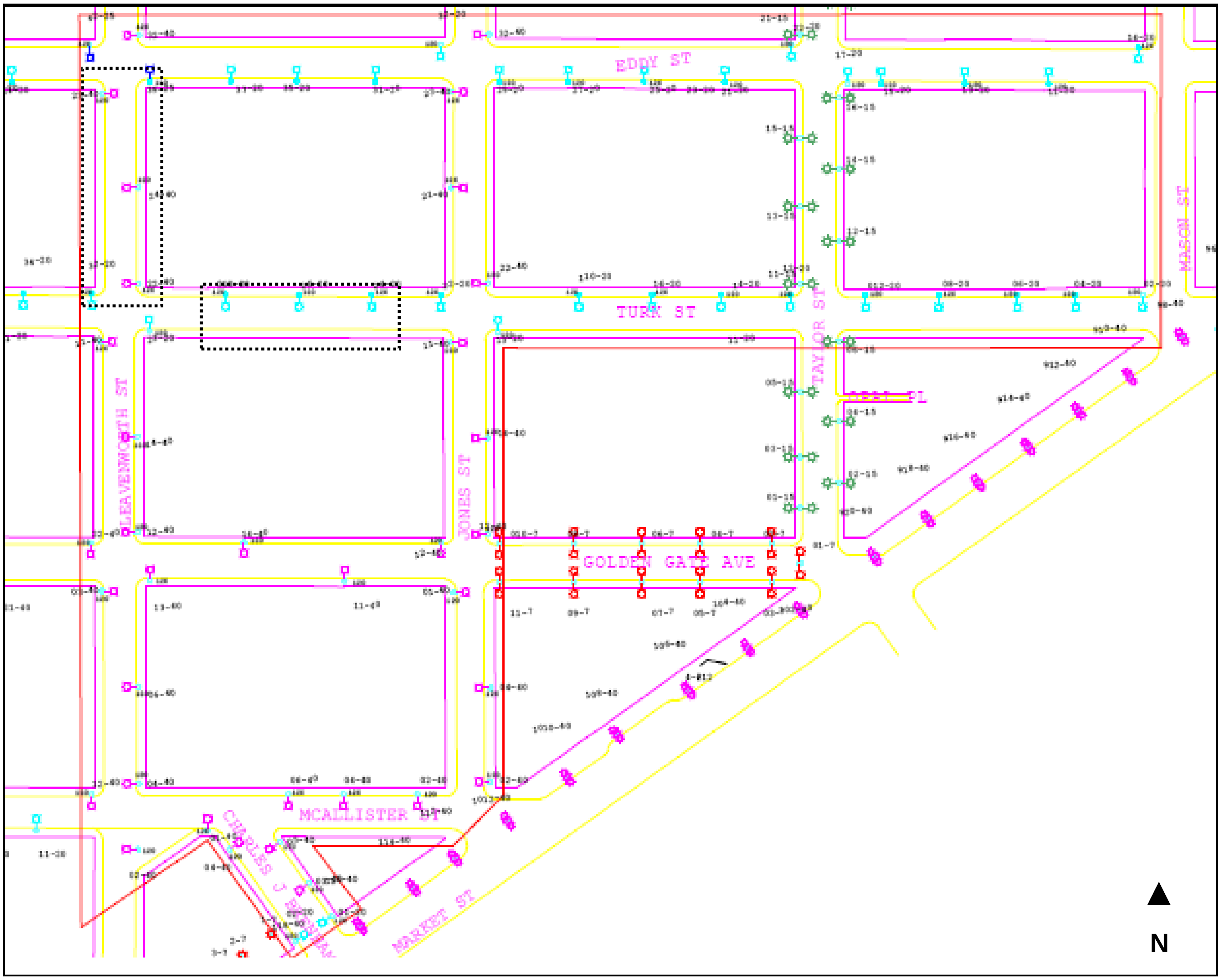

Figure 3: Tenderloin Pilot Location with Test Areas Outlined

For comparison with modeled lighting performance, limited photometric measurements were taken at selected locations under 3 consecutive streetlights on Leavenworth Street (North-South) and Turk Street (East-West). The test locations for field measurements were chosen based on minimizing interference from spill-over light and other location obstructions to photometric measurements.

Figure 4: Aerial View of Test Area Locations on Leavenworth (N/S) and Turk (E/W)

Streetlight Performance Monitoring Plan

The Streetlight Performance Monitoring Plan consisted primarily of illuminance measurements and time series power measurements. The measurements taken included: photopic illuminance, scotopic illuminance, correlated color temperature, watts, RMS amps, RMS volts, and power factor. Estimated annual energy usage from the lighting systems was also calculated based on the measured load from a single luminaire.

MEASUREMENT POINTS

Photometric measurements were taken at specific points identified on Leavenworth and Turk Streets, within the SFPUC pilot location in the Tenderloin District. The test areas for photometric measurements were identified through a site visit by SFPUC, PG&E, and Energy Solutions. Because of the challenges posed by the busy urban environment for completing illuminance field measurements per IESNA guidance,[17] the scope of field measurements was limited. Field data was collected primarily for comparison with thorough computer modeling results from an advanced photometric software package. Rather than prescribing a fine-scale grid of measurement points in the monitoring area, sample points were located to characterize maximum, intermediate, and

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[17] See LM – 50 – 99; IESNA Guide for Photometric Measurement of Roadway Lighting Installations.

minimum illuminance values. Measurements in each test area were taken under existing HPS luminaires with new lamps and cleaned or replaced lenses and under new LED luminaires after a designated burn in period of 100 hours continuous operation.

Measurement areas were chosen based on streetlight spacing and layout, and to minimize spill-over light from sources other than streetlights, as well as other obstructions to photometric measurements. Photometric measurements were taken between three consecutive streetlights. Additionally, two "buffer" streetlights – one on each side of the measurement area, were maintained with the same luminaire types as those being tested.

The streets in the demonstration area were 45' in width with three lanes of traffic in a single direction; the outer two of which included parking zones. Both photopic and scotopic illuminance measurements were taken at a height of 18" above ground, after civil twilight, and when ambient light from the moon was at a minimum.

For the field data points, three general types of readings were taken in the following arrangement:

- 3 High Range readings per street, at one lane spacing (15') in from the curb on the side of the street where streetlight pole was mounted and tranverse to each streetlight's location.
- 11 Mid Range readings per street; one for each streetlight at a distance of two lane spacings beyond curbside and tranverse to each streetlight's vertical location, and four points 1/3 distance of the pole spacing between each streetlight longitudinally and one lane spacing (15') in from either curb.
- 4 Low Range readings, 1/2 distance of the pole spacing longitudinally and at the street curb.

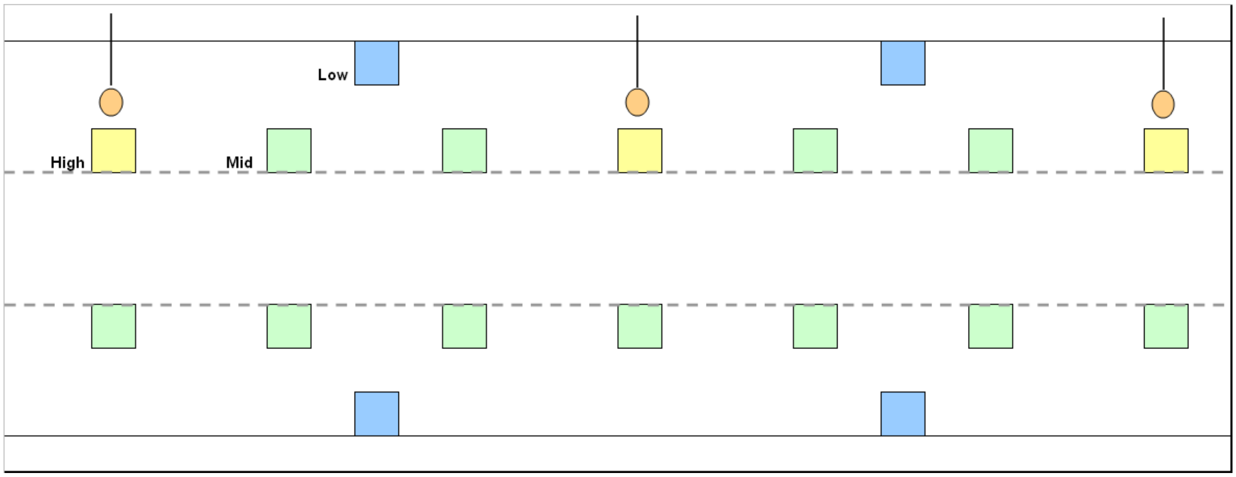

Figure 5: Field Photometric Measurement Point Locations

Correlated color temperature measurements were taken directly under each streetlight for both HPS and LEDs in the test area. If instrument limitations did not allow direct correlated color temperature measurements, chromaticity coordinates were measured and later converted to correlated color temperature based on published equations.[18] The method for calculating correlated color temperature values was identical for the HPS and LED luminaires. Power measurements were

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[18] McCamy, Calvin S. (April 1992). "Correlated color temperature as an explicit function of chromaticity coordinates". Color Research & Application 17 (2): 142–144.

5 minute averaged recordings logged over several days, using a Dent ElitePro Datalogger. Example time-series plots of luminaire power are included in Appendix A. Measurements included watts, RMS amps, RMS volts, and power factor and were taken on one luminaire in each test area.

Fieldwork activities required several visits to the sites. Monitoring equipment for power measurements was installed during the HPS lamp change-out and was removed after power monitoring on the LED luminaire was complete.

FIELD VISITS

An initial field visit was conducted to determine the most suitable testing areas in the pilot location and to verify street dimensions and establish the existing conditions. Additional visits were carried out for the following field activities:

- Supervise installation of electric power data loggers on one 400W HPS luminaire and one 200W HPS luminaire and one replacement LED luminaire for each.
- Observe the activation and installation of network controls on a streetlight, verify compatibility and operation.
- Mark measurement points in the test areas for photometric measurements and take photometric measurements to characterize the performance of the HPS streetlights. New HPS lamps were installed and lenses were cleaned or replaced in all fixtures to allow for an appropriate comparison of new HPS to new LED streetlights. The new HPS lamps were allowed to operate for at least 100 hours prior to the visit.
- Take photometric measurements to characterize the performance of the LED streetlights. New LED luminaires were installed to replace the HPS luminaires in the designated areas and were allowed at least 100 hours of operation prior to monitoring.
- Ground level and overhead photographs of the test areas illuminated by HPS and LED streetlights to provide qualitative indication of performance.

Monitoring equipment used in the execution of the Monitoring Plan is detailed below:

ILLUMINANCE METER

Solar Light SnP Meter PMA 220

CORRELATED COLOR TEMPERATURE METER

Konica Minolta Chroma Meter

POWER METER

Dent ElitePro Datalogger

DIGITAL CAMERA

Nikon D80

Network Controls Test Plan

The test plan for the network controls system was developed to address all of the major functions of the controls technology, which is designed to provide smart control and monitoring of streetlight assets to improve management of operations and information, enhance maintenance planning, increase response time to faults, report system data such as energy usage, and provide energy savings opportunities.

Most results from the test activities were qualitative in nature, including feedback from system users based on experience with system installation and operation, and observations during on-site functional testing with SFPUC personnel. This involved testing system options such as on/off commands, pulling reports on energy data and streetlight outages, and setting up luminaire groups and schedules. Logged energy data from the controls system was also compared with data from the loggers installed in the field for streetlight energy analysis. The four categories of test information and activities are described below:

TECHNOLOGY OVERVIEW AND EQUIPMENT DESCRIPTION

Information describing system design, components, and setup was collected from manufacturer contacts, product literature, and project managers and engineers. Information reviewed in this step included vendor specifications for component performance characteristics such as precision, durability, energy usage (reported, tested, or measured in-field), etc.

USER SURVEY AND INTERVIEW

A system operator survey document was prepared to collect user feedback on the control technology's advantages and drawbacks. Survey questions included both satisfaction scales and comment fields. The survey was completed by the primary system user at SFPUC. Additional feedback from communications with host personnel was also incorporated into test results.

FUNCTIONAL TESTING AND WEB INTERFACE DEMONSTRATION

The monitoring team collaborated with SFPUC personnel to test functionality of network controls system through dispatch of commands from the user interface to controlled lights and live observations and measurements at the test areas. Test engineers also previewed the user interface with the system operator and observed actions such input of scheduling commands, data queries, report production, streetlight mapping, etc. Actual controls commands were issued and system response was observed. Field-logged power data was compared with data recorded by the network controls system.

SYSTEM ECONOMICS

System cost estimates were proposed by the controls manufacturer for a larger scale order (1,000 - 10,000+ streetlights) and potential cost savings due to system installation (maintenance and energy savings) were projected in order to calculate system payback and present value for hypothetical large deployments in conjunction with LED streetlights.

Project Results and Discussion

Streetlight Performance

ILLUMINANCE

Due to high traffic activity in the pilot location, complete coverage of the test areas with grids of field measurement points was not feasible. Instead, limited illuminance measurements were taken in the field to provide representative performance data. The locations of the selected field measurement points are described in the Streetlight Performance Monitoring Plan section above. Scotopic illuminance was also measured at the field test points to provide an indication of the luminaires' ratios of scotopic output to photopic output (S/P ratios). For the field measurement points, three general types of readings were taken (see Figure 5):

- 3 High Range readings
- 11 Mid Range readings
- 4 Low Range readings

Because of the limited coverage of measurement points, common performance criteria for street lighting systems such as average illuminance and lighting uniformity cannot be determined from the field data. Nonetheless the field data does provide a useful basis for comparison of the changes in illuminance levels at the selected points under the base case HPS streetlights and the networked LED retrofits.

For estimations of overall lighting performance such as average illuminance and uniformity over the entire area of the demonstration streets, computer simulations were run with industry standard photometric modeling software (AGi 32). Modeling was done using manufacturer .ies files (produced by independent lab testing) for luminaire output and distribution and by dimensioning hypothetical streets with luminaire spacings and mounting heights equal to those measured in the test areas. Only the initial HPS and LED performance was modeled, assuming no light loss factors in the model for lamp or dirt depreciation.[19] Computer modeling of illuminance levels provided useful data for comparison of base case HPS performance to LED retrofit performance that eliminated field measurement variables such as spill-over light present from local sources other than streetlights, including wall packs and floodlights. Note that because the modeled locations and luminaire spacings for the two test areas were unique, performance comparisons between the two evaluated LED streetlight models based on model results is not valid or advisable.

Illuminance levels were also computer-modeled for the same point locations as those measured in the field to assess how closely the model's calculations came to representing measured light levels. Doing so, modeled results were found to be within 10% of field readings. Modeling was then carried out for illuminance grids covering the entire test areas. The simulated illuminance grids

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[19] Modeling maintained, or end-of-maintenance cycle, illuminance, which is typically the point at which a light source reaches 70% of its initial output, would require selecting appropriate light loss factors for the HPS and LED sources, but standard methods for determining these for the LED luminaires are not available.

closely followed IESNA guidance for illuminance evaluations of street lighting systems.[20] Based on pole spacing on each street, modeling resolution for the grids was 7.5' X 15' for Leavenworth Street and 7.5' X 9' for Turk Street. Photopic illuminance levels were calculated at the street surface level for the base case HPS luminaire and for the LED replacement luminaires. Modeled points were located in the following arrangement:

- 6 points transverse to the street lanes at 7.5' spacing (one half the width of each traffic lane), with two points per traffic lane beginning one half the point spacing (3.75') in from edge of traffic lane.
- Longitudinal (north-south) spacing between transverse points of 15' for Leavenworth Street, which had wider pole spacing, and 9' for Turk Street, beginning one half the point spacing in from the first luminaire in the modeled test area, and ending one half the point spacing before the last luminaire in the modeled test area.

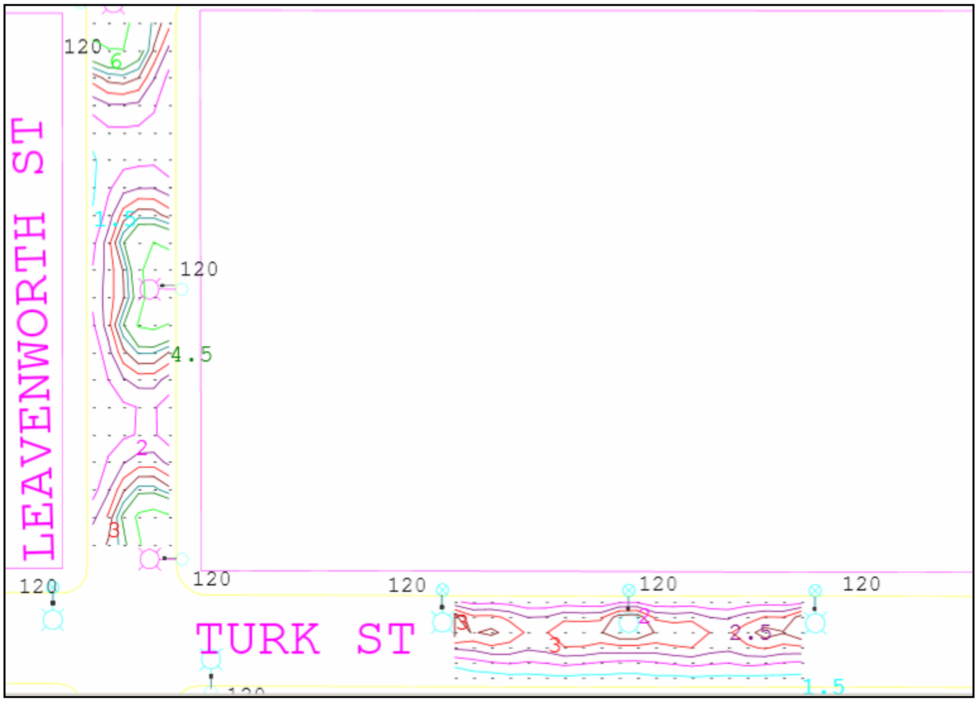

Figure 6: Sample Model Graphical Output for Test Area Grids

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[20] See LM – 50 – 99; IESNA Guide for Photometric Measurement of Roadway Lighting Installations. Recommendations call for three luminaire cycles; the monitored cycle and one complete cycle on either side. Due to the configuration of the test areas, only two luminaire cycles were modeled; with one complete cycle on either side lit in the same manner (HPS or LED) as the test areas.

METRICS

For the field data, the average of the 18 field measurement points for each test area would not be indicative of overall average illuminance levels since the field measurements did not cover the entire standard roadway grid. However, before and after comparison of average High Range, Mid Range, and Low Range field illuminance values does provide some indication of changes in illuminance levels. Field measured photopic and scotopic levels can also be used to calculate each light source's approximate S/P ratio.

Average illuminance and uniformity metrics over the entire test areas were calculated from computer model generated data. Average illuminance levels were calculated for all modeled points in the illuminance grids described above, and rounded to the nearest hundredth fc. The uniformity of illuminance provided by the streetlights over the modeled illuminance grids was evaluated using three metrics: coefficient of variation (CV), average-to-minimum uniformity ratio (AMU), and maximum-to-minimum uniformity ratio (MMU). CV, also known as relative standard deviation, is a measure of the disparity between the actual values of all points and the average of those values. It is calculated as the standard deviation of the distribution divided by the average illuminance. It is useful because it provides an indication of the uniformity of all points across the entire test areas. A lower CV is indicative of a more uniform distribution. AMU provides an indication of how low the minimum level is compared to the average of all values. It is calculated by dividing the average of all values by the single lowest value. MMU provides indication of the largest disparity in illuminance between any two points in the area of interest – the minimum value compared to the maximum value. It is calculated by dividing the single highest of all values by the single lowest value.

Average photopic and scotopic illuminance levels for the High, Mid, and Low Range HPS and LED field measurements are given below. Average illuminance and uniformity values based on computer modeled results for the HPS and LED streetlights are also shown, followed by surface plots generated for model results to provide a qualitative picture of illuminance distribution and changes. Approximate scotopic illuminance levels were scaled from computer-modeled photopic data by applying the field-measured S/P ratios. Surface plots were generated for the scotopic illuminance data as well.

HPS AND LED PERFORMANCE: FIELD RESULTS

It should be emphasized that this report includes analysis of two unique applications: 1) base case 400W HPS cobraheads replaced by LED streetlight A from one manufacturer, on a roadway with unique luminaire spacings, and 2) base case 200W HPS cobraheads replaced by LED streetlight B from a different manufacturer, on a different roadway with unique luminaire spacing. For both of these applications, the report analyzes the performance of the LED streetlight as compared to the base case HPS streetlight. However, it is not appropriate to compare the performance results of the two demonstrated LED options to each other.

The summary field data below shows a significant decrease in measured photopic illuminance levels from the 400W and 200W HPS base cases to the LED retrofits, though scotopic illuminance increased from the HPS to LEDs in almost every case. The S/P ratios calculated from measured photopic and scotopic averages show significantly higher relative scotopic output for the LED sources. For the Low Range field measurements on Turk Street (LED B), some influence from wall pack lighting along one side of the road appeared to influence scotopic readings, though the overall effect on calculated S/P ratios was found to be minimal.

Table IX: Measured Photopic Illuminance

Luminaire	400W HPS	LED A	% Change	200W HPS	LED B	% Change
High Range Illuminance (fc)	6.47	2.63	-59.4%	3.33	2.57	-22.8%
Mid Range Illuminance (fc)	2.30	1.25	-45.7%	1.93	1.36	-29.5%
Low Range Illuminance (fc)	0.98	0.50	-49.0%	1.85	0.90	-51.4%

Table X: Measured Scotopic Illuminance

Luminaire	400W HPS	LED A	% Change	200W HPS	LED B	% Change
High Range Illuminance (fc)	3.80	5.13	+35.0%	1.83	4.07	+122.4%
Mid Range Illuminance (fc)	1.33	2.28	+71.4%	1.01	2.24	+121.8%
Low Range Illuminance (fc)	0.60	0.80	+33.3%	1.95	1.43	-26.7%

Table XI: Measured Scotopic Illuminance and S/P ratios

Luminaire	S / P Ratio
400W HPS	0.58
LED A	1.84
200W HPS	0.63
LED B	1.62

HPS AND LED PERFORMANCE: MODEL RESULTS

To characterize the overall initial performance of the streetlight options, average photopic illuminance and uniformity metrics were calculated for the modeled data, which covered the entire test areas. As observed with the illuminance levels measured in the field, there was a significant reduction in average illuminance from the base case HPS to the LEDs on both streets.

Table XII: Summary of Modeled Photopic Illuminance

Luminaire	Average Illuminance (fc)	Coefficient of Variation	Average-to-Minimum Uniformity	Maximum-to-Minimum Uniformity
400W HPS	3.38	0.53	2.42	5.93
LED A	1.15	0.53	2.30	5.60
200W HPS	2.24	0.33	2.03	3.36
LED B	1.30	0.39	2.61	4.60

The IESNA standard for these roadways, classified as high pedestrian-conflict collectors, calls for average maintained illuminance of 1.2 fc (pavement reflectance class R2-R3) and AMU of 4.0. For Leavenworth Street, the 400W HPS base case, and for Turk Street, the 200W HPS base case, both the HPS and LED light sources initially met the average illuminance level in the standard (rounded to the tenths place). However, the standard's recommendations are for maintained performance over a light source's useful life, typically considered the length of time a source takes to depreciate to 70% initial output (L70). With depreciation over time, both of the LED sources would fall below the recommended average illuminance level. Higher initial output would therefore be necessary to maintain the recommended minimum illuminance level. The LED streetlight models may either need to be adjusted to a higher current setting that increases light output (possible with LED streetlight B) or replaced with a slightly higher output model to resolve maintained illuminance concerns. Energy usage would be expected to increase at higher outputs and luminaire lifetimes may be reduced at higher current settings.

Initial uniformity changed little from the HPS sources to the LED sources, though there is a slight decrease in uniformity moving from the 200W HPS base case to the LEDs. For both Leavenworth Turk Streets, the initial HPS and LED performance falls well within the AMU requirement.

Standard .ies files do not provide scotopic output for modeling purposes (scaling photopic lumen output based on spectral power distribution would be necessary). Therefore the light source S/P ratios calculated from measured levels were applied to modeled photopic illuminance levels to provide approximate scotopic illuminance levels. Average scotopic illuminance is provided below; the calculated scotopic levels are also used later for mesopic calculations. The LED replacements provided higher average scotopic illuminance than both the 400W and 200W HPS base cases.

Table XIII: Approximate Average Scotopic Illuminance

Luminaire	Average Illuminance (fc)
400W HPS	1.98
LED A	2.12
200W HPS	1.41
LED B	2.11

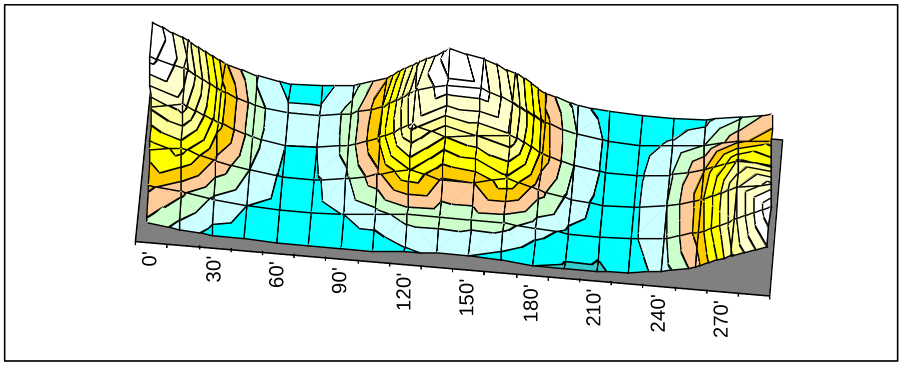
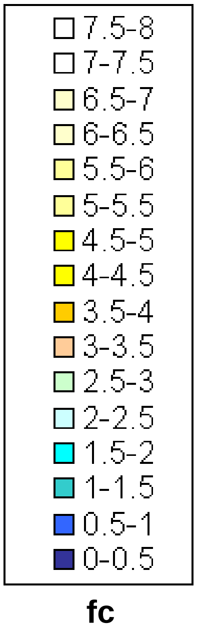


Figure 7: 400W HPS Photopic Surface Plot, Leavenworth Street



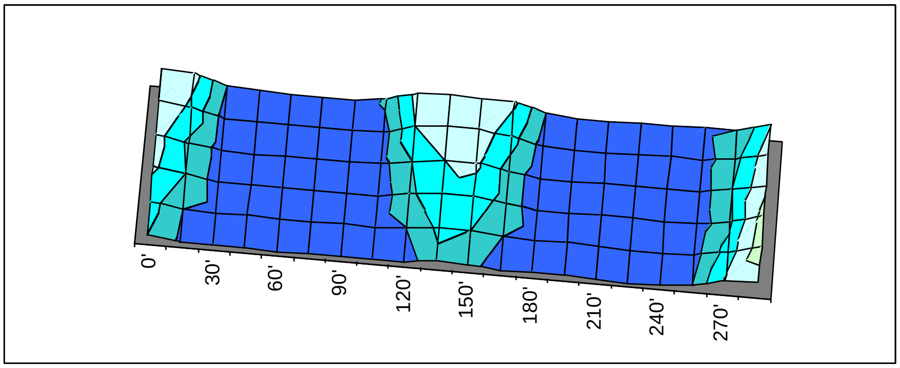


Figure 8: LED A Photopic Surface Plot, Leavenworth Street

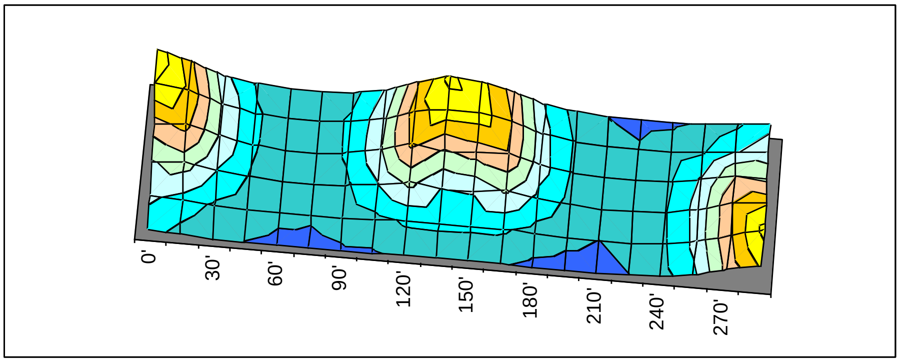


Figure 9: 400W HPS Scotopic Surface Plot, Leavenworth Street

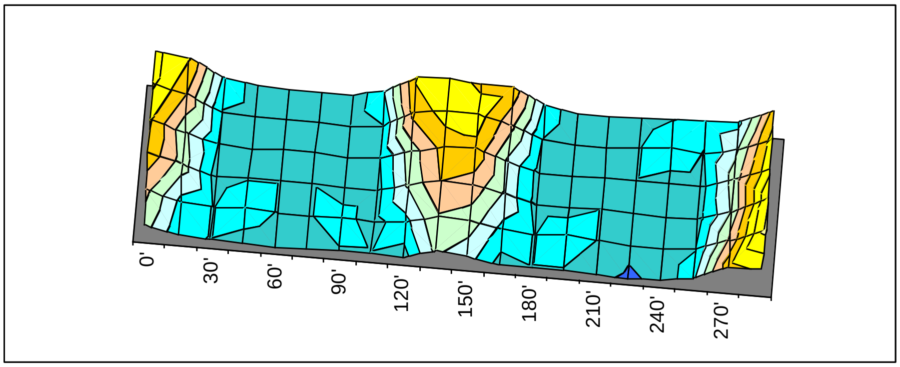


Figure 10: LED A Scotopic Surface Plot, Leavenworth Street

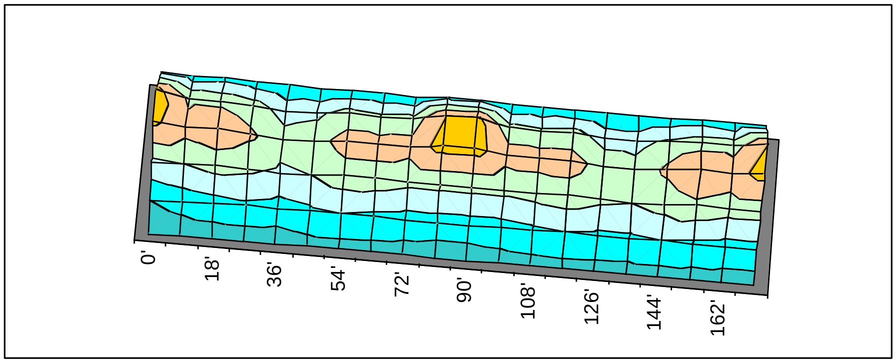


Figure 11: 200W HPS Photopic Surface Plot, Turk Street

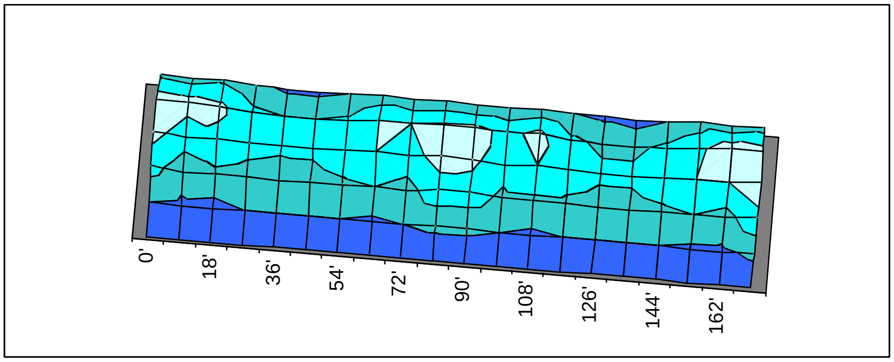
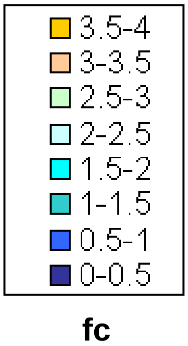


Figure 12: LED B Photopic Surface Plot, Turk Street



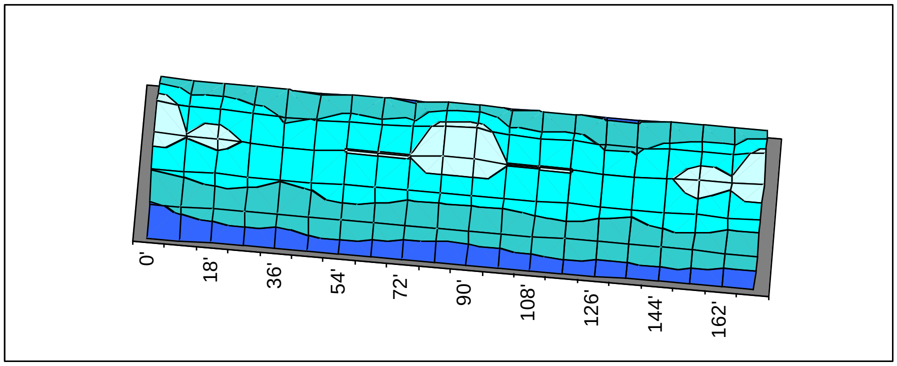


Figure 13: 200W HPS Scotopic Surface Plot, Turk Street

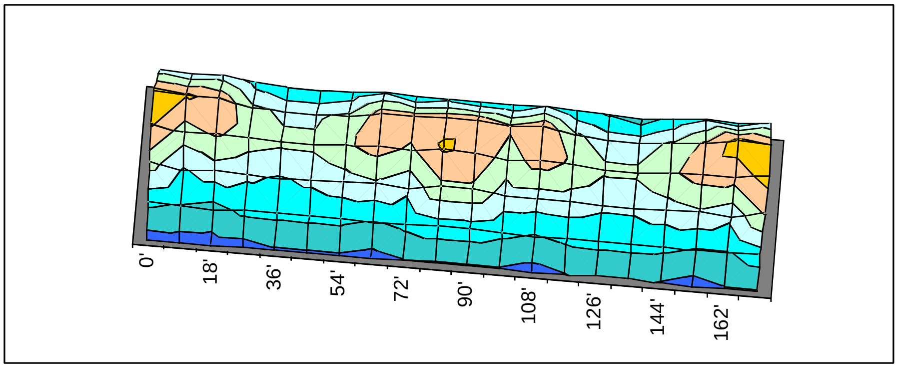


Figure 14: LED B Scotopic Surface Plot, Turk Street

HOST CONTACT LIGHTING PERFORMANCE QUESTIONNAIRE

The host contact was given a short questionnaire in order to understand the host's qualitative satisfaction with the lighting performance of the LED streetlight retrofits. In the questionnaire, the host contact was asked to state whether characteristics such as visibility, appearance, and safety were decreased, the same, or improved with the replacement streetlights. The host contact indicated that the replacement street lighting systems provided improved overall lighting performance. The host contact reported believing that visibility as a pedestrian, visibility as a driver, and the locations' overall appearances were improved for both LED streetlight installations. For the perceived safety of each location, the host contact believed that safety was about the same under the LED replacement of the 400W HPS streetlights and improved under the LED replacement of the 200W HPS streetlights. In general, the host reported being very satisfied with both LED streetlight options' performance.

MESOPIC ILLUMINANCE DISCUSSION

Commercial photometry traditionally measures light levels based on the photopic luminous efficiency function (Vλ). This is a well established response function that weights the visual effectiveness of wavelengths in the electromagnetic spectrum according to the human eye's response in levels of adaption over 3 cd/m^2 (e.g., daylight conditions), which are dominated by the eye's cone photoreceptors. However, under the lowest light conditions (adaption less than 0.001 cd/m$^{2)}$, when the eye's rods are the active photoreceptors, human perception of light follows a different response curve; the scotopic luminous efficiency function (V' λ). At intermediate levels between daylight and darkness (ambient photopic luminance in the 0.001 to 3 cd/m^2 range) typical of nighttime roadway lighting levels, rods and cones both provide levels of spectral sensitivity, with rods' importance diminishing and cones' increasing as light levels increase. In these intermediate levels, the photopic response curve and the scotopic response curve are both important. This is known as the mesopic range.

Light sources differ in their spectral power distribution, which influences their effectiveness at different light levels. Light sources considered "white" (e.g., metal halide, LED, induction) emit energy broadly across the visible spectrum. These broad spectrum sources appear white and excite multiple photoreceptors (e.g., short, medium, and long-wavelength cones and rods depending on the adaptation state). In contrast, narrow spectrum sources (e.g., HPS, LPS, and color-specific LEDs) do not appear white and may only excite a specific type of photoreceptor. Narrow spectrum sources may provide little or no energy at wavelengths sensed by the rods or short or medium-wavelength cones. Visual performance and apparent brightness at mesopic light levels can therefore be enhanced by light sources emitting light in the low to mid section of the visible light spectrum. Mesopic lighting is the subject of ongoing research, and the proper methods for including photopic and scotopic illumination in outdoor lighting analyses are under debate in the lighting community. Both the IESNA and CIE have formed technical committees to define and investigate mesopic performance, underscoring its increasing importance in the lighting discussion.[21] The IESNA has published a technical memorandum on the subject, TM-12-06, Spectral Effects of Lighting on Visual Performance at Mesopic Light Levels. This technical memorandum is currently undergoing revision to provide more specific recommendations for incorporating lamp spectral distribution effects under mesopic conditions into street lighting design.

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[21] CIE Technical Committee 1-58: "Visual Performance in the Mesopic Range" http://www.lightinglab.fi/CIETC1-58/index.html#
IESNA Mesopic Technical / Research Committee:
http://www.ies.org/about/committees/committees_view_action.cfm?committeeid=306

As traditional photometry relies only on photopic performance and does not account for the scotopic or mesopic characteristics of a light source, and due to the importance of scotopic and mesopic vision for roadway lighting levels, methods for calculating mesopic light levels were used in this study to more accurately represent nighttime performance. Over the past several years, several models have been developed, and three were used here to compare performance of the HPS and LED streetlights.

Mesopic Optimization of Visual Efficiency (MOVE) Model: The MOVE model is a performance-based model developed for the European Community by the Lighting Laboratory of Helsinki University of Technology.[22] The model is based on the results of vision experiments which evaluated subjects' ability to complete various tasks required for night-time driving. The MOVE model uses photopic and scotopic luminance values to calculate mesopic luminance values. The modeled photopic illuminance data and scotopic illuminance data (based on measured S/P ratios and modeled photopic illuminance) were converted into luminance, assuming that the roadway surface had a reflectance value of 0.07 and lambertian reflectance. The conversion formula is as follows:

L (luminance) = E (illuminance) * P (reflectance of the surface) / Π

The resulting photopic and scotopic luminance values were then used to calculate mesopic luminance values based on the MOVE equations discussed in Appendix B. Mesopic luminance values were then converted to mesopic illuminance values by the same formula.

Unified System of Photometry: The Lighting Research Center at Rennselaer Polytechnic Institute recently published an article on outdoor lighting visual efficacy through its ASSIST program (Alliance for Solid-State Illumination Systems and Technologies) that describes the unified system of photometry proposed by Rea et al in 2004.[23]

> "The unified system of photometry integrates both the scotopic and photopic luminous efficiency functions into a complete system that can be used across the entire range of light levels available to the human visual system. The system differentially weighs the scotopic and photopic luminous efficiency functions depending upon light level.[24]

The Lighting Research Center article published Rea's closed-form expression for combining photopic and scotopic luminance levels to calculate unified luminance. This approach, which is also detailed in Appendix B, was used with the modeled data and the resulting mesopic luminance values were converted to illuminance values for comparison.

Lumen Effectiveness Multipliers (LEMs): LEMs are another approach for quantifying the effectiveness of white light sources under low light conditions. They are light source – specific multipliers designed to be used with photopic luminance levels to calculate "effective" light levels produced by various light sources in night conditions. In 2001, Lewin proposed LEMs for four light sources[25] (HPS, LPS, Mercury, Metal Halide) based on previous studies of apparent brightness

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[22] Mesopic Optimisation for Visual Efficacy. Performance Based Model for Mesopic Photometry. Helsinki University of Technology Lighting Laboratory. Report 35. Espoo, Finland. 2005

[23] A proposed unified system of photometry. MS Rea PhD, FIES FSLL LC, JD Bullough MS, JP Freyssinier-Nova ,MS LC MSLL, and A Bierman MS. Lighting Research Center, Rensselaer Polytechnic Institute, Troy, NY, USA. Lighting Research and Technology. 362 (2004) pp. 85-111

[24] Outdoor Lighting: Visual Efficacy. ASSIST Recommends… Vol 6, Issue 2. Jan. 2009. Lighting Research Center.

[25] Lewin, Ian. "Lumen Effectiveness Multipliers for Outdoor Lighting Design." Journal of the Illuminating Engineering Society, JIES, Summer 2001. Illuminating Engineering Society of North America, New York, NY.

and visual performance in the mesopic range (Adrian, 1998;[26] He et al, 1998;[27] and Rea, 1999[28]). More recently Lewin has developed multipliers for four additional light sources (warm and cool-white LEDs, warm and cool-white Induction). LEMs trend toward higher values as the spectral distribution of the light source shifts to blue/green wavelengths and as luminance levels decrease. The LEMs used here for cool-white LEDs (CCT of 5,500K) were those reported by Lewin for brightness matching mesopic data developed by Adrian. While the LED luminaires in this study did not have precisely the same spectral distribution as the LEDs used to determine the LEMs, they can be assumed to be close enough to still be informative. A logarithmic regression of published cool white LED LEMs as a function of photopic luminance levels was computed. Photopic luminance from modeled illuminance data was then multiplied by the resulting interpolated LEMs to calculate mesopic luminance

Table XIV: LEMs for Evaluated Light Sources and Photopic Luminance Ranges

Photopic Luminance level (cd/m2)	.001	.01	.10	1.00	3.00	10.00
Cool White LED (5,500K CCT)	2.75	2.57	2.09	1.47	1.22	1.00
HPS	1.00	1.00	1.00	1.00	1.00	1.00

The following results from the various models show some variation in the way the different methods weigh the photopic and scotopic performance of the HPS and LED sources. In each case there is little or no difference between average photopic and mesopic illuminance for the HPS streetlights, while for the LED streetlights, mesopic illuminance is higher than photopic illuminance in each case. For the LED streetlights, the mesopic uniformity as measured by CV also shows slight improvement over photopic uniformity.

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[26] Adrian, Werner. "The Influence of Spectral Power Distribution for Equal Visual Performance in Roadway Lighting Levels." Proceedings: Vision at Low Light Levels. EPRI/LRO Fourth International Lighting Research Symposium. TR-110738. Lighting Research Office of the Electrical Producers' Research Institute, Palo Alto, California. 1999

[27] He, Junjian; Bierman, Andrew; Rea, Mark. "A System of Mesopic Photometry." International Journal of Lighting Research and Technology. Vol. 30, no. 4. Chartered Institution of Building Services Engineers, London, UK. 1998

[28] Rea, Mark. "A Unified System of Photometry for Lighting Applications." Proceedings of the CIE Symposium: 75 years of CIE Photometry, Budapest, 1999

Table XV: Comparison of Mesopic Illuminance Values, 400W HPS Base Case

Luminaire Type		Average Illuminance (fc)	Coefficient of Variation
400W HPS	**Modeled Photopic Values**	3.38	0.53
LED A		1.15	0.53
400W HPS	**MOVE Mesopic Values**	3.14	0.56
LED A		1.39	0.49
400W HPS	**Unified Luminance Method Values**	3.34	0.55
LED A		1.35	0.40
400W HPS	**LEM Effective Luminance Values**	3.38	0.53
LED A		1.99	0.46

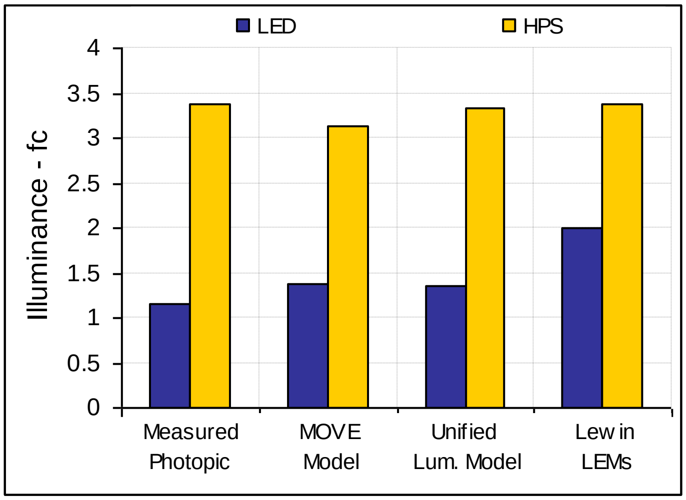


Figure 15: Leavenworth Mesopic Illuminance Plot

Table XVI: Comparison of Mesopic Illuminance Values, 200W HPS Base Case

Luminaire Type		Average Illuminance (fc)	Coefficient of Variation
200W HPS	**Modeled Photopic Values**	2.24	0.33
LED B		1.30	0.39
200W HPS	**MOVE Mesopic Values**	2.06	0.34
LED B		1.50	0.37
200W HPS	**Unified Luminance Method Values**	2.16	0.37
LED B		1.46	0.33
200W HPS	**LEM Effective Luminance Values**	2.24	0.33
LED B		2.24	0.35

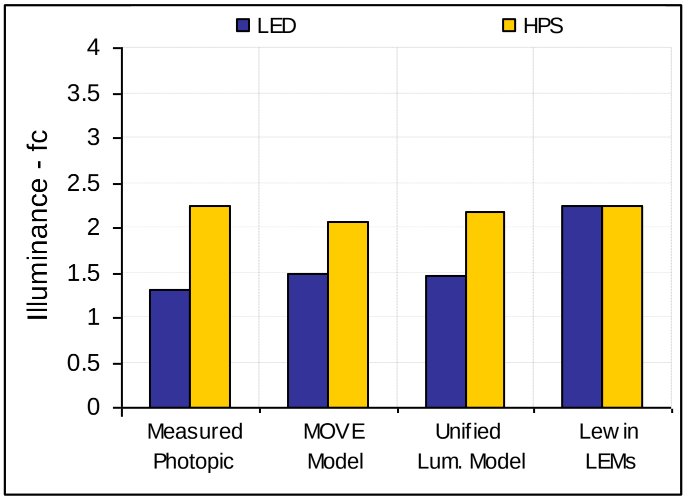


Figure 16: Turk Mesopic Illuminance Plot

For the LED light sources, the increase from photopic to mesopic light levels varied from around .2 to .9 fc (roughly a 12% to 73% increase) depending on the mesopic model used. At the illuminance levels found in roadway lighting standards like RP-8-00, changes of this order can be significant. Also note that the light levels for the demonstration areas were significantly higher than standard roadway illuminance levels at lower classifications such as low-conflict collectors or local roadways. At lower absolute light levels, scotopic output is more heavily weighted by mesopic models (exemplified in Table XIV above), so the relative mesopic performance of LED streetlights as compared to the HPS for lower illuminance applications would be expected to be even greater.

COLOR TEMPERATURE

CCT parameters were measured using a Konica Minolta Chromameter under each HPS luminaire and each LED luminaire in the two test areas. CCT was calculated from measured tristimulus coordinates. The average CCTs for the HPS and LED luminaires are provided below; all recorded values are given in Appendix A.

Table XVII: Average Measured Correlated Color Temperature

Luminaire	CCT (K)
400W HPS	1,881
LED A	6,317
200W HPS	1,812
LED B	4,832

PHOTOGRAPHIC COMPARISONS

To provide further qualitative indication of lighting performance, various ground level and overhead photographs were taken of the HPS luminaires and the LED luminaires on each street. These photographs were taken with a Nikon D80 digital camera using the same aperture, shutter speed, and ISO settings for the HPS and LED luminaires, and with white balance set to automatic.

<u>Ground Level Camera Settings</u>
Flash: No
Focal Length: 18 mm
F-Number: f/4.0
Exposure Time: .25 sec.
ISO Speed: 400
White Balance: Automatic

<u>Overhead Camera Settings</u>
Flash: No
Focal Length: 18 mm
F-Number: f/4.0
Exposure Time: .3 sec.
ISO Speed: 400
White Balance: Automatic

Figure 17: Overhead Shot of 400W HPS, Leavenworth Street

Figure 18: Overhead Shot of LED A, Leavenworth Street

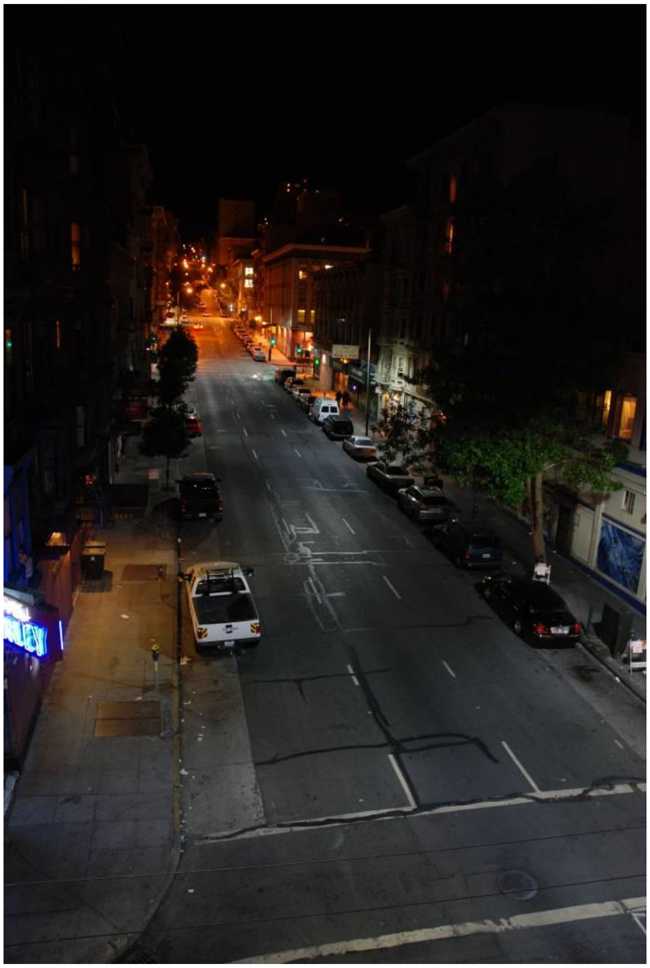


Figure 19: Street Level Shot of 400W HPS, Leavenworth Street

Figure 20: Street Level Shot of LED A, Leavenworth Street

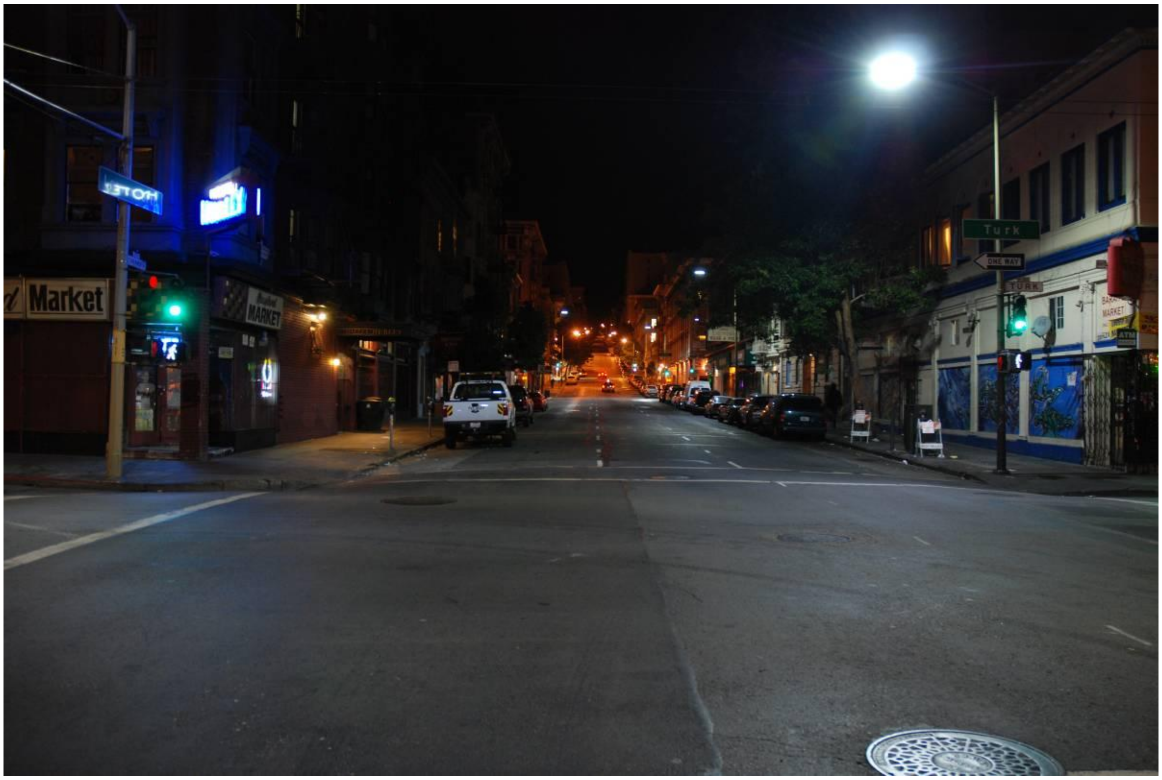


Figure 21: Overhead Shot of 200W HPS, Turk Street

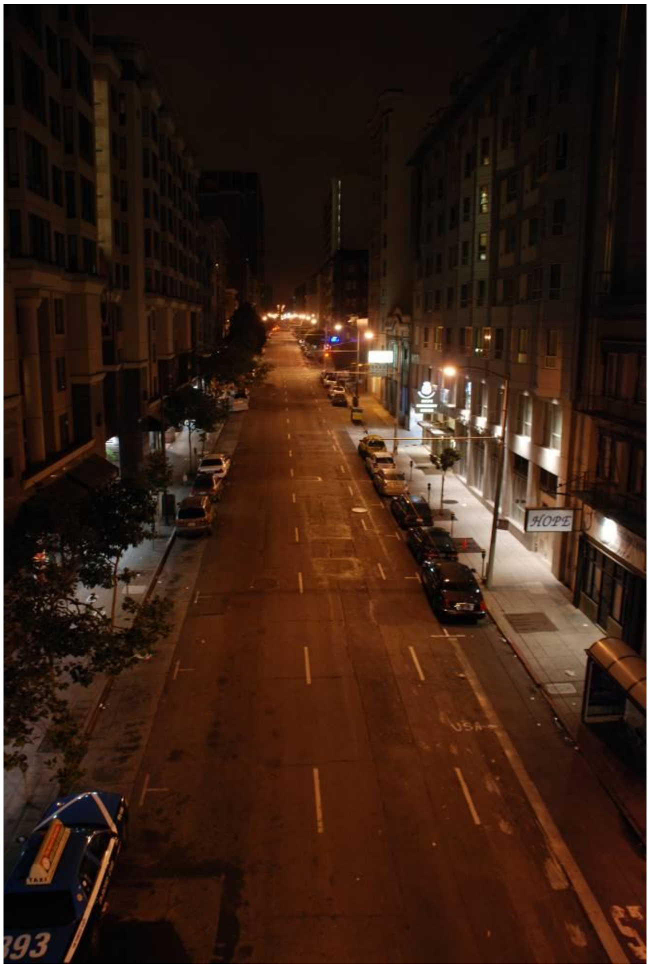
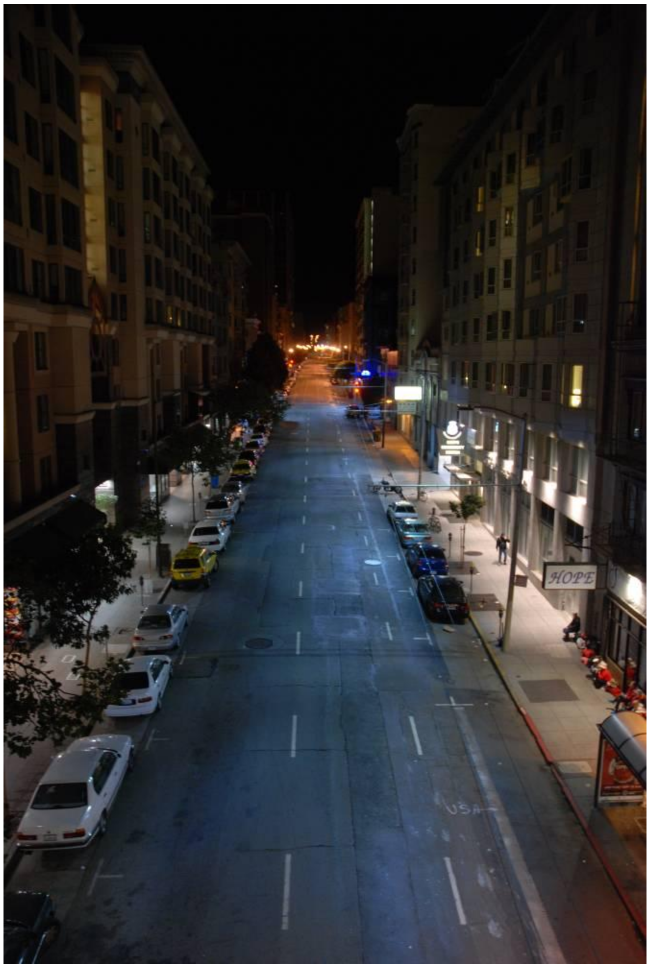


Figure 22: Overhead Shot of LED B, Turk Street



* Note that on Turk Street, the camera setting of automatic white-balance resulted in the LED source appearing slightly bluer than qualitatively observed in the field, likely due to compensation for the presence of a wide range of lighting sources in the frames, including the bright wall pack luminaires on the right hand side.

Figure 23: Street Level Shot of 200W HPS, Turk Street

Figure 24: Street Level Shot of LED B, Turk Street

ENERGY PERFORMANCE

Power data for the baseline HPS luminaires and the LED luminaires was recorded for one of each streetlight type using a DENT ElitePro weather proof data logger. The measurements were taken for a period of two weeks or more each. The monitoring team relied upon SFPUC personnel to install and remove the power meters.

The Leavenworth Street 400W base case HPS luminaire drew an average of 481.1W over the monitored period. The estimated annual energy consumption for this load, assuming 4,100 hours of operation, is 1,972 kWh. The Turk Street 200W base case HPS luminaire drew an average of 227.1W over the monitored period. The estimated annual energy consumption for this load, assuming 4,100 hours of operation, is 931 kWh.

Continuous power demand from the ROAM node was reported in product literature as 1.6W, so this value was subtracted from measured power to determine LED luminaire power only. Including weighted controls power (continuous system load from nodes and system gateway), which is calculated later in the Network Controls Performance section, average power for the Leavenworth Street LED luminaire (LED A) was 224.1W. This LED luminaire and controls power demand represents a savings of 53.4% versus the base case 400W HPS luminaire. Average power demand for the Turk Street LED luminaire (LED B) and controls was 93.6W. This LED luminaire and controls power demand represents a savings of 58.8% versus the base case 200W HPS luminaire.

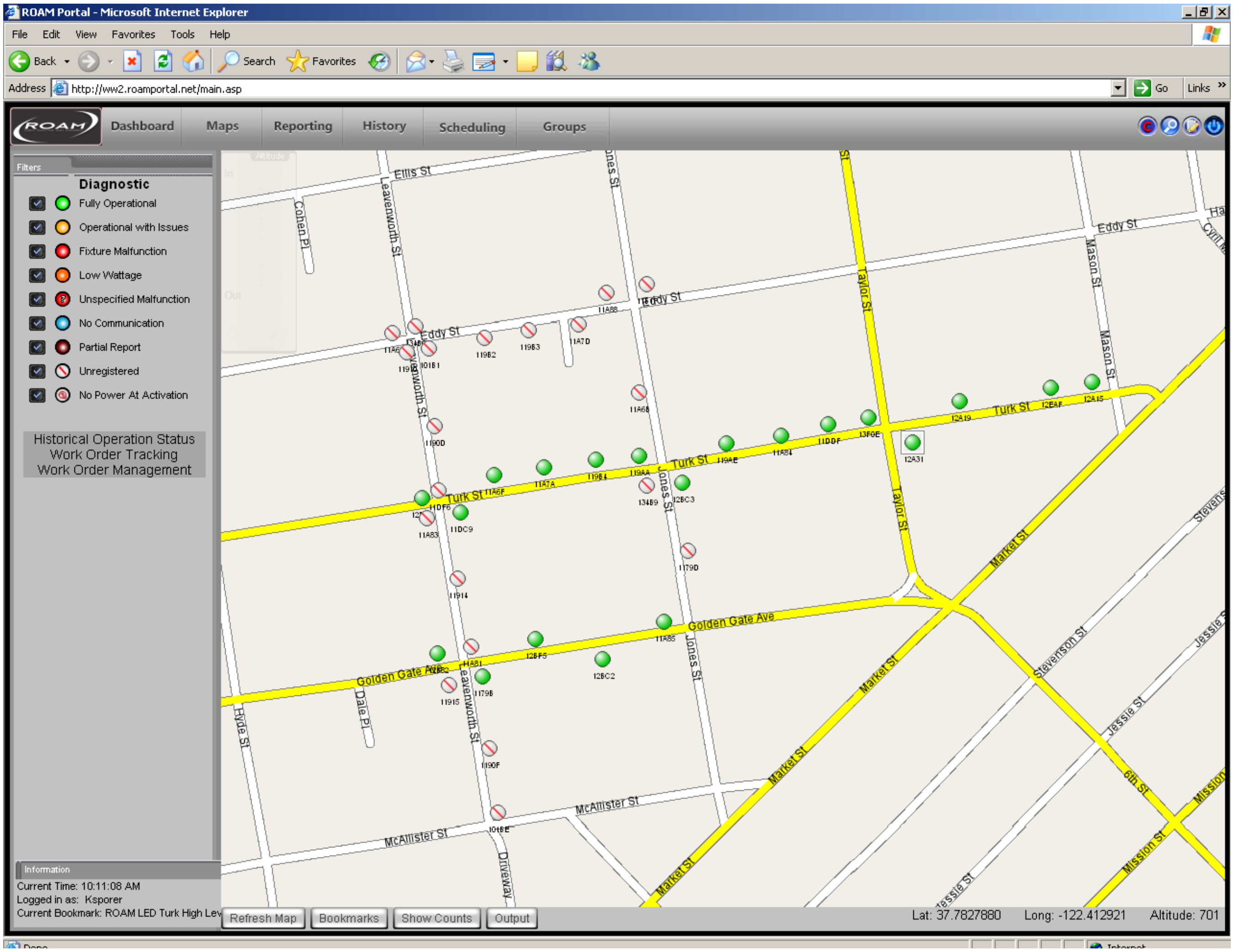
Table XVIII: Measured Power Data

Luminaire Type	Measured Luminaire Power (W)	Luminaire Power, Including Controls (W)	Power Savings (W)	% Savings Over Base Case Power
400W HPS	481.1	-	-	100.0%
LED A	220.7	224.1	257.0	53.4%
200W HPS	227.1	-	-	100.0%
LED B	90.2	93.6	133.5	58.8%

Network Controls Performance

FUNCTIONAL TESTING AND WEB INTERFACE DEMONSTRATION

Through street lighting field work and visits to SFPUC offices, the network controls system design, operation and many of its functions were observed. The system operator demonstrated the web interface used to manage network streetlights on August 14, 2009. A partially deployed network of 21 controlled streetlights was populated in the web interface; more nodes were installed later for the 57 streetlight pilot, including the unregistered locations visible in the following screenshot, which shows the layout of the Tenderloin pilot network. Green button icons represent the 21 luminaires controlled by ROAM nodes. The system user could click on the icons for detailed asset information or to open a command menu, which could be used to control a streetlight in real time. Nodes are displayed on the system map as buttons that change color depending on operation status (left frame). All registered nodes in the system were displaying as fully operational at the time of the system tour.

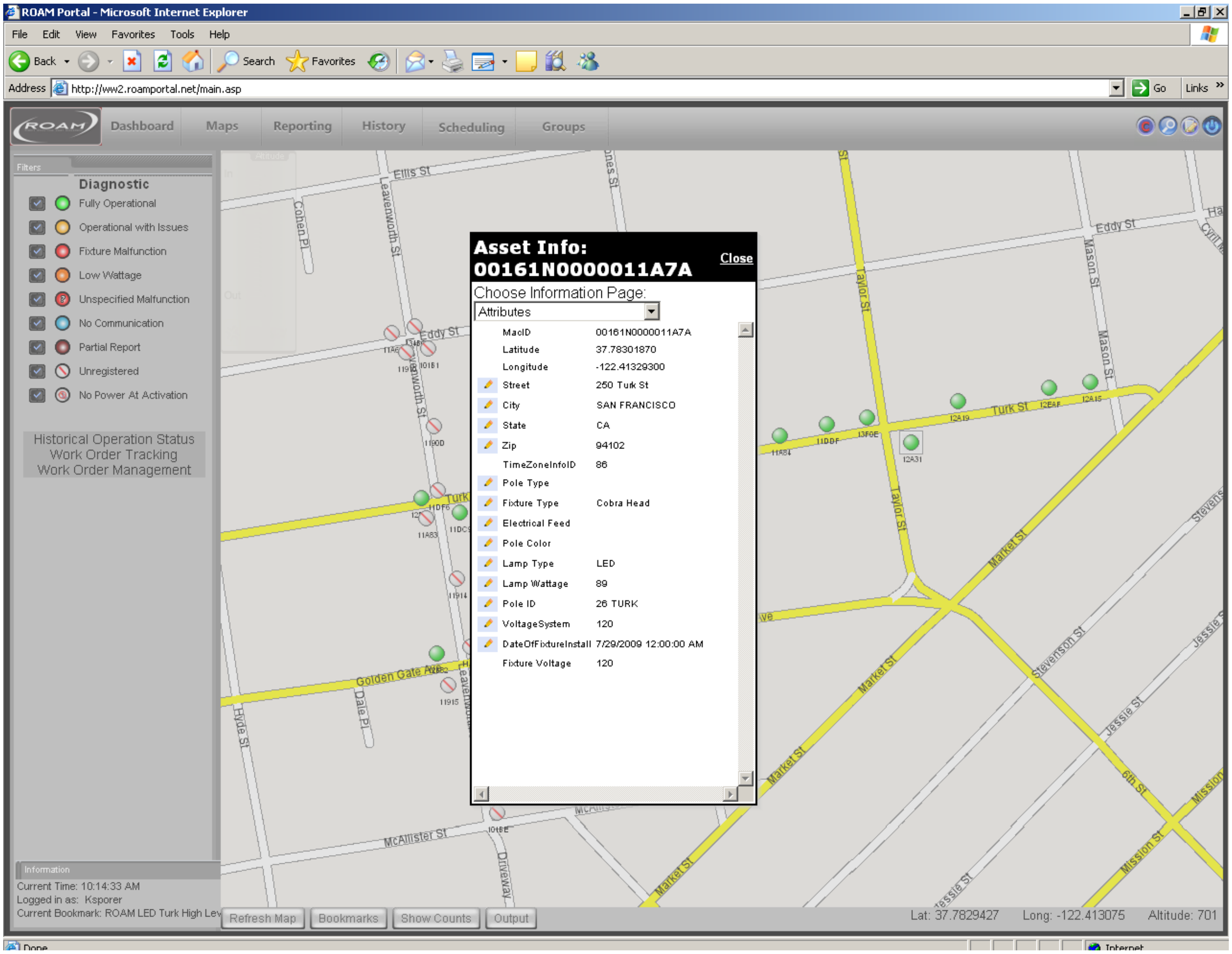


Current Time: 10:11:08 AM
Logged in as: Ksporer
Current Bookmark: ROAM LED Turk High Lev

Lat: 37.7827880 Long: -122.412921 Altitude: 701

Figure 25: ROAM Pilot System Overview Map

Detailed information for each streetlight could be obtained by right-clicking on the light icon on the map. A popup box appeared with options to see attribute details and operation information or work order history. Attribute info could also be edited from this view. Multiple lights could be selected by dragging a window across the streetlights of interest for history or command purposes.



Asset Info: 00161N0000011A7A Close

Choose Information Page: Attributes

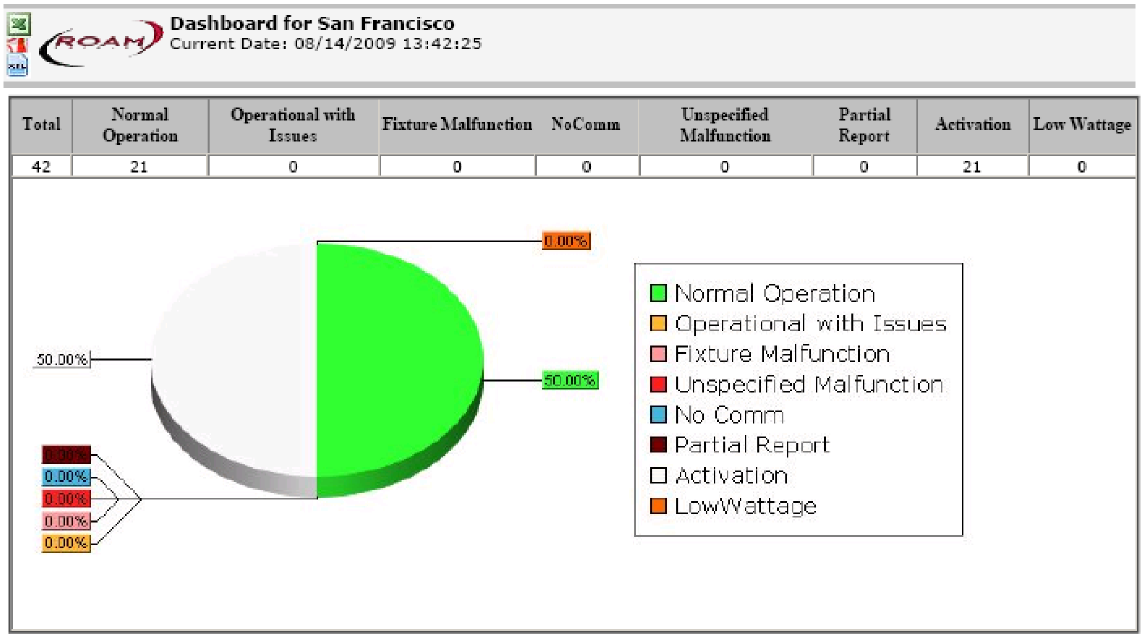
MacID	00161N0000011A7A
Latitude	37.78301870
Longitude	-122.41329300
Street	250 Turk St
City	SAN FRANCISCO
State	CA
Zip	94102
TimeZoneInfoID	86
Pole Type	
Fixture Type	Cobra Head
Electrical Feed	
Pole Color	
Lamp Type	LED
Lamp Wattage	89
Pole ID	26 TURK
VoltageSystem	120
DateOfFixtureInstall	7/29/2009 12:00:00 AM
Fixture Voltage	120

Current Time: 10:14:33 AM
Logged in as: Ksporer
Current Bookmark: ROAM LED Turk High Lev

Lat: 37.7829427 Long: -122.413075 Altitude: 701

Figure 26: ROAM Node Attribute Display

The six tab bar at the top of the page allows the user to select overview screens of interest. Along with the network map, the ROAM front page also has options for Dashboard (as shown below), History, Reporting, Scheduling, and Groups screens.



Dashboard for San Francisco
Current Date: 08/14/2009 13:42:25

Total	Normal Operation	Operational with Issues	Fixture Malfunction	NoComm	Unspecified Malfunction	Partial Report	Activation	Low Wattage
42	21	0	0	0	0	0	21	0

Figure 27: ROAM Pilot System Operations Dashboard

USER INTERFACE FUNCTIONALITY AND EASE OF USE

The system operator reported that for the most part the ROAM interface, system menus and functions were intuitive and simple to use, which appeared to be the case during the network interface tour.

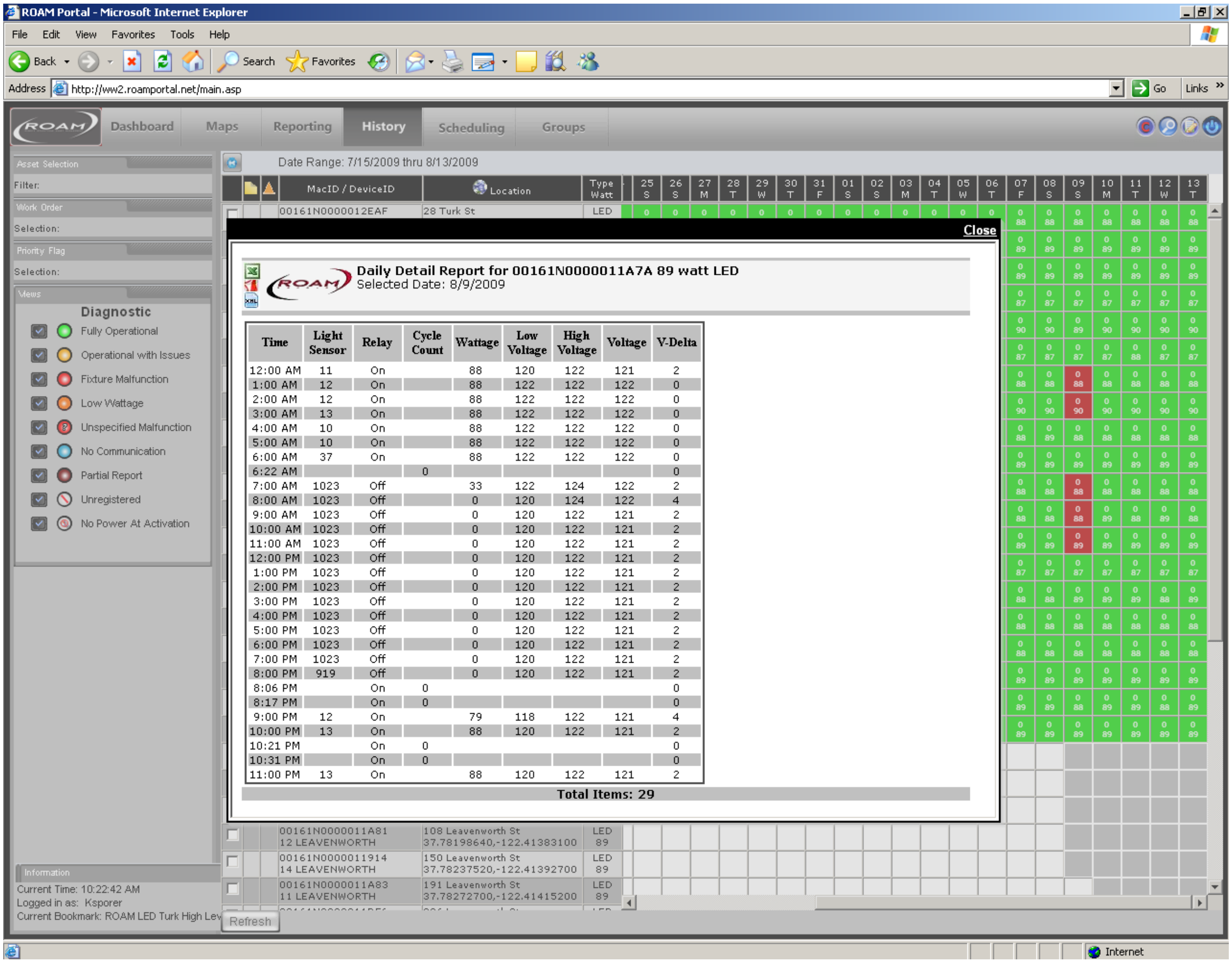
ON / OFF CONTROLS:

The ROAM nodes include standard electronic photocells and network radios; the default operation of each luminaire was photocontrol. Through the web interface, manual or scheduled control of on/off functions was also possible. On-site observation, data logging and system power reports verified that when on/off commands were sent from the web interface, the luminaires responded appropriately. Schedules allowed on/off control either by fixed times or floating schedules relative to daily sunrise and sunset times provided by virtual astronomical time clock.

POWER MEASUREMENT, DATA COLLECTION AND REPORTING

The system reports operation status for all nodes in the network and is capable of exporting luminaire operation status and hourly power averages to .csv and .pdf files for further analysis, lagging one day after recording. Operation issues are also reported with color coded icons on the system map. However, real-time operation information such as on/off status or power draw was not available in the system; it could be assumed that fully operational nodes (green) are operating according to schedule but actual on/off status or power readings must be pulled the following day or later (the system can archive for several years). Also, though individual luminaire power reports were available for any prior day, a system-wide power report was not available, though ROAM reported that this option would be easily customizable per customer request.

An example of the system's records for on /off times and hourly power averages and low/high voltage readings for a single streetlight is displayed below. Hourly voltage and power information could also be plotted for a given day. ROAM-recorded LED streetlight wattage and on/off times agreed with field data from power data loggers.



Current Time: 10:22:42 AM
Logged in as: Ksporer
Current Bookmark: ROAM LED Turk High Lev

00161N0000012EAF | 28 Turk St | LED

Daily Detail Report for 00161N0000011A7A 89 watt LED
Selected Date: 8/9/2009

Time	Light Sensor	Relay	Cycle Count	Wattage	Low Voltage	High Voltage	Voltage	V-Delta
12:00 AM	11	On		88	120	122	121	2
1:00 AM	12	On		88	122	122	122	0
2:00 AM	12	On		88	122	122	122	0
3:00 AM	13	On		88	122	122	122	0
4:00 AM	10	On		88	122	122	122	0
5:00 AM	10	On		88	122	122	122	0
6:00 AM	37	On		88	122	122	122	0
6:22 AM			0					0
7:00 AM	1023	Off		33	122	124	122	2
8:00 AM	1023	Off		0	120	124	122	4
9:00 AM	1023	Off		0	120	122	121	2
10:00 AM	1023	Off		0	120	122	121	2
11:00 AM	1023	Off		0	120	122	121	2
12:00 PM	1023	Off		0	120	122	121	2
1:00 PM	1023	Off		0	120	122	121	2
2:00 PM	1023	Off		0	120	122	121	2
3:00 PM	1023	Off		0	120	122	121	2
4:00 PM	1023	Off		0	120	122	121	2
5:00 PM	1023	Off		0	120	122	121	2
6:00 PM	1023	Off		0	120	122	121	2
7:00 PM	1023	Off		0	120	122	121	2
8:00 PM	919	Off		0	120	122	121	2
8:06 PM		On	0					0
8:17 PM		On	0					0
9:00 PM	12	On		79	118	122	121	4
10:00 PM	13	On		88	120	122	121	2
10:21 PM		On	0					0
10:31 PM		On	0					0
11:00 PM	13	On		88	120	122	121	2

Total Items: 29

MacID / DeviceID	Location	Type Watt
00161N0000011A81 12 LEAVENWORTH	108 Leavenworth St 37.78198640,-122.41383100	LED 89
00161N0000011914 14 LEAVENWORTH	150 Leavenworth St 37.78237520,-122.41392700	LED 89
00161N0000011A83 11 LEAVENWORTH	191 Leavenworth St 37.78272700,-122.41415200	LED 89

Figure 28: ROAM Node Operation History

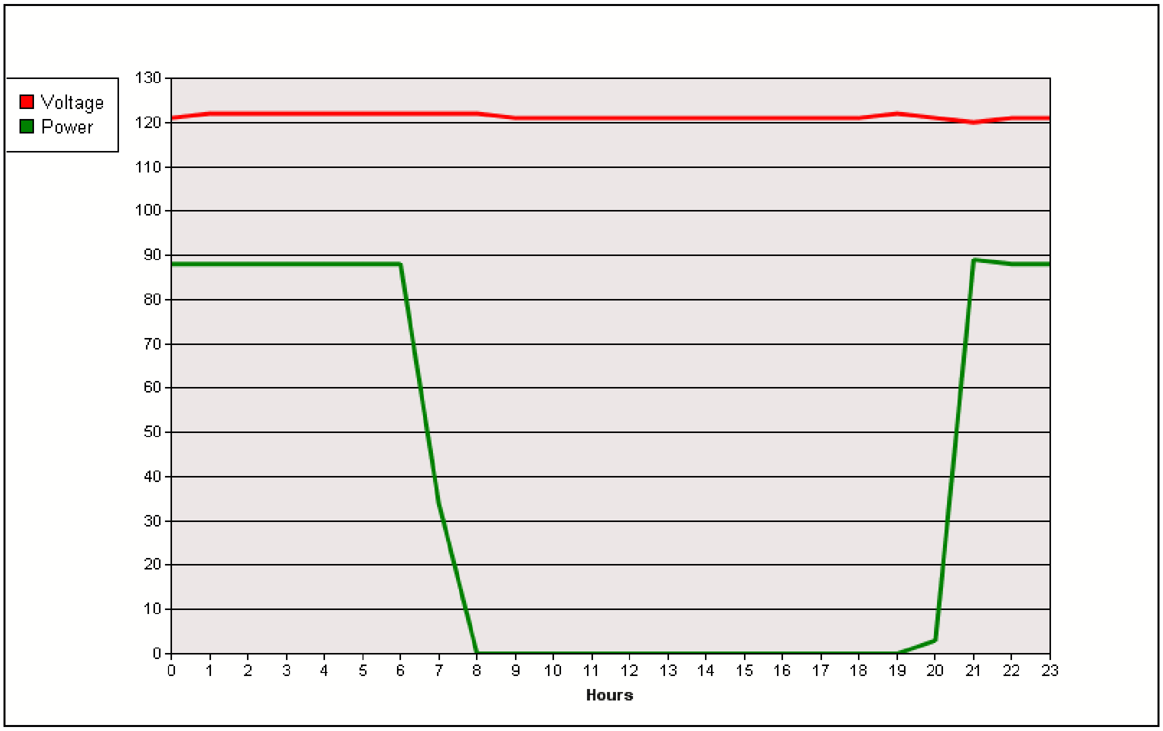
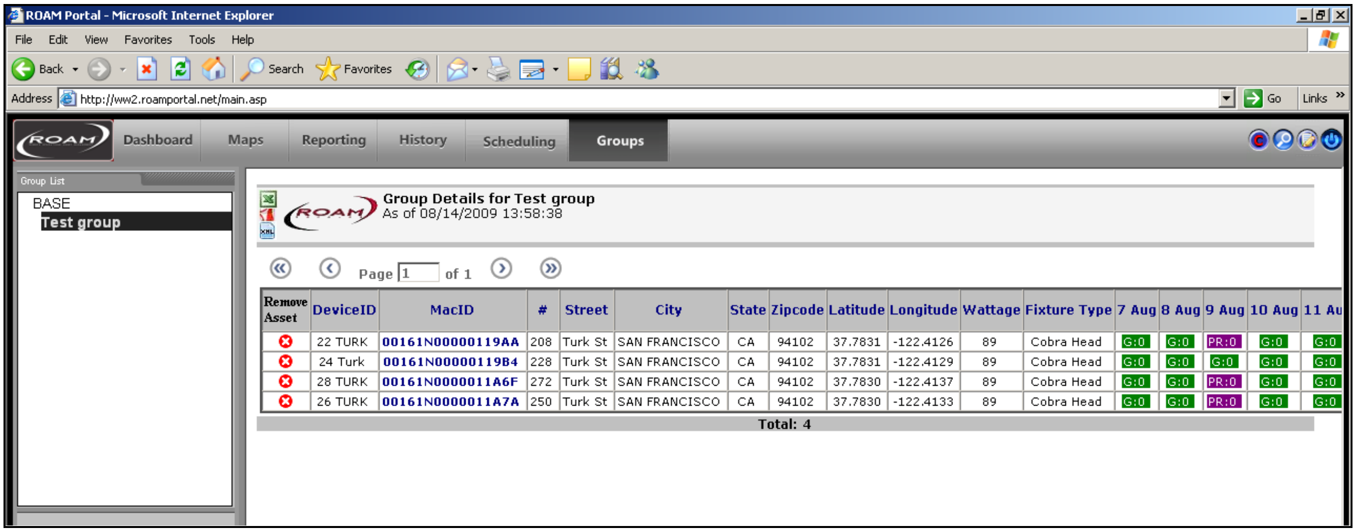


Figure 29: ROAM Node Daily Power and Voltage Cycle

LUMINAIRE GROUPING AND SCHEDULING

The ROAM default operation for on/off commands is standard electronic photocell control, but groups of luminaires could be scheduled for different on/off operation if desired. The scheduling function could not be used until assets were assigned to a group, which was created in the group tab view according to selected geographic area or malfunction type. During functional testing, a group of 4 luminaires was successfully created and the process was found to be simple to understand:



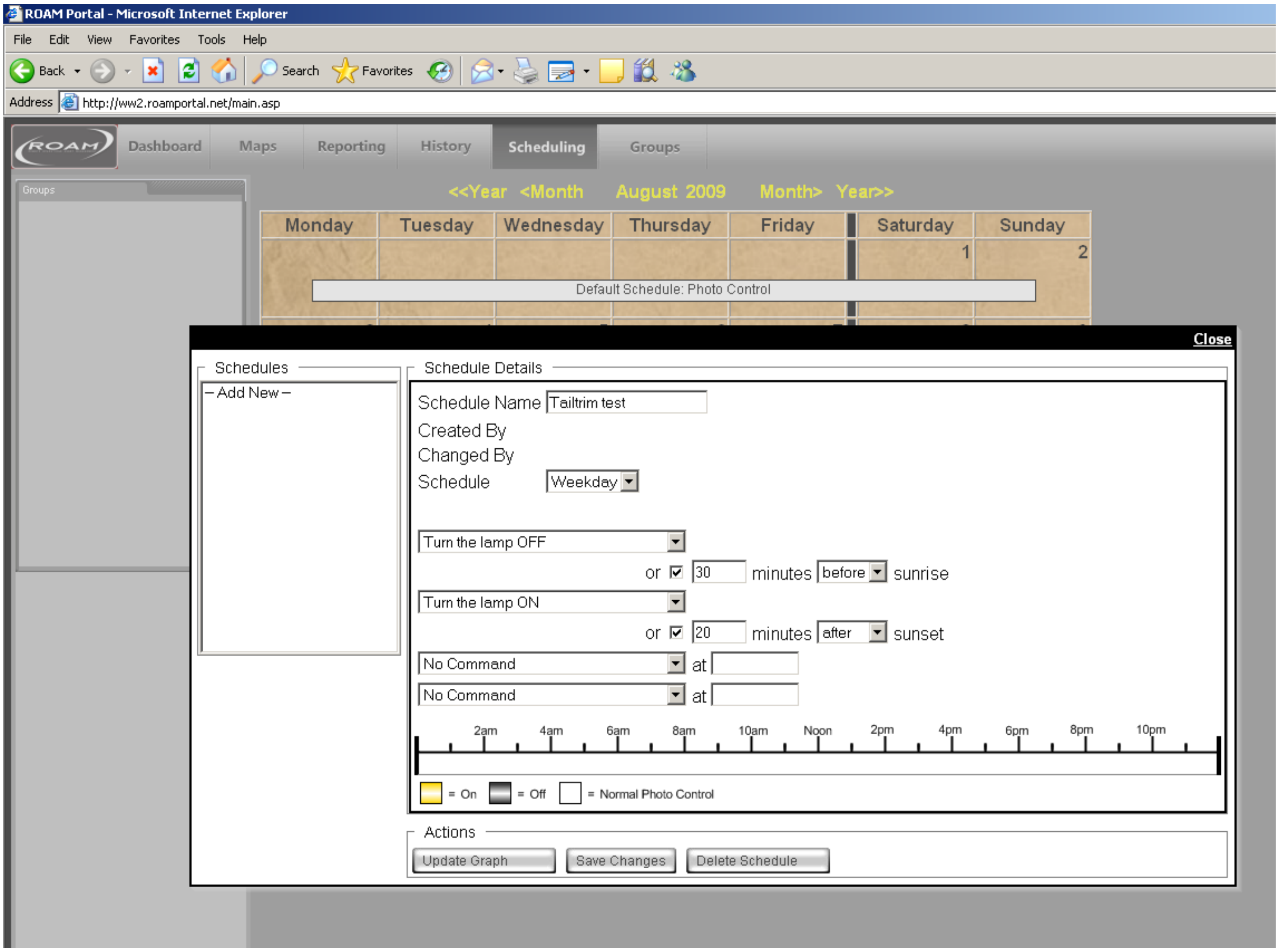
Group Details for Test group
As of 08/14/2009 13:58:38

Remove Asset	DeviceID	MacID	#	Street	City	State	Zipcode	Latitude	Longitude	Wattage	Fixture Type	7 Aug	8 Aug	9 Aug	10 Aug	11 Au
☒	22 TURK	00161N00000119AA	208	Turk St	SAN FRANCISCO	CA	94102	37.7831	-122.4126	89	Cobra Head	G:0	G:0	PR:0	G:0	G:0
☒	24 Turk	00161N00000119B4	228	Turk St	SAN FRANCISCO	CA	94102	37.7831	-122.4129	89	Cobra Head	G:0	G:0	G:0	G:0	G:0
☒	28 TURK	00161N0000011A6F	272	Turk St	SAN FRANCISCO	CA	94102	37.7830	-122.4137	89	Cobra Head	G:0	G:0	PR:0	G:0	G:0
☒	26 TURK	00161N0000011A7A	250	Turk St	SAN FRANCISCO	CA	94102	37.7830	-122.4133	89	Cobra Head	G:0	G:0	PR:0	G:0	G:0

Total: 4

Figure 30: ROAM Test Scheduling Group Detail View

For given groups of streetlights, schedules could be set by four methods: a weekly schedule, an event schedule, a schedule that adjusts daily based on astronomical sunrise and sunset, or default standard photocontrol operation. During testing, the process for saving newly created schedules was unclear, but the system operator was able to contact ROAM customer support during the exercise to resolve questions. A test schedule adjusting on/off times daily based on astronomical sunset and sunrise was successfully created. Subsequent power data pulled from the system indicated that the test schedule enacted one day later than intended; the reason being unclear. Ideally new schedules enacted by the system operator would take effect immediately; this issue was relayed to ROAM for evaluation and follow up.



Schedule Name Tailtrim test

Created By

Changed By

Schedule Weekday

Turn the lamp OFF

or ☑ 30 minutes before sunrise

Turn the lamp ON

or ☑ 20 minutes after sunset

No Command at

No Command at

🟨 = On ⬛ = Off ☐ = Normal Photo Control

Figure 31: ROAM Group Scheduling Window

OUTAGES, MAINTENANCE WORK ORDERS AND TRACKING SYSTEM

The host site uses Maximo Asset Management Software for work orders and job tracking in the streetlight maintenance division, so the ROAM features for these tasks have not been explored by the operator. However, the ROAM interface reports on outages, non-communicating nodes, and other status messages from each networked luminaire and this information could be used to identify and manage maintenance needs. In fact, during the pilot study period, the system identified and reported non-communicating nodes when a blown fuse caused an outage on a string of streetlights that included several streetlights equipped with ROAM nodes.

INSTALLATION AND COMMISSIONING

The process for installing and commissioning network nodes for luminaire control appeared to be efficient and easy to learn. The ROAM system includes activation equipment that is used to step through the assignment of attribute data in the field for each network node. This information is then uploaded to the network and the node is located and assigned in the controls topology. A customized activation manual was provided with the pilot system and was accompanied by a custom bar-coded "Activation Handbook" that according to system installers made the entry of attribute information extremely easy. Each ROAM node has a unique MAC identification, which is read by a barcode scanner during activation to associate a deployed node with the asset information collected during installation.

The process of activating and installing a ROAM node in the field was observed. The process involved using a PDA to scan activation steps in a handbook, which initiated attribute data entry (pole ID, fixture type, etc). The PDA typically synchs with a GPS device to record the precise coordinates of a node location, though manual address entry is possible if the GPS fails to locate. All node info is then transmitted to the ROAM customer network database from the PDA. During the field trial, attribute information for the node was successfully entered, though GPS connectivity was an issue due to interference from tall surrounding buildings. This did not present a significant problem as the location information was later easily entered from the desktop application.

Figure 32: ROAM Node Activation Equipment

CUSTOMER ACCEPTANCE

A user survey document was prepared to collect customer feedback on various aspects of the operator experience. The survey was given to the primary system user, the SFPUC Maintenance Planner for the Utility Services Group. Survey questions covered installation and commissioning, operation and functionality, customer support, and overall satisfaction. Generally, the operator reported that the system was intuitive to use and the functionalities added value to maintenance and planning routines. The operator also reported satisfaction with customer support and interest in implementing the network controls on a larger scale if budget allows. The operator did note however in the user survey questionnaire that without dimming controls, the energy savings benefits of the controls technology was limited.

The survey respondent was asked for comments and numeric satisfaction responses on a scale of 1 (most satisfied) to 5 (least satisfied).

SYSTEM INSTALLATION AND COMMISSIONING

Ease of installation:

Most Satisfied : [✓ 1] 2 3 4 5 : Least Satisfied

The initial installation of the ROAM system was extremely simple…installations were consistent with the installation of a photocell.

Compatibility with existing lighting system:

Most Satisfied : [✓ 1] 2 3 4 5 : Least Satisfied

Control system utilized NEMA twist-lock type receptacle.

Training for system installation:

Most Satisfied : [✓ 1] 2 3 4 5 : Least Satisfied

Due to the simple nature of the product, only a brief explanation of the instillation process was provided to the crew. More detailed training was available if required.

Commissioning:

Most Satisfied : 1 [✓ 2] 3 4 5 : Least Satisfied

A comprehensive activation manual and a custom bar-coded "Activation Handbook" was provided …made entering attribute information extremely easy. GPS connectivity was issue due to interference from tall buildings. This was not a significant problem as coordinates were easily entered from the desktop

OPERATION AND FUNCTIONALITY

System interface ease of use:

Most Satisfied : 1 [✓ 2] 3 4 5 : Least Satisfied

I found the interface and its functions to be almost intuitive. The one module that I experienced difficulty with was the scheduling feature. I believe that some of the difficulty was encountered by attempting to use the function without training.

Training and experience required to operate:

Most Satisfied : [✓ 1] 2 3 4 5 : Least Satisfied

Operations, management, and maintenance functions:

Most Satisfied : [✓ 1] 2 3 4 5 : Least Satisfied

The functionality of the system is completely value added from a maintenance perspective. Currently our maintenance activities are reactionary and initiated from public feedback. The ROAM system enables our maintenance activities to be proactive.

Energy benefits:

Most Satisfied : 1 2 3 [✓ 4] 5 : Least Satisfied

The current systems energy benefit is low, this would be somewhat improved with the dimming feature currently in development.

Data and reporting capabilities:

Most Satisfied : 1 [✓ 2] 3 4 5 : Least Satisfied

CUSTOMER SUPPORT

Most Satisfied : [✓ 1] 2 3 4 5 : Least Satisfied

Customer support has been provided immediately at each request.

OVERALL SATISFACTION

Most Satisfied : [✓ 1] 2 3 4 5 : Least Satisfied

ENERGY PERFORMANCE

While the network controls offer significant operational benefits, energy savings potential through the ROAM system installed for the pilot was limited as dimming features to allow adaptive scheduling were not included. Scheduled reductions in run time could also have provided energy savings though changing streetlight operation schedules was not desired by the host so this was not tested in the demonstration. ROAM reports that its technology has the necessary architecture to provide dimming commands to a ROAM-enabled fixture. In order for dimmable streetlights to respond to ROAM commands, ROAM has developed prototype Dimming Control Modules (DCM) that can be integrated into the fixture and connected to dimmable electronic ballasts or drivers. The DCM will reportedly be compatible with any fixture that has a 0-10v dimmable ballast or driver and will be available in volume production in early summer of 2010. A bi-level dimming control will also be available for fixtures with non-continuous dimming drivers.

The ROAM system components also require power to operate. In order to remain in communication with the network, the ROAM nodes draw a small amount of power and the system gateway must also be continuously powered to link the streetlight network to the internet server. The power used by the nodes and gateway can be divided across the networked streetlight inventory to represent controls power on a per streetlight basis. A table of network controls power and annual energy use is given below for a typical ROAM system configuration based on manufacturer-reported power demand from controls and field-measured luminaire power. At only a few watts per streetlight, the total additional power due to controls is minimal, representing a 2% to 4% increase in system power for the LED options evaluated in this study. Note that the system gateway is designed to manage 2,000 or more networked luminaires, though conservatively it is assumed below that each system gateway manages 1,000 streetlights. Even so, the system gateway only represents around 0.01W per streetlight.

Table XIX: Weighted Controls Power per Streetlight

System Component	Power	Component : Streetlight Ratio	Runtime Factor[29] (Component Hours / Streetlight Hours)	Weighted Power per Streetlight
ROAM Node	1.60	1:1	2.14	3.42
System Gateway	5.50	1:1000	2.14	0.01
			Total Controls Power per Streetlight	3.43
			Annual Controls Energy Use per Streetlight	14.06 kWh

Streetlight and Network Controls Economic Performance

Advanced streetlights and controls offer cost savings advantages over time but require additional upfront investment. The SFPUC demonstration was a pilot installation of 57 networked streetlights, but for economic projections higher volume replacement scenarios make more sense, as unit costs for the streetlights and controls would be lower and more realistic. The streetlight and controls manufacturers were asked to provide cost information for installations of 1,000+ streetlights.

ECONOMIC ANALYSIS SCENARIOS

Longer lasting, lower power LED streetlights should result in lower annual maintenance and energy costs. The network controls may further reduce maintenance costs by streamlining maintenance practices such as outage identification. If the LED streetlights and controls included dimming features (which they did not in the SFPUC pilot), adaptive street lighting strategies could be adopted to further reduce lighting power for low vehicle/pedestrian conflict periods and even more energy savings could accrue.

Based on estimated equipment and installation costs and energy and maintenance savings, economic performance was evaluated through simple payback[30] and net present value (NPV) analyses[31] for LED luminaires with and without network controls relative to incumbent HPS luminaires on photocell controls.

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[29] Since controls components run continuously, to add controls load to the streetlight on-state power, controls power must be multiplied by a factor of 24 hours (daily controls runtime) / 11.23 hours (average streetlight nightly runtime, assuming 4,100 hours per year): 2.14. Multiplying this factor by the number of controls components per streetlight gives total controls power per streetlight.

[30] Simple payback, in units of years, is defined as a project's initial cost divided by resulting annual savings.

[31] NPV calculations were based on a project analysis term of 15 years, an annual escalation rate for energy, labor and maintenance of 3%, and a cost of capital of 4.5%. Readers are advised to use their own rates and assumptions. See Appendix D: Economic Data and Calculations.

Three LED streetlight deployment scenarios were considered for the two applications evaluated in this report:

1. Non-networked LEDs: Replacement of HPS streetlights with LED streetlights switched by standard photocells rather than network controls; scenario includes energy and maintenance savings due to LED streetlights only
2. Networked LEDs: Replacement of HPS streetlights with ROAM-networked LED streetlights; includes LED savings and additional maintenance savings from network controls
3. Hypothetical Adaptive Networked LED Scenario: Replacement of HPS streetlights with dimmable networked LED streetlights set at full power for half of the night and dimmed to 50% power for half of the night; includes highest energy savings and maintenance savings from LED streetlight and network controls

The outlined adaptive scenario is purely hypothetical and is not feasible for the SFPUC pilot location as the LED streetlights and controls did not include dimming options. The example is meant only to be illustrative of what would be possible with dimmable networked LED streetlights, especially in light of ROAM's plans to introduce dimming controls in the future. Also, most utility billing options for street lighting electricity do not include metered rate schedules, which would be necessary for a customer to realize cost savings from reduced streetlight energy use through adaptive lighting strategies. The rate schedule issue may need to be addressed for streetlight network controls technology to achieve widespread adoption.

Economic estimates are sensitive to site-specific variables such as maintenance and energy costs and material costs such as the HPS and LED luminaires and controls equipment. SFPUC provided annual streetlight maintenance statistics and budget information. Assumptions were made about maintenance savings from LED streetlights and network controls based on available information. Savings estimates also depend upon assumptions for LED luminaire lifetime, which is a function of the life of all parts of the luminaire (LEDs, driver, housing, coating, etc.). Manufacturers' claims for luminaire lifetimes are highly variable. Both LED streetlight manufacturers whose streetlights were evaluated offer various other LED streetlight models at different price points and outputs that may be more appropriate for other 400W and 200W HPS replacement projects, depending on location variables (pole spacing, road width, vehicle and pedestrian traffic, etc.). Readers are advised to use cost estimates and equipment lifetime assumptions appropriate for their own location- and project-specific analyses.

ESTIMATED ENERGY COSTS

SFPUC owns and maintains the street lighting system in the pilot area and provides the streetlights' electrical service. SFPUC electric rates were used for an assumed baseline annual usage of 4,100 hours. For customer-owned and maintained streetlights in PG&E service territory, street lighting electricity is billed under the LS-2 rate schedule, which charges a monthly fixed rate per streetlight based on assumed annual operation of 4,100 hours and a standard energy rate.[32] For comparison,

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[32] The LS-2 schedule released in May of 2009 includes monthly rate bins for LED streetlights of various wattages. LS-2 bills streetlights at flat monthly charges that, under Class A rates, include a small monthly "facilities" fee ($.187) and energy charges listed for various lamp types (HPS, LPS, MH, MV, induction, and LED), wattage bins, and voltage service. These energy charges are calculated based on assumed ballast losses for each lamp type and wattage bin, and annual hours of operation.

((Lamp wattage + ballast losses) x 4,100 hours/12 months/1000) x streetlight kWh rate of $0.12206/kWh the economic analyses were also run with PG&E rates; the higher PG&E energy costs increased the value of the energy savings and improved the economic performance of the LED streetlight investment scenarios.

The power draw for the 400W and 200W nominal HPS streetlights was assumed to be the respective wattages measured in the field, which included ballast losses. The assumed wattages of the non-networked LED streetlights were the wattages measured in the field for the LED streetlights, excluding controls load. The wattages of the network controlled LED streetlights are the field-measured wattages plus the weighted controls load discussed previously. The annual hours of operation were assumed to be the same for networked and non-networked options. In reality, network controls may save unnecessary run time by detecting day-burning streetlights for repair more quickly; on the other hand, controls would also detect outages for repair sooner. The net effect was assumed to be zero for the sake of economic calculations here. For the adaptive network controlled LEDs, the LED wattages were assumed to be the weighted average of the networked streetlight wattage at full power for half of each night and 50% power for half of each night.[33]

Table XX: Estimated Street lighting Load and Annual Energy Costs and Savings

Scenario	Luminaire Power[32]	Annual Energy Use	Annual Energy Cost	Annual Energy Cost Savings	% Savings
400W HPS	481.1	1,972	$197	$0	-
Non Networked LEDs	220.7	905	$90	$107	54%
Networked LEDs	224.1	919	$92	$105	53%
Adaptive Networked LEDs	168.9	693	$69	$128	65%
200W HPS	227.1	931	$93	$0	-
Non Networked LEDs	90.2	370	$37	$56	60%
Networked LEDs	93.6	384	$38	$55	59%
Adaptive Networked LEDs	71.1	291	$29	$64	69%

STREETLIGHT AND NETWORK CONTROLS COSTS

The bulk purchase rate per LED luminaire used in the pilot (1000+ units) was reported by the vendors as **$850** for LED streetlight A, which replaced the 400W HPS, and **$710** for LED streetlight B, which replaced the 200W HPS. Note that as the output of LED streetlight B was roughly half that of streetlight A (see Table VIII: Listed HPS and LED Luminaire Performance), the luminaire cost relative to light output was significantly higher for LED streetlight B. Without

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[33] Adaptive luminaire power was calculated as:
(((LED luminaire power, no controls / 2) + LED luminaire power, no controls) / 2) + weighted controls load
In the PG&E case, for energy cost savings it is assumed that the streetlights would be charged half time at the rate bin corresponding to the LED streetlight wattage at full power, and half time for the rate bin corresponding to the LED streetlights at half power. For the 400W HPS replacement, the monthly combined adaptive rate per streetlight equaled $7.169 and for the 200W HPS replacement the combined adaptive rate equaled $3.104.

network controls, the LED system would have to include a photocell, at a price of **$12** each according to the SFPUC. For the hypothetical adaptive scenario, versions of the LED streetlights with 0-10v dimming drivers are assumed to carry a **$25** premium over non-dimming options. The costs of the 400W and 200W HPS luminaires, including fixture, lamp, ballast, starter and photocell were quoted at **$217** and **$198** respectively.

The estimated cost for an at-scale deployment of the piloted network controls technology was quoted by the controls manufacturer as **$75/streetlight**, inclusive of luminaire node and system gateway (amortized over 1,000 streetlights). An additional minimal software licensing cost of $1,600 for an entire system was given, which would add some cost on a per-streetlight basis, but was small enough for large deployments ($0.16/streetlight for a 10,000 unit system for example) that it was not included in this analysis. However, it was assumed that for the dimmable, adaptive street lighting scenario, the ROAM system would be more expensive as well, since it would require the additional DCM to interface with the dimmable driver. An additional **$25/streetlight** (above the incremental cost of dimming drivers) was assumed for the dimming controls.

Table XXI: Estimated Streetlight and Controls Costs

Scenario	Luminaire Cost	Controls Cost	Total Cost	Total Cost Incl. Sales Taxes	Cost Premium over HPS
400W HPS	$205	$12	$217	$238	-
Non Networked LEDs	$850	$12	$862	$944	297%
Networked LEDs	$850	$75	$925	$1,013	326%
Adaptive Networked LEDs	$875	$100	$975	$1,068	349%
200W HPS	$186	$12	$198	$217	-
Non Networked LEDs	$710	$12	$722	$791	265%
Networked LEDs	$710	$75	$785	$860	296%
Adaptive Networked LEDs	$735	$100	$835	$914	322%

ESTIMATED INSTALLATION AND MAINTENANCE COSTS

Installation and maintenance costs used in this analysis were estimated based on available data; due to uncertainties on reported costs and maintenance totals, these estimates should not be considered absolute. Readers are advised to use appropriate cost assumptions for their particular application.

SFPUC provided information on total streetlight inventory and annual repairs and costs for each type and wattage of streetlight that SFPUC maintains. From the reported inventory sizes and annual repair visits and costs for the 400W and 200W HPS categories, annual maintenance costs for each streetlight type were estimated. The SFPUC's standard streetlight maintenance practice is spot, or 'burn-out," replacement based on complaints and observed outages, rather than rolling group replacements.

Based on the reported annual labor and material costs from 2008 to maintain SFPUC's streetlight inventory of over 17,000 lights in the 70W – 400W nominal range, an average annual cost of maintenance per streetlight of **$30.32** was calculated. Annual maintenance activity and cost data could be differentiated according to streetlight wattage, in which case it was found that the 400W streetlights had a much higher frequency of replacement in 2008 (92%) than would be expected based on rated lamp life. Consequently, much higher annual maintenance costs were found ($144/streetlight). The 200W streetlight maintenance cycle and costs ($26/streetlight) were roughly in-line with the inventory-average maintenance costs. The underlying reason or reasons for the unusually high frequency of lamp failures for the 400W HPS streetlights was not clear.

Post-analysis, summary historical maintenance data from earlier years (2004 to 2007) was obtained, which showed a historic annual replacement frequency for the 400W HPS lamps of 40% to 60%; lower than that observed in the differentiated cost data from 2008, but still high enough to bear out a wide disparity in maintenance frequency and cost between the 400W and 200W HPS streetlights. Because the reason for this high 400W HPS replacement frequency is not clear and may not be typical, the inventory-average maintenance cost per streetlight was seen as more widely applicable and was used for the economic calculations summarized in the tables below. However, economic calculations were also performed using the differentiated maintenance costs for specific applicability to SFPUC's case; these results are discussed below as well.

The SFPUC's labor cost for installation of a streetlight on an existing pole was estimated at **$112**, which agrees with data from previous studies. This installation cost is assumed to be the same for HPS and LED (networked or non-networked) luminaires.

ESTIMATED MAINTENANCE SAVINGS

The manufacturers of the LED streetlights assessed in this study both publish predicted lives of 80,000+ hours, or over 20 years, for the LEDs used in the luminaires. These lifetimes are far longer than the HPS rated lamp lives of 18,000 hours (roughly 4.4 years) for the 400W lamps and 24,000 hours (roughly 5.9 years) for the 200W HPS lamps. In fact, for SFPUC's 400W HPS streetlights, it was found that most lamps are replaced every year. While LED streetlights are expected to outlast HPS lamps, it is likely that LED luminaires will still require some level of maintenance for occasional catastrophic failure and periodic routine visits for cleaning, inspection, and so forth. As an emerging technology, LED streetlights have been operating in field installations for a relatively short period of time and there is no historical data for real, long-term performance and maintenance costs. Calculating the expected maintenance cost for an LED street lighting system is subject to many uncertainties, requiring assumptions about the annual probability of luminaire failure, before and after warranty, etc. Furthermore, the industry standard method for measuring LED chip lumen maintenance (LM-80-08) does not provide a method for measuring lifetime of the whole luminaire, which includes multiple components (LEDs, driver, housing, coating, etc.).[34] The expected useful life of the luminaire will likely not be the same as that of the LED package.

Even so, in general it is expected that there will be significant maintenance savings due to longer LED luminaire lifetimes. Estimated maintenance savings from recent reports on LED streetlight retrofit demonstrations in Oakland and San Francisco, CA have ranged from 59% to 100%.[35] Because of the many uncertainties inherent in attempting to quantify maintenance savings, for this report, a simplifying and conservative assumption of 50% maintenance savings due to LED streetlights alone was used.

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[34] The current industry-standard testing procedure for LED lumen depreciation, IESNA LM-80-08, does not include a method for extrapolating beyond the required 6,000 hours of testing. The IESNA is currently working on development of a standardized method (TM-21) for extrapolation of LM-80 data, but this has not been finalized. As a result, there is no industry standard methodology to properly verify manufacturers' claims for lumen maintenance.

[35] See Cook, et. al. PG&E Emerging Technologies Reports referenced previously.

No data was available on additional maintenance savings for LED streetlights due to network controls, though remote outage detection and automated maintenance orders and tracking would almost certainly have cost savings benefits. ROAM reports that in a Glendale, AZ installation of the ROAM network on over 18,000 HPS streetlights, more than 50% maintenance savings have been achieved.[36] However, these savings were achieved on HPS streetlights, whereas LED streetlights would independently be expected to achieve significant maintenance savings, and many of the maintenance benefits of the two technologies may overlap (fewer service calls, reduced maintenance visits, etc.). Without hard data on network controls maintenance savings in conjunction with LED streetlights, a general assumption of 20% additional maintenance savings (above LED streetlight savings) was made here (70% savings total). Again, readers should use their own estimates for maintenance savings when evaluating these technologies for their specific applications.

Table XXII: Estimated Maintenance Costs and Savings

Scenario	Annual Maintenance Cost	Annual Maintenance Savings	% Savings
400W and 200W HPS	$30	-	-
Non Networked LEDs	$15	$15	50%
Networked LEDs	$09	$21	70%
Adaptive Networked LEDs	$09	$21	70%

Comparisons between the networked and non-networked LED scenarios and the baseline HPS options were made for replacement at end-of-useful life / new construction economics in which LED luminaires with network controls are installed instead of the standard 400W or 200W HPS luminaires, and retrofit economics in which LED luminaires are installed in place of existing and fully functional 400W or 200W HPS luminaires.

Because annual maintenance costs and potential savings can vary widely from case to case, plots of retrofit simple payback as a function of assumed maintenance savings are provided later.

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[36] ROAM reported maintenance savings were due to fewer service calls for customer care functions such as outage resolution, fewer repeat maintenance trips due to lack of information, elimination of system patrolling, more effective maintenance activities due to detailed attribute data, maximized system life due to "day burner" detection, and optimized equipment warranty recovery with ongoing performance database.

REPLACEMENT AT END-OF-USEFUL LIFE / NEW CONSTRUCTION ECONOMICS

For replacement of HPS streetlights at end-of-useful life or for new construction projects, the cost of luminaire installation was assumed to be the same for either LEDs or HPS. The incremental cost of the project was therefore only the difference in material costs between the LED and the HPS streetlights. For networked streetlights, this cost included $75 of material costs for the controls components ($100 for adaptive networked streetlights).

Table XXIII: Replacement at End-of-Useful Life / New Construction Economics

Scenario							
Base Case	LED Case	Initial Cost	Annual Energy Savings	Annual Maintenance Savings	Simple Payback (Years)	15 Year NPV	Project IRR
400W HPS	Non-networked	$706	$107	$15	5.8	$926	18.7%
	Networked	$775	$105	$21	6.1	$919	17.5%
	Networked, Adaptive	$830	$128	$21	5.6	$1,167	19.5%
200W HPS	Non-networked	$574	$56	$15	8.0	$381	12.3%
	Networked	$643	$55	$21	8.5	$374	11.4%
	Networked, Adaptive	$698	$64	$21	8.2	$443	12.0%

As this table demonstrates, for replacement at end-of-useful life and for new construction scenarios, the savings achieved by retrofit to LED luminaires alone was enough to pay for the incremental cost in 5.6 to 8.5 years. Net present values ranged from under $400 to over $1,000. Interestingly, for both evaluated applications, there was relatively little difference in simple payback for non-networked, networked, and adaptive networked options; annual savings were always higher for the more expensive options.

There is typically a direct correlation between LED price and light output for a given manufacturer's product line. However, as noted previously, LED streetlights from two different manufacturers were used in the two applications evaluated here. For the SFPUC pilot, the LED luminaires selected to replace the 200W HPS streetlights had a higher relative cost per lumen of light output than the LED luminaires selected to replace the 400W HPS streetlights, resulting in the specific economic conclusions shown here. These economic conclusions should not be used to generalize for all cases and it is strongly recommended that readers use cost estimates appropriate for their own location and project specific analyses.

Using SFPUC annual maintenance costs differentiated for the 400W HPS and 200W HPS base cases, the 400W HPS scenarios achieved paybacks of 4 years or less, largely due to high maintenance savings (from $72 per year in the non-networked scenarios to $101 per year in the networked scenarios). NPV was in the $1,700 (non-networked) to $2,200 (adaptive networked) range. Paybacks and NPV using differentiated maintenance costs for the 200W HPS scenarios were very similar to those calculated using average maintenance costs, since the costs did not differ greatly ($26 per year versus $30 per year).

At the same inventory-averaged annual maintenance savings as in the table above, but applying PG&E streetlight rates and an incentive level of $150 per streetlight, the economics improved for all of the LED streetlight and controls options. For the 200W HPS base case, the energy cost savings increase by roughly $20 per year, which combined with the lower initial project cost due to incentives brought paybacks under 6 years and nearly doubled NPV. The impact was less for the 400W HPS base case, though paybacks improved by over one year in each scenario and NPV by $225 (non-networked) to over $300 (adaptive networked).

RETROFIT ECONOMICS

For retrofit economics, the cost of deploying LED streetlights and network controls is the full material and installation cost of the LED luminaires and controls. This necessarily increased the length of simple payback and reduced net present value.

Table XXIV: Retrofit Economics

Scenario							
Base Case	**LED Case**	**Initial Cost**	**Annual Energy Savings**	**Annual Maintenance Savings**	**Simple Payback (Years)**	**15 Year NPV**	**Project IRR**
400W HPS	**Non-networked**	$1,056	$107	$15	8.7	$576	11.0%
	Networked	$1,125	$105	$21	8.9	$570	10.6%
	Networked, Adaptive	$1,180	$128	$21	7.9	$818	12.6%
200W HPS	**Non-networked**	$903	$56	$15	12.7	$52	5.3%
	Networked	$972	$55	$21	12.8	$45	5.1%
	Networked, Adaptive	$1,026	$64	$21	12.0	$114	6.0%

For the retrofit scenarios, the payback periods increased to 7.9 to 12.8 years and NPV was reduced significantly, though remaining positive in each case.

Using the differentiated SFPUC annual maintenance costs for the 400W HPS and 200W HPS base cases, the 400W HPS scenarios again achieved much lower paybacks due to high maintenance savings. Retrofit paybacks ranged from 5.2 (adaptive networked) to 5.9 (non-networked) years and NPV was in the $1,300 (non-networked) to $1,900 (adaptive networked) range. Economic results for the 200W HPS base case scenarios were again similar to those using the average maintenance cost; paybacks were around 13 years. NPV was only $5 for the networked scenario but improved to $74 for the networked adaptive scenario.

Again, the economics improved significantly if PG&E electricity rates and incentives were applied. For the 200W HPS case, simple payback dropped to around 9 years for each scenario and the NPV of the investments was in the $400 to $500 range. Simple paybacks for the 400W HPS case were each around 7 years and NPV increased to $800 to $1,100.

Calculated simple payback periods and NPV for each LED option are sensitive to estimated energy and maintenance cost savings, as well as cost of capital and cost escalator assumptions, which will vary for each customer. To demonstrate the effect of maintenance savings on project payback periods, the following figures plot LED retrofit paybacks for the two evaluated applications through a range of assumed maintenance savings.

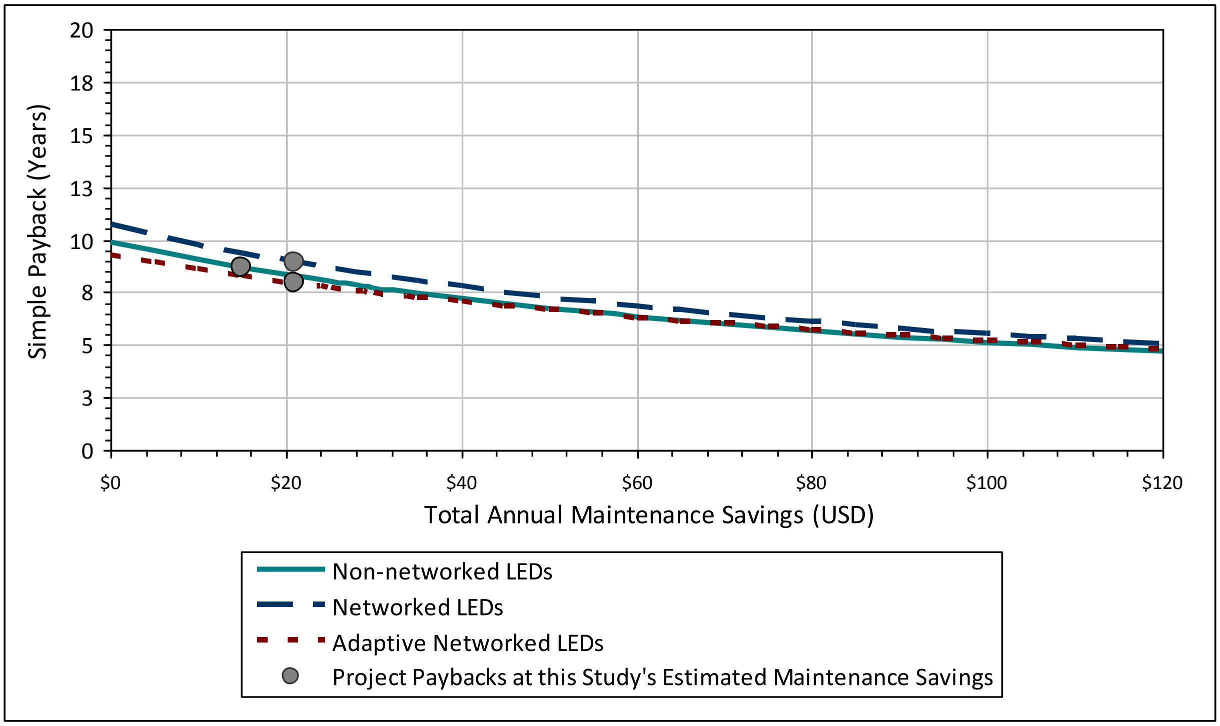

Figure 33: Maintenance Savings Impact on Retrofit Payback for 400W HPS Base Case

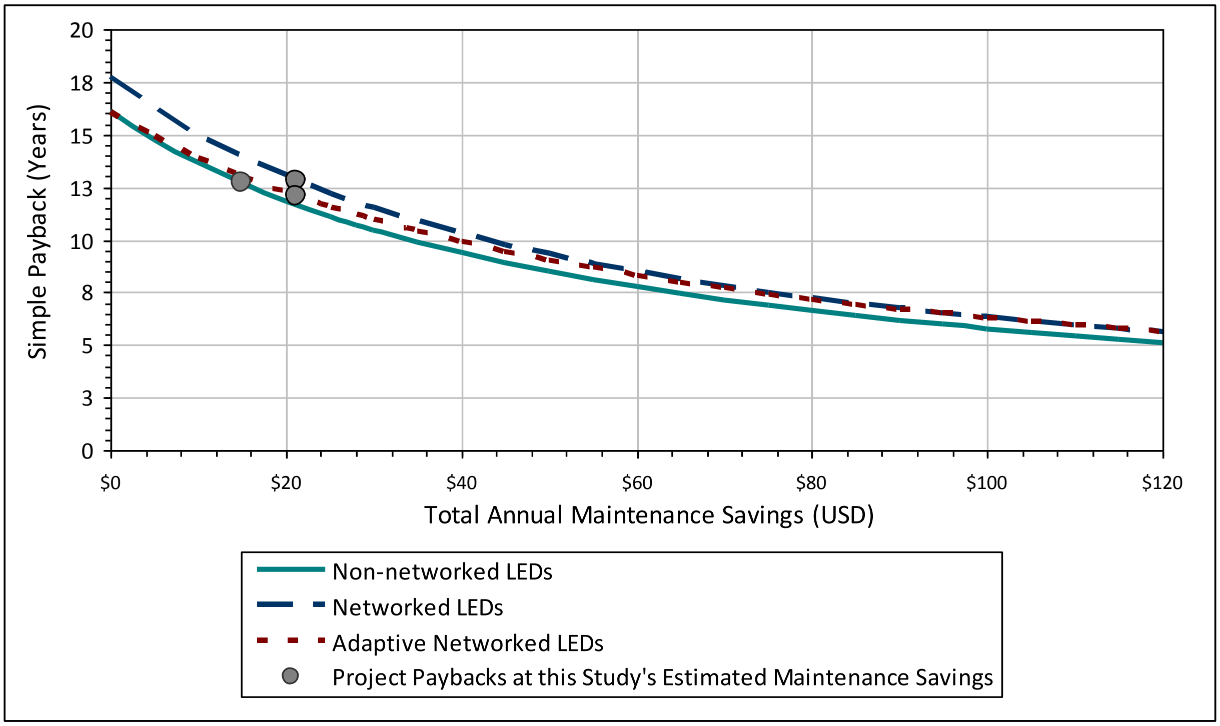

Figure 34: Maintenance Savings Impact on Retrofit Payback for 200W HPS Base Case

Discussion

At the current state of the technology, LED streetlights can be a viable, cost effective replacement for incumbent technologies such as HPS and have the potential to deliver significant energy savings. Streetlight network controls can provide enhanced, more efficient asset management and the ability to more accurately track streetlight energy usage, but significant energy savings benefits will depend on the ability to dim streetlights to adjust lighting power adaptively based on changing conditions. In most cases, new streetlight energy billing structures and methods would be required for customers to realize many of the potential economic benefits.

The demonstrated streetlight and controls technologies both showed promise in terms of wider-scale adoption. The LED streetlights performed to the satisfaction of the host site and provided initial lighting performance that met IESNA recommended levels, though to maintain recommended lighting levels over the long-term performance, slightly higher output sources would likely be required in the demonstration cases. The piloted network controls system was found to be simple to deploy and effective to use. The controls system also proved useful in tracking streetlight operating status, sending remote on/off commands, and logging streetlight runtime and energy usage.

A variety of LED street lighting options are now available for a range of distributions and roadway layouts. Consider the numerous manufacturers and models of streetlights that have qualified for PG&E's incentive program, which requires independent lab testing according to standard IESNA test procedures of all products and sets performance requirements for minimum efficacy, CRI and CCT. The qualified list has grown to over 70 luminaire models from 5 manufacturers. The DOE acknowledges that streetlights are an active area of the LED market that is capturing the interest of efficiency programs and municipalities.[37] Though recent demonstrations are proving savings, testing has also shown wide performance ranges. The DOE and Environmental Protection Agency are in the process of finalizing, with stakeholder input, ENERGY STAR® solid-state outdoor lighting criteria including new performance metrics such as Fitted Target Efficacy to help customers better differentiate between LED options in the growing market.

Along with lighting performance considerations such as efficacy, distribution, spectral power distribution, etc, other technical features of LED replacement options must be proven for the technology to succeed. Well-designed luminaires compatible with existing infrastructure (wiring, mounting, etc.) and that will withstand environmental factors over time will emerge as winners in the competitive marketplace.

Similar qualities will be expected of advanced controls options if they are to become more prevalent also. Compatibility with existing infrastructure and emerging street lighting options, durability, reliability, and performance all need to be guaranteed before large and costly street lighting networks are rolled out. Experience in early adopter locations like Glendale, AZ and California cities like Los Angeles, San Jose, and San Francisco should help planners understand the potential and limitations of network controls options and designs.

LED LUMINAIRE PERFORMANCE CONSIDERATIONS

Lighting quality, product reliability, energy usage, and cost are the key performance factors for LED streetlights. If LED streetlights can perform as well or better than incumbent technologies from a lighting quality perspective, and can do so using less energy, it is likely that the LED streetlight

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[37] Hitting the Target: ENERGY STAR SSL Outdoor Lighting Criteria. Jason Tuenge, LC, LEED AP Pacific Northwest National Laboratory DOE Webcast October 8, 2009

market will continue to grow. However, LED streetlights will also need to live up to lifetime claims to maintain momentum, and costs, which have been decreasing steadily, may still need to come more in line with those of other options.

Photometric results from this study showed that average photopic illuminance from the LED streetlights installed for the demonstration was lower than that from the incumbent HPS streetlights. While fulfilling IESNA minimum illuminance recommendations initially, the LED streetlights would need to provide higher light output to maintain minimum illuminance over the streetlights' lifetimes. Nonetheless, the host site contact felt that lighting performance was improved with the LED luminaires. Light source characteristics like color rendering and spectral power distribution, which do not necessarily directly affect photopic illuminance levels, can at least qualitatively be said to have enhanced visual information in the pilot area (see field photos). Most lighting guidelines are currently written only for photopic lighting performance and do not yet account for the mesopic advantages that LED streetlights demonstrate. The IESNA Technical Memo dealing with mesopic lighting (TM-12) is currently undergoing revisions to provide more specific recommendations for incorporating light source spectral distribution effects under mesopic conditions into street lighting design.

It is important to note that the modeled and measured photometric performance is specific to the LED products and site characteristics evaluated in this test. As with traditional lighting sources, performance of LED products varies widely between manufacturers and should be evaluated independently for specific products under consideration.

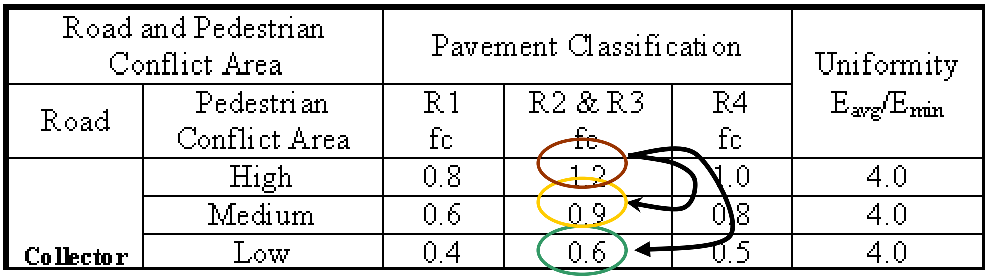
NETWORK CONTROLS PERFORMANCE CONSIDERATIONS

The features that network controls systems offer streetlight managers will vary, but are almost certain to represent improvement over basic photocell control. It is important that the functions promised by the technology, such as flexible scheduling, system energy reporting, outage detection, and maintenance tracking deliver once systems are installed. Testing and verification of system operation will be critical, especially given that these systems are more complex than the controls technology they are replacing. In the case of this pilot, further development and testing of features such as the scheduling module needs to be carried out so that users can easily input new operation schedules to maximize the system's effectiveness. Pilots demonstrating these technologies in real world applications, and underscoring challenges that manufacturers need to address, will help cities understand the value of controls for street lighting inventories and estimate their benefits for future installations.

The energy savings measured in the SFPUC pilot were a result of switching to lower power LED streetlights. The non-dimming network controls option installed for the pilot did not offer significant energy savings potential, unless operators were willing to reduce streetlight runtime, which was not desired in this case. Adaptive scheduling, such as the hypothetical 100%/50% power scenario evaluated here, could significantly improve energy savings, though this would required dimmable LED streetlights and compatible controls.

Standards such as RP-8-00 do not currently specifically address adaptive strategies, which have only recently become possible with the advent of easily dimmable light sources like LEDs. As an example of how an adaptive schedule might be implemented, consider the following abridged version of the RP-8-00 standard, showing recommended illuminance levels for collector roadways based on pedestrian conflict levels. From high to low pedestrian conflict in the collector roadway classification, the recommended illuminance drops 50%, from 1.2 to 0.6 fc.

Table XXV: Hypothetical Use of RP-8-00 Classifications to Implement Adaptive Lighting Strategies



Road and Pedestrian Conflict Area		Pavement Classification			Uniformity E_{avg}/E_{min}
Road	Pedestrian Conflict Area	R1 fc	R2 & R3 fc	R4 fc	
Collector	High	0.8	1.2	1.0	4.0
	Medium	0.6	0.9	0.8	4.0
	Low	0.4	0.6	0.5	4.0

Roadway lighting systems are typically designed for the conditions of highest anticipated traffic volume and highest anticipated pedestrian activity, but an adaptive lighting strategy would recognize that for many hours of the evening and early morning, the actual traffic and pedestrian activity is much lower. Recommended light levels under these lower activity conditions would also be lower per RP-8-00. The savings implications are significant, but are predicated on controls options that allow dimming schedules. Future standards guidelines would help clarify acceptable adaptive street lighting strategies by directly addressing this point.

Another key point of interest, and a highly touted feature of network controls, is the ability to monitor and meter streetlight energy usage. This is an improvement from the city and utility perspective because currently streetlights operate as un-metered load and it is not always known when they are not operating properly; i.e. lamp failures or day burning lights. How the energy data from these systems is going to be used is another question. Ideally, some form of communication with utility information systems would be available to transfer data collected by the streetlight network for monitoring and billing purposes. This will be especially important for adaptive lighting scenarios, where streetlight wattage is not a fixed point. Similarly, there will need to be some standardization in terms of the frequency and accuracy of power measurements recorded by network controls systems. Utilities such as PG&E maintain strict requirements for revenue-grade metering, such as accuracy of ±2%, testing in compliance with ANSI C12.1-2008 American National Standard for Electricity Meters, programmability for rolling interval demand calculations, etc. Some of these standards may not apply to streetlight controls system, but key elements like accuracy would need to be met by streetlight network controls technology to be of the most value.

POTENTIAL SAVINGS

In the case of this study, HPS streetlights were replaced with LED streetlights that saved over 50% power while providing satisfactory performance according to the pilot host, with initial illuminance meeting IESNA recommendations. In order to meet maintained illuminance recommendations, LED streetlights with slightly higher initial output would be required. In terms of total photopic lumen output, HPS is already a relatively efficient technology; but LED streetlights compete with the photopic efficacy ranges of HPS while providing higher scotopic output. In other HPS-to-LED streetlight retrofits, LEDs have shown similar competitiveness and savings.[38] The parasitic power of the piloted network controls technology proved to be low, but without dimming capabilities, the controls added little energy benefit. However, the controls manufacturer is launching a controls package compatible with 0-10v dimming streetlights in the near future, which opens the door to adaptive streetlight scheduling and additional energy savings.

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[38] Cook, et al. San Francisco and Oakland Reports.

A 2002 DOE report estimated annual energy usage of 31 TWh in the US from streetlights alone for an inventory of approximately 38 million luminaires.[39] HPS and other HID sources account for almost 85% of all roadway lighting electricity use in the U.S. Based on these and other findings, it could be assumed that LEDs are capable of replacing a large fraction of today's HID streetlights. If they were network controlled, energy savings would depend on the controls strategies employed, the controls and streetlights' ability to dim, and whether or not adaptive street lighting became a widespread practice. If the entire roadway inventory of HID lights were replaced with networked LEDs operating on average at 50% baseline power, the achievable annual energy savings would be almost 12,900 GWh, which represents a CO_2 emissions reduction of almost 10 million metric tons, or an equivalent savings of 22 million barrels of oil.[40]

ECONOMIC FEASIBILITY

Market adoption of networked LED streetlights on a large scale will hinge not only on lighting and energy performance, but also on economic competitiveness. The initial investment in LED streetlights and network controls will only be made if system savings warrant the extra upfront cost. The cost premium for the LED streetlights alone compared with the cost of the incumbent HPS luminaires was roughly 260% to 300%, and including network controls was 320% to 350%. These higher-cost options will only be economically feasible if they provide significant benefits over their lifetime. Energy and maintenance savings represent the ongoing value of a networked LED streetlight investment, but the degree of savings will depend on a given location's maintenance costs and how much savings these technologies enable.

For the SFPUC case, replacement of HPS streetlights with non-networked LED streetlights at end-of-useful life and in new construction projects resulted in payback periods of about 6 to 8 years, with attractive project rates of return. Including network controls would change the paybacks only marginally, as the additional upfront costs were recovered through higher estimated maintenance savings. Network controls also would require a minimum number of replacements in the same area to be worthwhile, since isolated networked streetlights are not feasible. However, with an RF-based wireless system, network build-out over time is possible as long as sufficient nodes are present to provide communication pathways to local internet gateways. When feasible, there is a clear economic case for proposing replacement of HPS luminaires at end-of-useful life with networked LED streetlights in the SFPUC service area, with a 15-year NPV of about $400 to $1000 for the two applications evaluated.

Retrofit cases are more costly as the incremental project cost includes the entire equipment cost and installation labor costs, so even with high annual savings project paybacks will be longer. For the two applications evaluated, payback periods ranged from about 8 to 13 years. Again, there was relatively little difference in simple payback between the non-networked, networked, and dimmable networked options.

In PG&E territory, higher energy rates for street lighting and a recently launched incentive programs for LED streetlights improve the economic outlook for non-networked and networked LED streetlights. For the replacement of HPS with LED streetlights, paybacks improved to between 4 and 6 years for end-of-useful life and new construction projects and around 7 to 9 years for retrofit cases. PG&E's LED streetlight incentive program is also important in that it provides guidance in terms of performance and quality by qualifying only products that are more likely to deliver long term lighting performance and energy savings.

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[39] Navigant Consulting, Inc. (2002). "US Lighting Market Characterization, Volume I."

[40] See the EPA's Greenhouse Gas Equivalencies Calculator http://www.epa.gov/RDEE/energy-resources/calculator.html

It should be emphasized that for street lighting customers to realize the energy cost savings achievable through adaptive street lighting or simple scheduling changes with network controls, metered rate schedules based on actual energy usage are necessary. Furthermore, controls technologies with metering capabilities will need to deliver data at acceptable accuracy and in a format that can be shared with utilities for billing purposes.

Conclusion

This assessment of the SFPUC networked LED street lighting pilot answered many questions about the lighting and controls technologies deployed and raised several points that should be considered for future studies and possible incentive programs, especially as LED streetlights and network controls are installed at scale in locations around the U.S.

Remote, web-based control, monitoring, and management of street lighting inventories is possible through available network controls technologies.

Network controls communication strategies are more complex than standard photocell controls, but RF mesh networking with photocell-adapted streetlight nodes represents a simple, effective solution that presents few infrastructure or installation challenges.

Streetlight network controls add valuable asset management services, from outage detections to energy monitoring, but without dimming controls and dimmable streetlights, energy benefits are limited to scheduling shorter run times and other on/off strategies. Adaptive street lighting practices that increase energy benefits would be possible with dimmable LEDs and compatible controls, but questions remain as to how dimming schedules based on cyclical traffic and pedestrian volume would comply with current and future lighting standards. Clarifications from the standards community will be necessary for widespread implementation of energy savings strategies through network control systems.

Streetlight energy monitoring via network controls is possible and was demonstrated with the piloted technology. Further work is necessary to outline how controls system data collection will translate into revenue-grade metering for utilities and customers, and how utilities will develop appropriate rate schedules to bill actual streetlight energy use.

LED streetlights as replacements for incumbent HPS streetlights can achieve photopic performance within roadway lighting standards (though in the demonstration cases slightly higher output would have been necessary for long-term performance) and improve scotopic performance. Further development of standards and procedures to account for scotopic and mesopic lighting performance in nighttime conditions, such as IESNA TM-12, will be crucial for quantifying these benefits.

While large scale network controls and LED streetlights projects will require upfront capital outlay, they can deliver positive net present value and reasonable paybacks if maintenance and energy savings are high. Economics were most attractive in new construction and replacement at end-of-useful life scenarios where incremental project cost was lower. Retrofit projects, with estimated paybacks ranging from 8 to 13 years for the applications evaluated here, will become more economically attractive as the initial LED streetlight costs continue to come down. Economic performance depends heavily on assumed maintenance costs and savings and the upfront cost of the streetlights and controls; many options are available with a range of price points. Incentive programs can also help offset some of the initial costs and differentiate higher quality products.

Many standards and voluntary rating programs are being developed to further assist potential LED street lighting customers in selecting appropriate products, such as DOE's ENERGY STAR criteria for SSL outdoor lighting and IESNA's forthcoming TM-21 that is expected to provide standard methods for predicting LED device life. Similar standards development on the network controls side would also be helpful.

Appendix A: Monitoring Data

POWER DATA

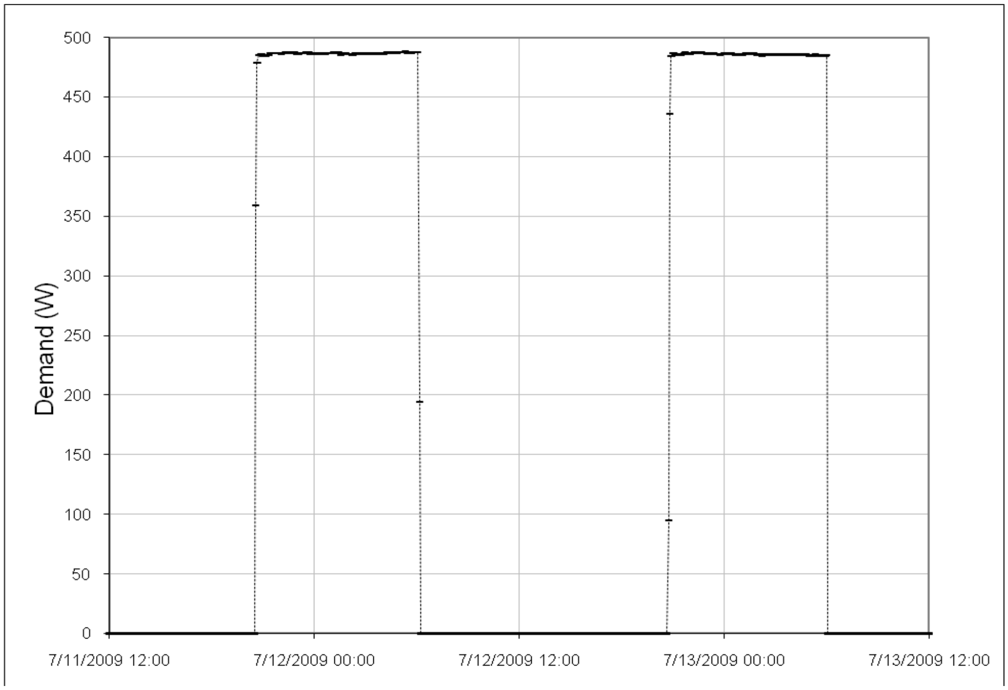


Figure 35: Sample of HPS Power Demand Data Series, Leavenworth Street

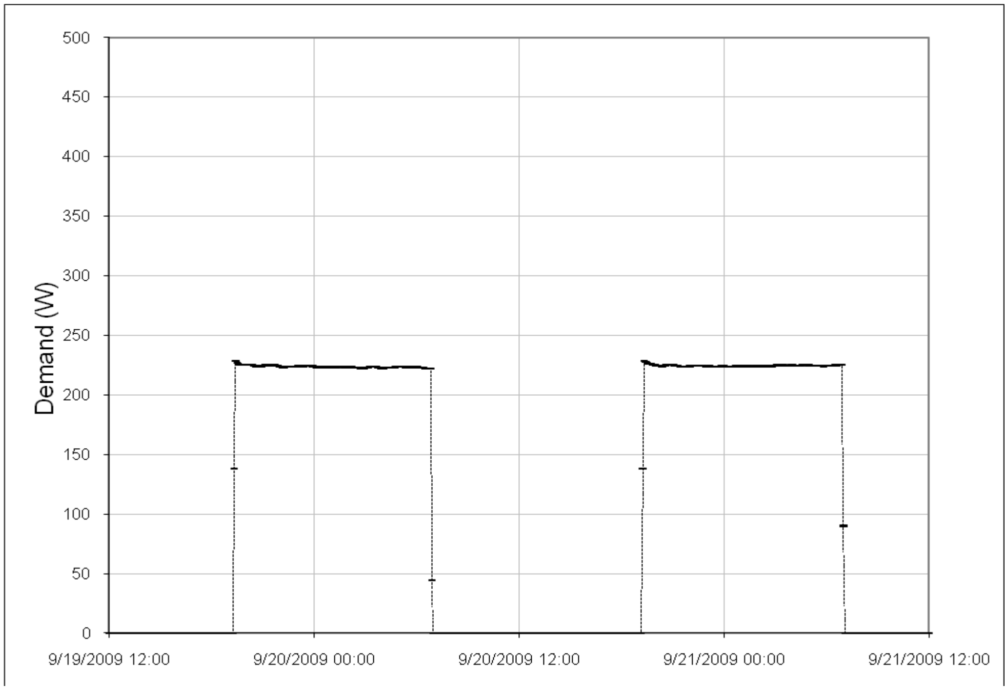


Figure 36: Sample of LED Power Demand Data Series, Leavenworth Street

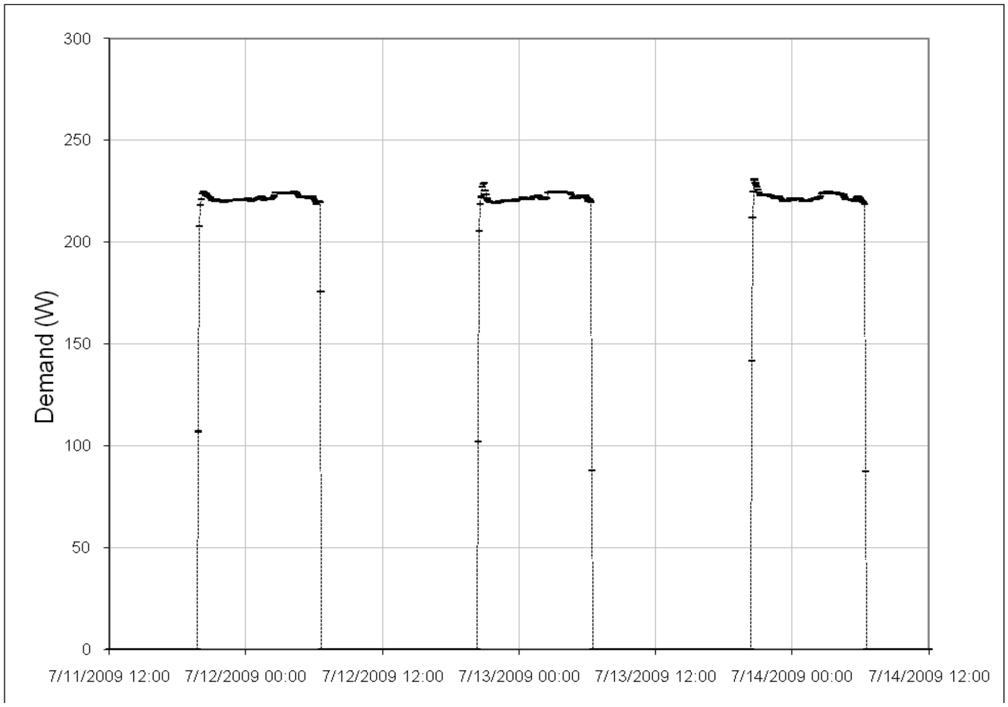


Figure 37: Sample of HPS Power Demand Data Series, Turk Street

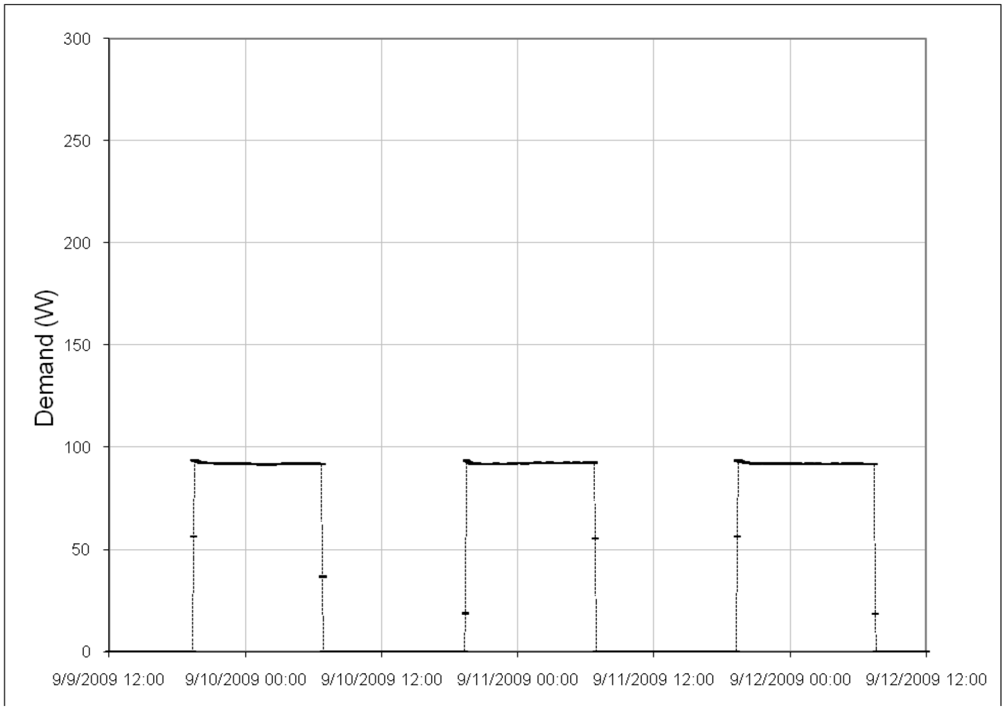


Figure 38: Sample of LED Power Demand Data Series, Turk Street

MODELED ILLUMINANCE DATA

Table XXVI: Modeled HPS Photopic Illuminance, Leavenworth Street (fc)

	0'	15'	30'	45'	60'	75'	90'	105'	120'	135'	150'	165'	180'	195'	210'	225'	240'	255'	270'	285'
3.75'	2.9	2.3	1.8	1.7	1.6	1.5	1.6	1.6	1.9	2.1	2	1.8	1.5	1.4	1.4	1.7	2.2	3.2	5.4	7
11.25'	3.6	3.1	2.4	2	1.8	1.8	2	2.3	2.7	2.7	2.7	2.7	2.2	1.9	1.7	1.9	2.4	3.7	5.9	8
18.75'	4.2	4.7	3.4	2.5	1.9	1.9	2.4	3.4	4.5	3.4	3.5	4.4	3.2	2.3	1.8	1.9	2.5	3.8	6	6.7
26.25'	5.6	6.3	4.2	2.7	2	2	2.7	4.1	6.2	5	5.5	5.9	3.8	2.5	1.9	1.9	2.4	3.5	5.1	4.9
33.75'	7.7	6.7	4.2	2.7	2.1	2.1	2.7	4	6.4	7.4	7.4	6	3.7	2.5	1.9	1.8	2.1	2.5	3.4	3.8
41.25'	8.3	6.2	3.6	2.4	1.8	1.8	2.3	3.5	5.9	7.9	7.1	5.6	3.3	2.2	1.7	1.5	1.6	1.8	2.4	3.2

Table XXVII: Modeled LED Photopic Illuminance, Leavenworth Street (fc)

	0'	9'	18'	27'	36'	45'	54'	63'	72'	81'	90'	99'	108'	117'	126'	135'	144'	153'	162'	171'
3.75'	1.1	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
11.25'	1.5	1.7	1.8	1.9	1.8	1.9	2	1.9	1.8	1.8	1.8	1.8	1.9	2	1.9	1.9	2	1.9	1.8	1.8
18.75'	2.4	2.5	2.7	2.6	2.4	2.5	2.8	2.8	2.6	2.6	2.6	2.6	2.7	2.8	2.6	2.5	2.7	2.9	2.7	2.7
26.25'	3.6	3.2	3.4	3.1	2.7	2.8	3.2	3.2	3.2	3.7	3.7	3.2	3.2	3.2	2.8	2.7	3.1	3.5	3.3	3.7
33.75'	3.7	2.9	2.9	2.7	2.3	2.4	2.7	2.6	2.7	3.5	3.6	2.7	2.6	2.7	2.3	2.3	2.6	2.8	2.8	3.5
41.25'	1.9	1.7	1.8	1.7	1.6	1.5	1.6	1.6	1.5	1.8	1.8	1.5	1.6	1.6	1.5	1.5	1.6	1.7	1.6	1.7

Table XXVIII: Modeled HPS Photopic Illuminance, Turk Street (fc)

	0'	15'	30'	45'	60'	75'	90'	105'	120'	135'	150'	165'	180'	195'	210'	225'	240'	255'	270'	285'
3.75'	1.5	0.9	0.8	0.7	0.6	0.7	0.8	0.8	0.7	1.4	1.2	0.7	0.8	0.8	0.6	0.5	0.6	1	2.1	2.2
11.25'	1.7	1	0.8	1	0.8	0.8	0.9	0.7	1	1.6	1.5	1	0.8	1	0.8	0.6	0.6	0.8	1.7	2.8
18.75'	2.1	1.5	0.7	0.8	0.8	0.8	0.7	0.7	1.4	1.9	1.8	1.3	0.7	0.7	0.8	0.7	0.6	0.7	1.4	2.7
26.25'	2.2	1.4	0.8	0.6	0.8	0.8	0.6	0.8	1.5	2	2.1	1.3	0.7	0.6	0.7	0.8	0.7	0.7	1.5	2.4
33.75'	2.5	1.9	0.8	0.7	0.7	0.7	0.6	0.8	2	2.3	2.3	1.7	0.8	0.6	0.6	0.8	1	0.8	1.3	2.3
41.25'	2.5	2.2	1	0.7	0.6	0.6	0.6	1.1	2.2	2.3	2.1	2.1	1	0.6	0.6	0.7	0.8	0.9	1	2

Table XXIX: Modeled LED Photopic Illuminance, Turk Street (fc)

	0'	9'	18'	27'	36'	45'	54'	63'	72'	81'	90'	99'	108'	117'	126'	135'	144'	153'	162'	171'
3.75'	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.5	0.6	0.6	0.6	0.6	0.5	0.6	0.7	0.7	0.6	0.5	0.6	0.6
11.25'	1	0.9	0.8	1	1	1	1	0.9	1	1.1	1.1	1	0.9	1	1	1	1	0.9	0.9	1.1
18.75'	1.7	1.2	1.4	1.3	1.2	1.3	1.4	1.5	1.3	1.8	1.8	1.4	1.4	1.4	1.3	1.3	1.4	1.5	1.3	1.9
26.25'	2.2	1.7	1.9	1.7	1.6	1.6	1.8	2	1.8	2.2	2.1	1.7	2	1.8	1.6	1.6	1.8	2	2	2.3
33.75'	2.3	2.2	2.1	1.6	1.5	1.5	1.6	2	2	2.1	2.1	1.9	2.1	1.6	1.4	1.4	1.6	1.9	2.3	2.2
41.25'	1.4	1.3	1.4	1.1	0.9	0.9	1	1.2	1	1.1	1	1	1.2	1	0.9	0.8	1	1.2	1.1	1.3

MEASURED ILLUMINANCE DATA

Table XXX: Measured HPS Photopic Illuminance, Leavenworth Street (fc)

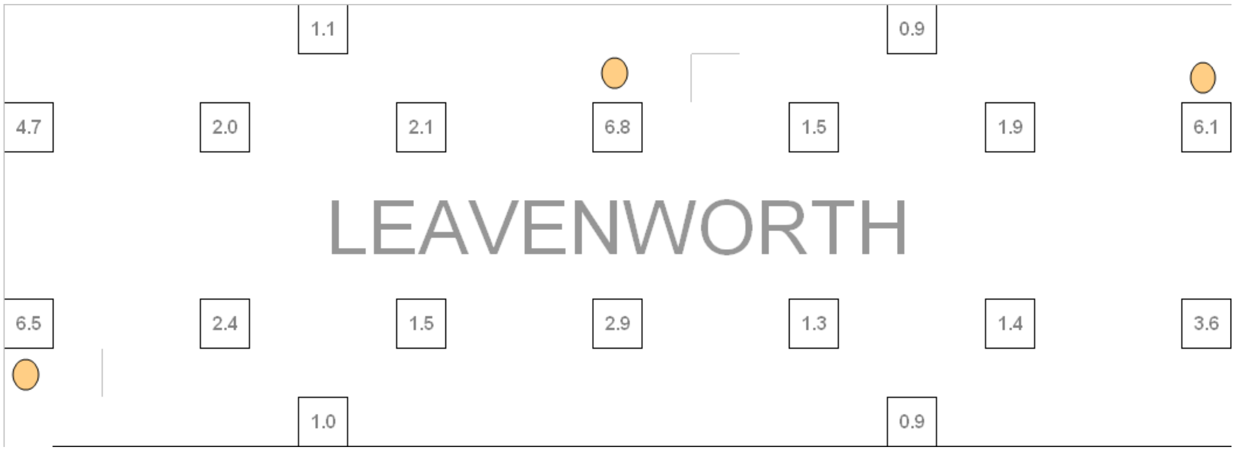


Table XXXI: Measured LED Photopic Illuminance, Leavenworth Street (fc)

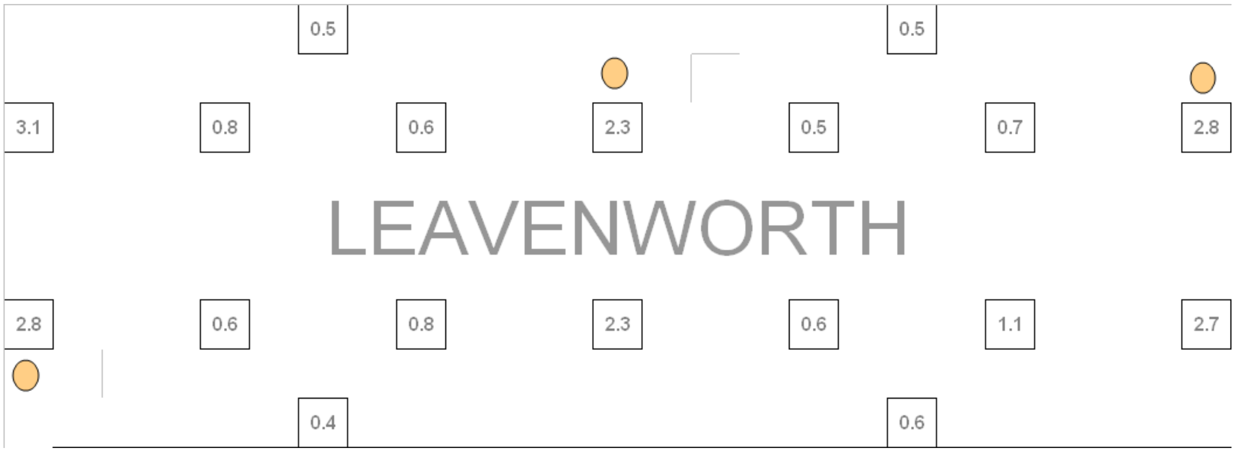


Table XXXII: Measured HPS Scotopic Illuminance, Leavenworth Street (fc)

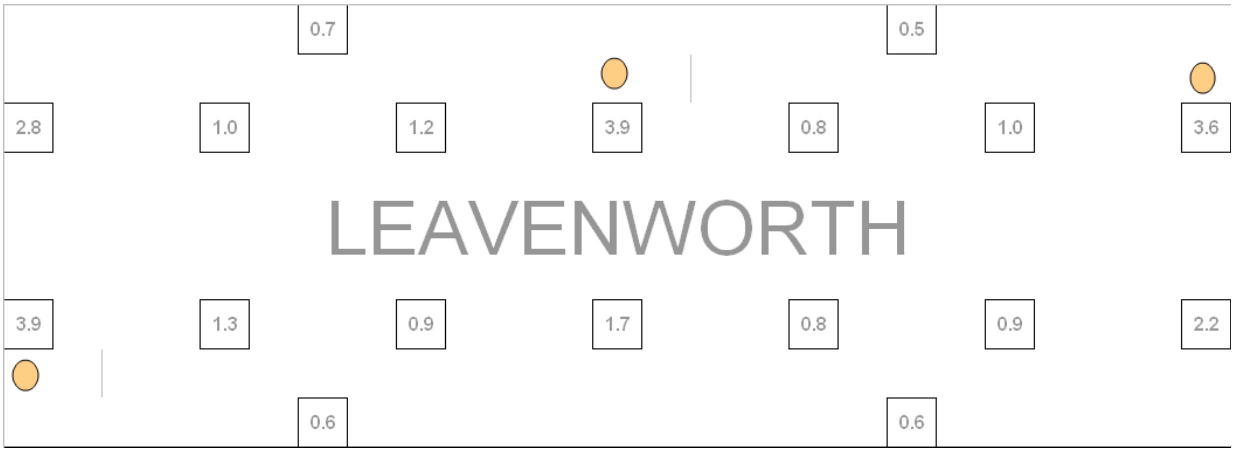


Table XXXIII: Measured LED Scotopic Illuminance, Leavenworth Street (fc)

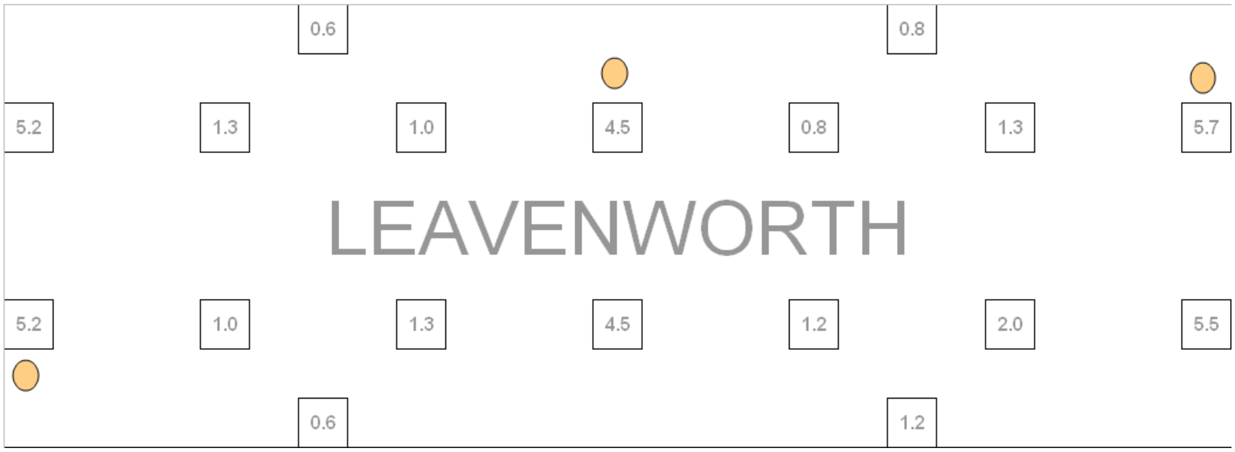


Table XXXIV: Measured HPS Photopic Illuminance, Turk Street (fc)

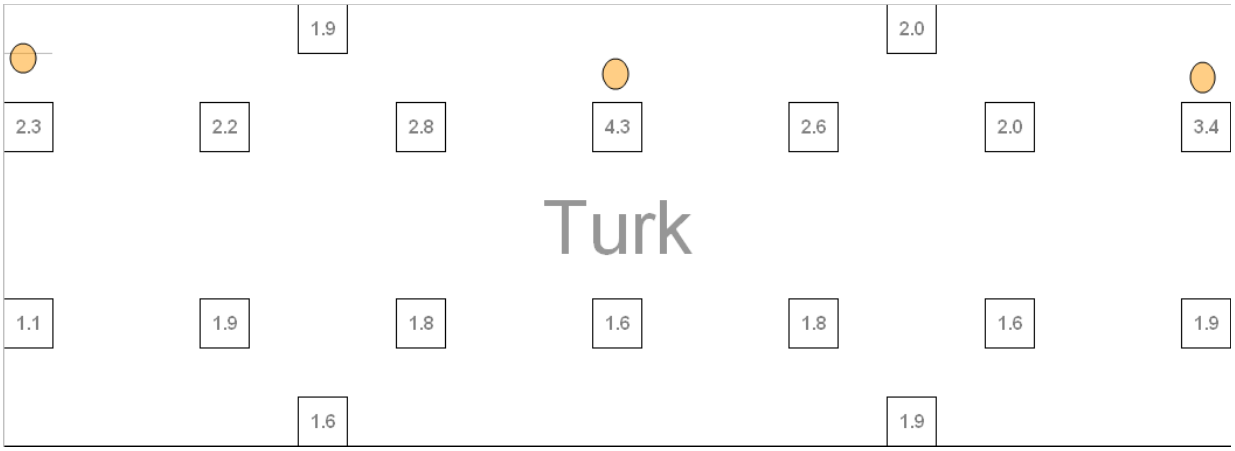


Table XXXV: Measured LED Photopic Illuminance, Turk Street (fc)

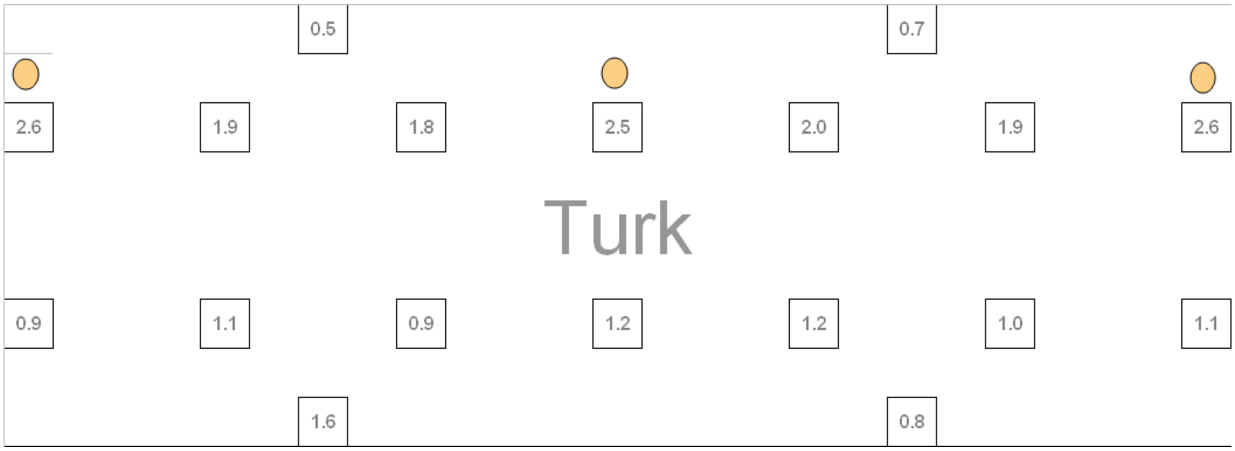


Table XXXVI: Measured HPS Scotopic Illuminance, Turk Street (fc)

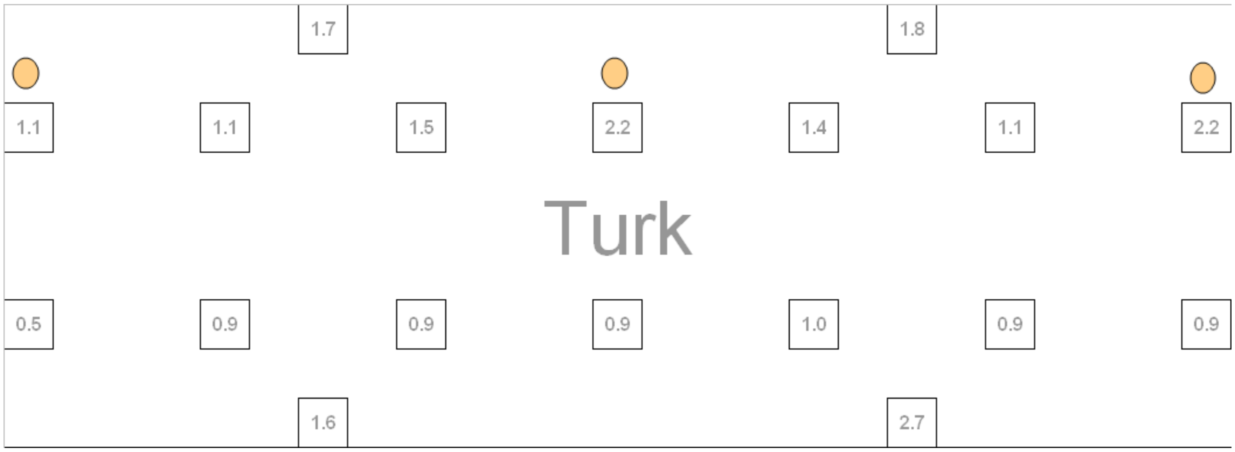
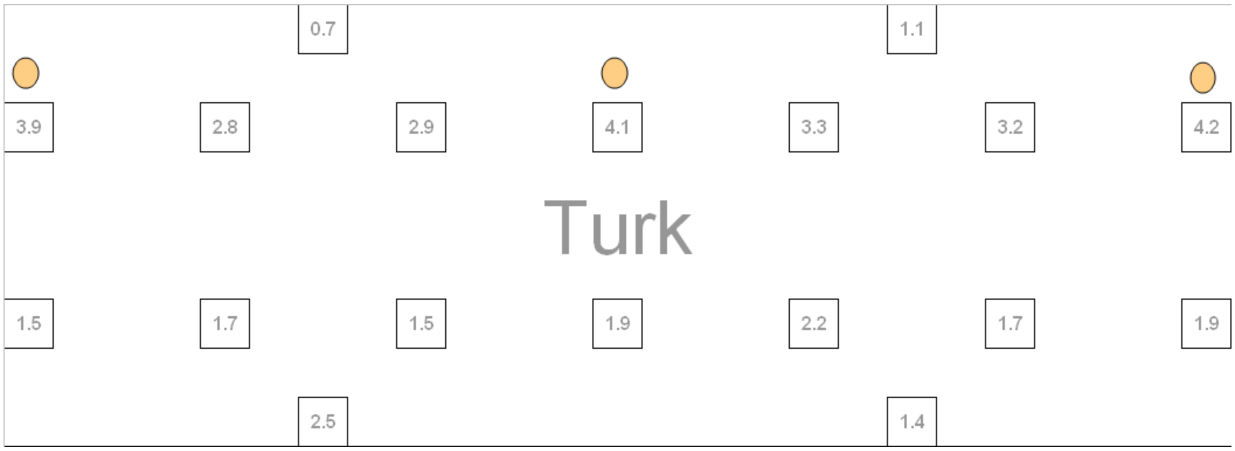


Table XXXVII: Measured LED Scotopic Illuminance, Turk Street (fc)



CORRELATED COLOR TEMPERATURE

Table XXXVIII: Correlated Color Temperature of HPS and LED Luminaires, Leavenworth Street

HPS Luminaires	Correlated Color Temp (K)	LED Luminaires	Correlated Color Temp (K)
1	1879	1	6312
2	1876	2	6328
3	1887	3	6309
Avg	1881	*Avg*	6317

Table XXXIX: Correlated Color Temperature of HPS and LED Luminaires, Turk Street

HPS Luminaires	Correlated Color Temp (K)	LED Luminaires	Correlated Color Temp (K)
1	1789	1	4744
2	1866	2	4902
3	1781	3	4851
Avg	1812	*Avg*	4832

Appendix B: Mesopic Illuminance Calculations

For mesopic calculations, field photopic and scotopic illuminance measurements were used to calculate average scotopic-to-photopic illuminance ratios, which were used to convert modeled photopic illuminance data to scotopic illuminance data. Both photopic and scotopic illuminance levels at each point were then converted to luminance values, assuming a reflectance of 0.07 (IES road surface class R 2, 3):

1) fc to lx: E (illuminance, lx) = E (illuminance, fc) / (0.092903 fc/lx)

2) L (luminance, cd/m^2) = E (illuminance, lx) * P (surface reflectance, 0.07) / Π

UNIFIED SYSTEM OF PHOTOMETRY

With modeled illuminance data converted to luminance, using the unified system of photometry to calculate mesopic luminance is straightforward. Rea's closed-form expression for combining photopic and scotopic luminance levels to calculate unified (mesopic) luminance, as published in the ASSIST article referenced in the text, is:

$$L_{mesopic}\ (cd/m^2) = 0.834P - 0.335S - 0.2 + \sqrt{(0.696P^2 - 0.333P\ \ 0.56PS + 0.113S^2 + 0.537S + 0.04)}$$

P = photopic luminance (cd/m^2)
S = scotopic luminance (cd/m^2)

Resulting mesopic luminance was converted to mesopic illuminance for comparison with original modeled photopic levels and mesopic results from other models.

MESOPIC OPTIMIZATION OF VISUAL EFFICIENCY (MOVE) MODEL:

The MOVE model is a performance-based model developed at the Lighting Laboratory at the Helsinki University of Technology. It was developed using the results of vision experiments which evaluated subjects' ability to complete various tasks required for night-time driving. The MOVE model's mesopic spectral luminous efficiency function is:

$$L_{mesopic} = ((X_i * P + (1 - X_i) * S * 683/1699)) / (X_i + (1 - X_i) * (683/1699))$$

X_i is the weighting factor between the photopic and scotopic spectral luminous efficiency functions, defined as:

$$X_{i+1} = 1.49 + 0.282 * Log ((X_i * P/683 + (1 - X_i) * S/1699) / (1 - 0.65 * X_i + 0.65 * X_i * X_i))$$

X_1 = 0.5
P = photopic luminance (cd/m^2)
S = scotopic luminance (cd/m^2)

X_i converges to a single value after several iterations; the model used 20 iterations to calculate the weighting factor. Resulting mesopic luminance values were converted to illuminance.

LUMEN EFFECTIVENESS MULTIPLIERS (LEM):

Based on previous studies of apparent brightness and visual performance in the mesopic range, Lewin developed LEMs in 2001 for light sources that could be multiplied into photopic luminance levels to arrive at mesopic luminance.

> "The subject is complex, and many variables are involved. If, however, better vision is achievable through judicious selection of the light source type, then it may be reasonable to treat lighting achieved with white sources as having a higher "effectiveness" than HPS lighting. The concept of "Lumen Effectiveness Multipliers", LEM, has been developed, whereby a luminance level computed using the normal photopic response curve of the eye and lamp manufacturer's rated lumens can be multiplied by the LEM to represent an effective increase in lighting level resulting from use of an improved lamp spectrum."[41]

LEM's were developed based on Adrian's brightness matching mesopic functions and He and Rea's reaction time mesopic functions (as discussed previously). The original light sources were HPS, LPS, Mercury Vapor, and Metal Halide. More recently Lewin has developed multipliers for four additional light sources; warm and cool white LEDs, warm and cool white Induction.

Lewin's brightness matching function LEMs for a reference "Cool White" LED source were used here. LEMs are only published for certain photopic luminance levels, as shown in the following table. Because converted luminance values from field data ranged from 0.1 to over 1.9 cd/m², it was necessary to interpolate between reported LEMs. A logarithmic regression of LED LEMs as a function of photopic luminance was computed through the range of published LEMs for cool white LEDs. Photopic luminance from modeled illuminance data was multiplied by the resulting LEMs to calculate mesopic luminance:

Table XL: LEMs for Evaluated Light Sources and Photopic Luminance Ranges

Photopic Luminance level (cd/m²)	.001	.01	.10	1.00	3.00	10.00
Cool White LED (5,500K CCT) LEM	2.75	2.57	2.09	1.47	1.22	1.00
HPS LEM	1.00	1.00	1.00	1.00	1.00	1.00

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[41] Lewin, Ian. "Lumen Effectiveness Multipliers for Outdoor Lighting Design." Journal of the Illuminating Engineering Society, JIES, Summer 2001. Illuminating Engineering Society of North America, New York, NY.

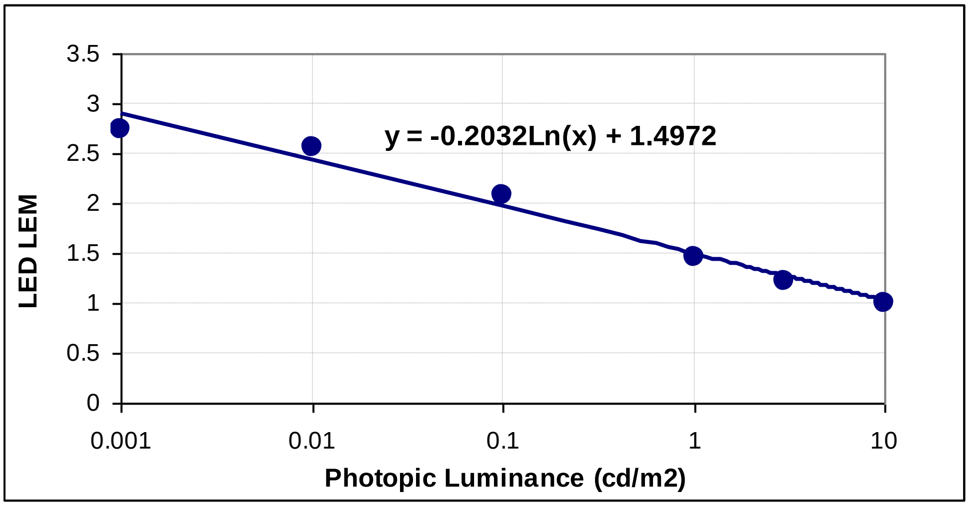


Figure 39: LEMs as a Function of Photopic Luminance

LED: $L_{mesopic} = L_{photopic} * (-0.2032 * Ln (L_{photopic}) + 1.4972)$

Appendix C: Network Controls Survey Results

Emerging Technologies Street Lighting Network Controls Feedback Survey

TECHNOLOGY

SITE INFORMATION

Site Contact: [redacted]
Title: Maintenance Planner
Host Site: San Francisco

INSTALLATION AND COMMISSIONING

1. On a scale of 1-5, with 1 being the easiest and 5 being the most difficult, how would you characterize the overall ease of installation of streetlight network controls system?

   [✓ 1] 2 3 4 5

   Comments, including relevant feedback received from installation staff:

   The initial installation of the ROAM system was extremely simple and was comprise of five nodes and a gateway. The entire installation was completed in approximately 45 minutes. The system arrived pre-programmed (Lat/Long coordinates previously sent to ROAM) from the factory. Subsequent node installations were consistent with the installation of a Photocell.

2. On a scale of 1-5, with 1 being the easiest and 5 being the most difficult, how would you characterize the streetlight network controls system's compatibility with existing lighting circuits and wiring (i.e. required modifications to local wiring, hardware, etc)?

   [✓ 1] 2 3 4 5

   Comments:

   Control system utilized NEMA twist lock type receptacle.

3. On a scale of 1-5, with 1 being the easiest and 5 being the most difficult, how would you characterize the training required to prepare your field staff for system installation?

   [✓ 1] 2 3 4 5

   Comments:

   Due to the relatively simplistic nature of the product, only a brief explanation of the instillation process was provided to the crew. More detailed training was available if required.

1. On a scale of 1-5, with 1 being the easiest and 5 being the most difficult, how would you characterize the commissioning process for the controls network, i.e. programming and populating the streetlight database in the system, establishing communication and connectivity across the network, and network interface setup?

   1 [✓ 2] 3 4 5

   Comments:

   A comprehensive activation manual was provided with the system and was accompanied by a custom bar coded “Activation Handbook”, designed specifically for our installation. This made entering attribute information extremely easy. GPS connectivity became an issue in some of the installation areas due to interference from tall buildings. This was not a significant problem as the Lat/Long coordinates were easily entered from the desktop application. Node communication typically took 2-3 days (quiet period) to become unrestricted

2. Briefly explain the process for setting up and commissioning the network controls system for your streetlights, including issues encountered and resolution to challenges in network commissioning.

   The commissioning was facilitated via a PDA with bar code reading capability, scanning that following steps:

   1. Customer ID
   2. Booklet ID
   3. Login
   4. Node Activation (collecting data)
   5. Connect GPS
   6. ROAM node bar code
   7. Enter pole number
   8. Fixture Voltage
   9. Lamp Type
   10. Lamp Wattage
   11. Fixture/Luminaire Type
   12. Pole Style
   13. Save data
   14. Send data

   All bar coded information included a variety of selectable information based on our City’s current installation of street lighting equipment.

GPS communication was the only issue that was encountered during the installation. This was easily overcome by adding the Lat/Long coordinates via the desktop application. Precise GPS accuracy is not critical for us; approximate coordinates were retrieved from the ROAM map contained in the Portal. Node coordinates were updated through a feature in the portal. Essentially, the entire installation could have been commissioned from my desk, taking minutes to program each node.

SYSTEM OPERATION AND FUNCTIONALITY

1. Please identify the primary users of the network controls system (organization, unit, and title):

   San Francisco Public Utilities Commission- Power Enterprise

   Utility Services Group

2. On a scale of 1-5, with 1 being the easiest and 5 being the most difficult, how would you characterize the ease of use of the streetlight network control system interface and its functions?

   1 [✓ 2] 3 4 5

   Comments:

   I found the interface and its functions to be almost intuitive. The one module that I experienced difficulty with was the scheduling feature. I believe that some of the difficulty was encountered by attempting to use the function without training.

3. On a scale of 1-5, with 1 being the easiest and 5 being the most difficult, how would you characterize the training and experience required for you or your staff to become familiar and comfortable with operating the streetlight network controls system?

   [✓ 1] 2 3 4 5

   Comments:

4. On a scale of 1-5, with 1 being the most useful and 5 being the least useful, how would you characterize the usefulness of the functions that the streetlight network controls system provides to improve streetlight operations and management practices?

   [✓ 1] 2 3 4 5

   Comments:

   The functionality of the system is completely value added from a maintenance perspective. Currently our maintenance activities are reactionary and initiated from public feedback. The ROAM system enables our maintenance activities to be proactive, providing an added benefit of improved public perception.

5. On a scale of 1-5, with 1 being very high and 5 being very low, how would you characterize the energy benefits that the network controls system provides your street lighting system?

   1 2 3 [✓ 4] 5

   Comments:

The current systems energy benefit is low, this would be somewhat improved with the dimming feature currently in development.

1. On a scale of 1-5, with 1 being very high and 5 being very low, how would you characterize the maintenance benefits that the network controls system provides your street lighting system?

   [✓ 1] 2 3 4 5

   Comments:

   I completely changes our process of identifying and organizing maintenance activities. Group maintenance becomes possible with the implementation of the ROAM system.

2. On a scale of 1-5, with 1 being the most useful and 5 being the least useful, how would you characterize the usefulness of the data and reporting capabilities that the controls network offers?

   1 [✓ 2] 3 4 5

   Comments:

Please indicate which functions are available in the network control interface and which you plan to use:

	Available	Plan to Use
Manual Scheduling	☑	☑
Time clock Scheduling	☑	☑
Dimming	☐	☐
Streetlight grouping	☑	☑
Energy monitoring	☑	☑
Ballast, luminaire temperature	☐	☐
Voltage fluctuation	☑	☑
Pole Tilt	☐	☐
Outage detection	☑	☑
Maintenance tickets, reports	☑	☐
Data reports	☑	☑

Other features:

☐ ☐
☐ ☐
☐ ☐

1. If this technology met your minimum cost-effectiveness requirements, would you be inclined to implement it widely throughout your street lighting fleet?

   [✓ Yes] No Maybe

   Comments:

CUSTOMER SUPPORT

2. On a scale of 1-5, with 1 being the easiest and 5 being the most difficult, how would you characterize the customer support from the streetlight network controls manufacturer or vendor?

   [✓ 1] 2 3 4 5

   Comments:

   Customer support has been provided immediately at each request.

OVERALL SATISFACTION

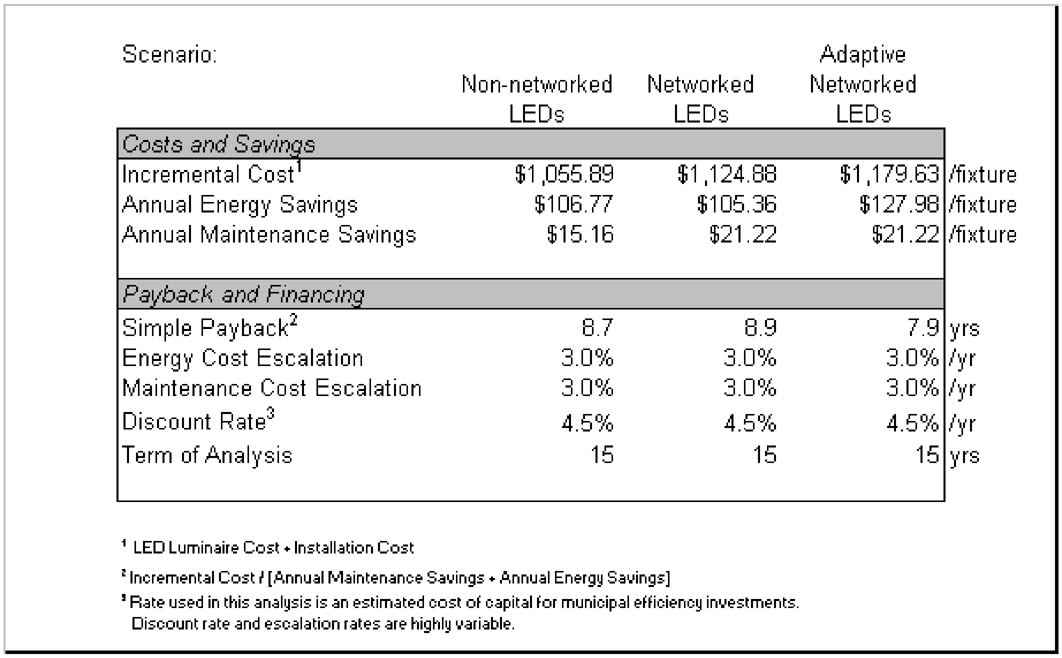
3. On a scale of 1-5, with 1 being the highest and 5 being the lowest, how would you rate your overall satisfaction with the streetlight network controls system?

   [✓ 1] 2 3 4 5

   Final Comments:

Appendix D: Economic Data and Calculations

Table XLI: Retrofit Economic Assumptions, 400W HPS Base Case



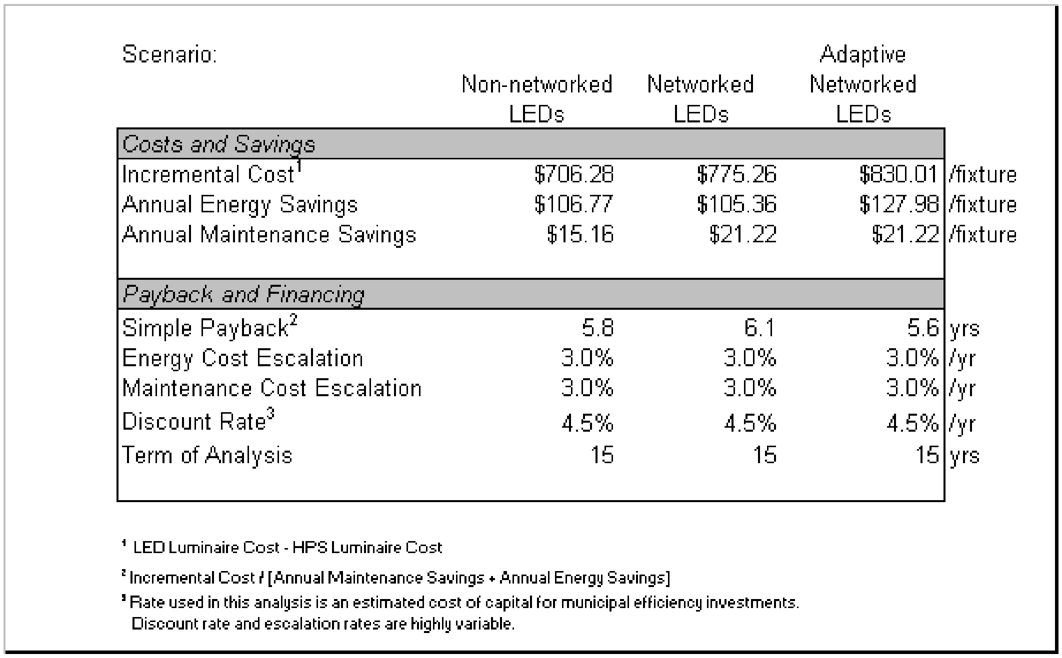
Scenario:	Non-networked LEDs	Networked LEDs	Adaptive Networked LEDs	
Costs and Savings				
Incremental Cost[1]	$1,055.89	$1,124.88	$1,179.63	/fixture
Annual Energy Savings	$106.77	$105.36	$127.98	/fixture
Annual Maintenance Savings	$15.16	$21.22	$21.22	/fixture
Payback and Financing				
Simple Payback[2]	8.7	8.9	7.9	yrs
Energy Cost Escalation	3.0%	3.0%	3.0%	/yr
Maintenance Cost Escalation	3.0%	3.0%	3.0%	/yr
Discount Rate[3]	4.5%	4.5%	4.5%	/yr
Term of Analysis	15	15	15	yrs

[1] LED Luminaire Cost + Installation Cost

[2] Incremental Cost / [Annual Maintenance Savings + Annual Energy Savings]

[3] Rate used in this analysis is an estimated cost of capital for municipal efficiency investments. Discount rate and escalation rates are highly variable.

Table XLII: End-of-Useful Life/New Construction Economic Assumptions, 400W HPS Base Case



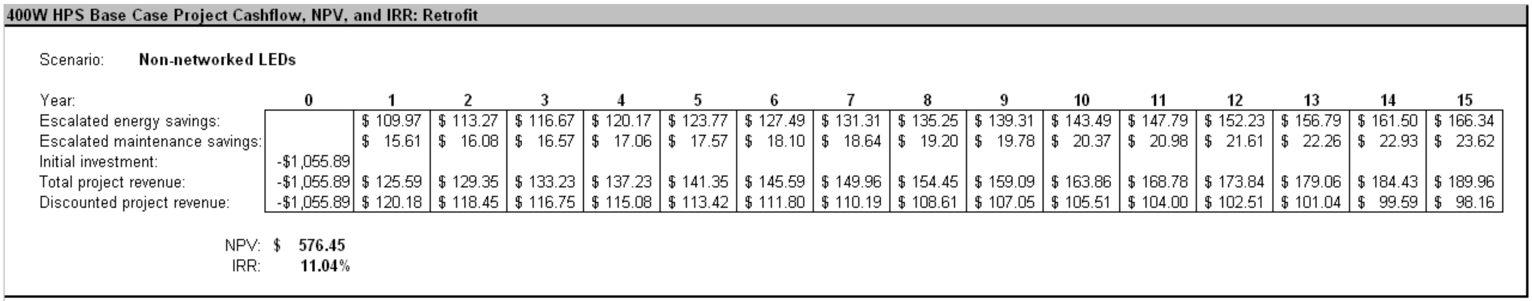
Scenario:	Non-networked LEDs	Networked LEDs	Adaptive Networked LEDs	
Costs and Savings				
Incremental Cost[1]	$706.28	$775.26	$830.01	/fixture
Annual Energy Savings	$106.77	$105.36	$127.98	/fixture
Annual Maintenance Savings	$15.16	$21.22	$21.22	/fixture
Payback and Financing				
Simple Payback[2]	5.8	6.1	5.6	yrs
Energy Cost Escalation	3.0%	3.0%	3.0%	/yr
Maintenance Cost Escalation	3.0%	3.0%	3.0%	/yr
Discount Rate[3]	4.5%	4.5%	4.5%	/yr
Term of Analysis	15	15	15	yrs

[1] LED Luminaire Cost - HPS Luminaire Cost

[2] Incremental Cost / [Annual Maintenance Savings + Annual Energy Savings]

[3] Rate used in this analysis is an estimated cost of capital for municipal efficiency investments. Discount rate and escalation rates are highly variable.

Table XLIII: Retrofit Cash Flow Scenarios, 400W HPS Base Case

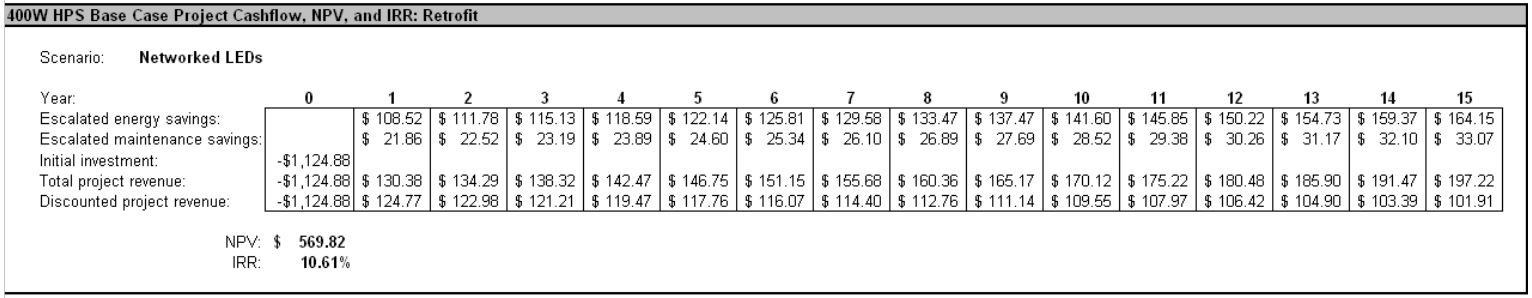


400W HPS Base Case Project Cashflow, NPV, and IRR: Retrofit

Scenario: **Non-networked LEDs**

Year:	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Escalated energy savings:		$ 109.97	$ 113.27	$ 116.67	$ 120.17	$ 123.77	$ 127.49	$ 131.31	$ 135.25	$ 139.31	$ 143.49	$ 147.79	$ 152.23	$ 156.79	$ 161.50	$ 166.34
Escalated maintenance savings:		$ 15.61	$ 16.08	$ 16.57	$ 17.06	$ 17.57	$ 18.10	$ 18.64	$ 19.20	$ 19.78	$ 20.37	$ 20.98	$ 21.61	$ 22.26	$ 22.93	$ 23.62
Initial investment:	-$1,055.89															
Total project revenue:	-$1,055.89	$ 125.59	$ 129.35	$ 133.23	$ 137.23	$ 141.35	$ 145.59	$ 149.96	$ 154.45	$ 159.09	$ 163.86	$ 168.78	$ 173.84	$ 179.06	$ 184.43	$ 189.96
Discounted project revenue:	-$1,055.89	$ 120.18	$ 118.45	$ 116.75	$ 115.08	$ 113.42	$ 111.80	$ 110.19	$ 108.61	$ 107.05	$ 105.51	$ 104.00	$ 102.51	$ 101.04	$ 99.59	$ 98.16

NPV: $ **576.45**
IRR: **11.04%**

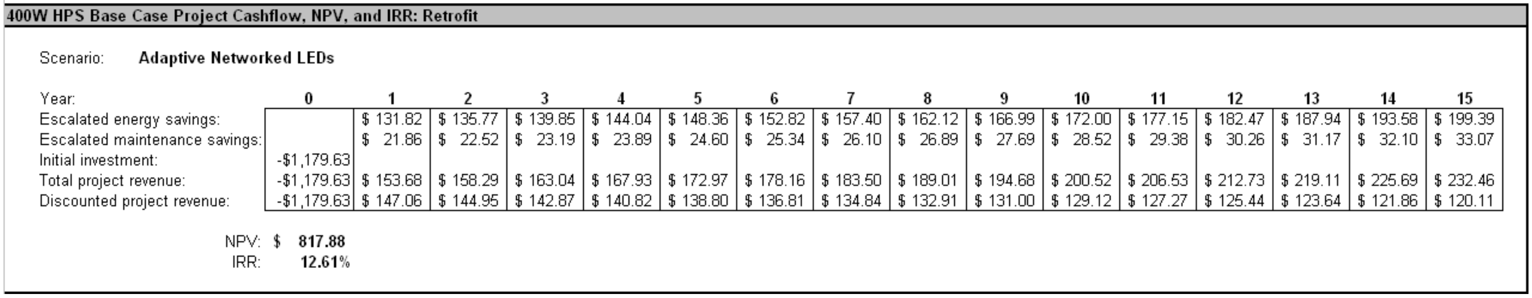


400W HPS Base Case Project Cashflow, NPV, and IRR: Retrofit

Scenario: **Networked LEDs**

Year:	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Escalated energy savings:		$ 108.52	$ 111.78	$ 115.13	$ 118.59	$ 122.14	$ 125.81	$ 129.58	$ 133.47	$ 137.47	$ 141.60	$ 145.85	$ 150.22	$ 154.73	$ 159.37	$ 164.15
Escalated maintenance savings:		$ 21.86	$ 22.52	$ 23.19	$ 23.89	$ 24.60	$ 25.34	$ 26.10	$ 26.89	$ 27.69	$ 28.52	$ 29.38	$ 30.26	$ 31.17	$ 32.10	$ 33.07
Initial investment:	-$1,124.88															
Total project revenue:	-$1,124.88	$ 130.38	$ 134.29	$ 138.32	$ 142.47	$ 146.75	$ 151.15	$ 155.68	$ 160.36	$ 165.17	$ 170.12	$ 175.22	$ 180.48	$ 185.90	$ 191.47	$ 197.22
Discounted project revenue:	-$1,124.88	$ 124.77	$ 122.98	$ 121.21	$ 119.47	$ 117.76	$ 116.07	$ 114.40	$ 112.76	$ 111.14	$ 109.55	$ 107.97	$ 106.42	$ 104.90	$ 103.39	$ 101.91

NPV: $ **569.82**
IRR: **10.61%**



400W HPS Base Case Project Cashflow, NPV, and IRR: Retrofit

Scenario: **Adaptive Networked LEDs**

Year:	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Escalated energy savings:		$ 131.82	$ 135.77	$ 139.85	$ 144.04	$ 148.36	$ 152.82	$ 157.40	$ 162.12	$ 166.99	$ 172.00	$ 177.15	$ 182.47	$ 187.94	$ 193.58	$ 199.39
Escalated maintenance savings:		$ 21.86	$ 22.52	$ 23.19	$ 23.89	$ 24.60	$ 25.34	$ 26.10	$ 26.89	$ 27.69	$ 28.52	$ 29.38	$ 30.26	$ 31.17	$ 32.10	$ 33.07
Initial investment:	-$1,179.63															
Total project revenue:	-$1,179.63	$ 153.68	$ 158.29	$ 163.04	$ 167.93	$ 172.97	$ 178.16	$ 183.50	$ 189.01	$ 194.68	$ 200.52	$ 206.53	$ 212.73	$ 219.11	$ 225.69	$ 232.46
Discounted project revenue:	-$1,179.63	$ 147.06	$ 144.95	$ 142.87	$ 140.82	$ 138.80	$ 136.81	$ 134.84	$ 132.91	$ 131.00	$ 129.12	$ 127.27	$ 125.44	$ 123.64	$ 121.86	$ 120.11

NPV: $ **817.88**
IRR: **12.61%**

Table XLIV: End-of-Useful Life/New Construction Cash Flow Scenarios, 400W HPS Base Case

400W HPS Base Case Project Cashflow, NPV, and IRR: End-of-Useful Life / New Construction

Scenario: **Non-networked LEDs**

Year:	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Escalated energy savings:		$ 109.97	$ 113.27	$ 116.67	$ 120.17	$ 123.77	$ 127.49	$ 131.31	$ 135.25	$ 139.31	$ 143.49	$ 147.79	$ 152.23	$ 156.79	$ 161.50	$ 166.34
Escalated maintenance savings:		$ 15.61	$ 16.08	$ 16.57	$ 17.06	$ 17.57	$ 18.10	$ 18.64	$ 19.20	$ 19.78	$ 20.37	$ 20.98	$ 21.61	$ 22.26	$ 22.93	$ 23.62
Initial investment:	-$706.28															
Total project revenue:	-$706.28	$ 125.59	$ 129.35	$ 133.23	$ 137.23	$ 141.35	$ 145.59	$ 149.96	$ 154.45	$ 159.09	$ 163.86	$ 168.78	$ 173.84	$ 179.06	$ 184.43	$ 189.96
Discounted project revenue:	-$706.28	$ 120.18	$ 118.45	$ 116.75	$ 115.08	$ 113.42	$ 111.80	$ 110.19	$ 108.61	$ 107.05	$ 105.51	$ 104.00	$ 102.51	$ 101.04	$ 99.59	$ 98.16

NPV: $ **926.06**
IRR: **18.65%**

400W HPS Base Case Project Cashflow, NPV, and IRR: End-of-Useful Life / New Construction

Scenario: **Networked LEDs**

Year:	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Escalated energy savings:		$ 108.52	$ 111.78	$ 115.13	$ 118.59	$ 122.14	$ 125.81	$ 129.58	$ 133.47	$ 137.47	$ 141.60	$ 145.85	$ 150.22	$ 154.73	$ 159.37	$ 164.15
Escalated maintenance savings:		$ 21.86	$ 22.52	$ 23.19	$ 23.89	$ 24.60	$ 25.34	$ 26.10	$ 26.89	$ 27.69	$ 28.52	$ 29.38	$ 30.26	$ 31.17	$ 32.10	$ 33.07
Initial investment:	-$775.26															
Total project revenue:	-$775.26	$ 130.38	$ 134.29	$ 138.32	$ 142.47	$ 146.75	$ 151.15	$ 155.68	$ 160.36	$ 165.17	$ 170.12	$ 175.22	$ 180.48	$ 185.90	$ 191.47	$ 197.22
Discounted project revenue:	-$775.26	$ 124.77	$ 122.98	$ 121.21	$ 119.47	$ 117.76	$ 116.07	$ 114.40	$ 112.76	$ 111.14	$ 109.55	$ 107.97	$ 106.42	$ 104.90	$ 103.39	$ 101.91

NPV: $ **919.43**
IRR: **17.48%**

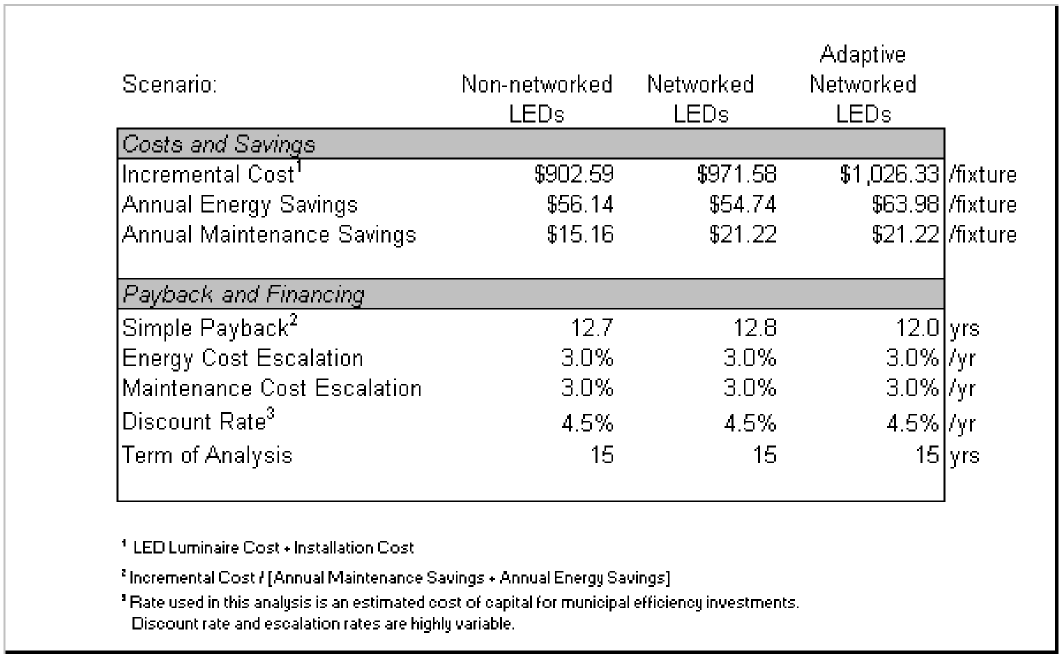
400W HPS Base Case Project Cashflow, NPV, and IRR: End-of-Useful Life / New Construction

Scenario: **Adaptive Networked LEDs**

Year:	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Escalated energy savings:		$ 131.82	$ 135.77	$ 139.85	$ 144.04	$ 148.36	$ 152.82	$ 157.40	$ 162.12	$ 166.99	$ 172.00	$ 177.15	$ 182.47	$ 187.94	$ 193.58	$ 199.39
Escalated maintenance savings:		$ 21.86	$ 22.52	$ 23.19	$ 23.89	$ 24.60	$ 25.34	$ 26.10	$ 26.89	$ 27.69	$ 28.52	$ 29.38	$ 30.26	$ 31.17	$ 32.10	$ 33.07
Initial investment:	-$830.01															
Total project revenue:	-$830.01	$ 153.68	$ 158.29	$ 163.04	$ 167.93	$ 172.97	$ 178.16	$ 183.50	$ 189.01	$ 194.68	$ 200.52	$ 206.53	$ 212.73	$ 219.11	$ 225.69	$ 232.46
Discounted project revenue:	-$830.01	$ 147.06	$ 144.95	$ 142.87	$ 140.82	$ 138.80	$ 136.81	$ 134.84	$ 132.91	$ 131.00	$ 129.12	$ 127.27	$ 125.44	$ 123.64	$ 121.86	$ 120.11

NPV: **$ 1,167.49**
IRR: **19.53%**

Table XLV: Retrofit Economic Assumptions, 200W HPS Base Case



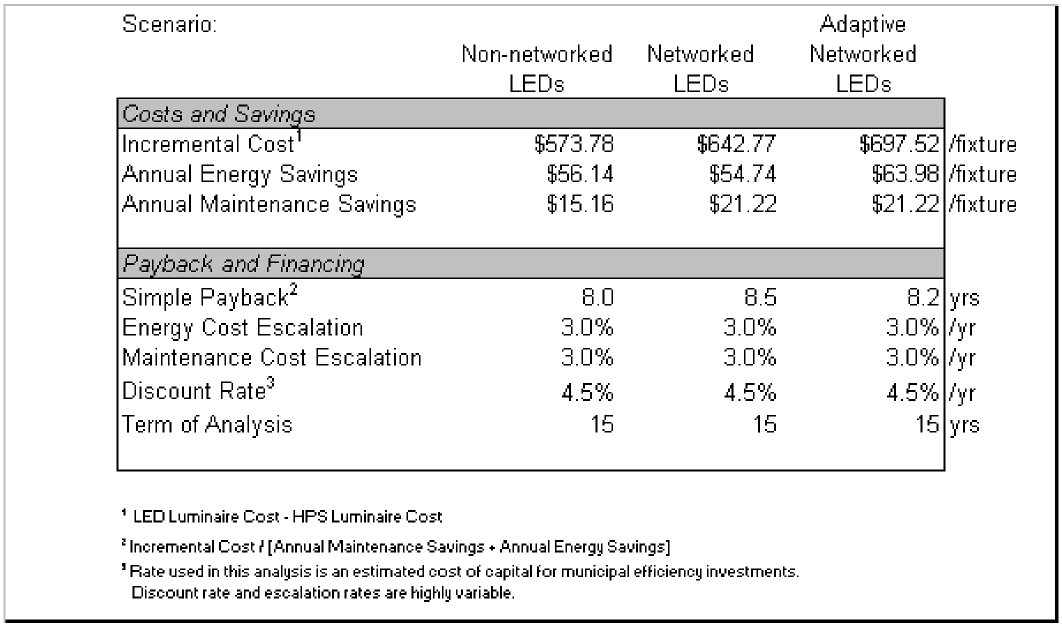
Scenario:	Non-networked LEDs	Networked LEDs	Adaptive Networked LEDs	
Costs and Savings				
Incremental Cost[1]	$902.59	$971.58	$1,026.33	/fixture
Annual Energy Savings	$56.14	$54.74	$63.98	/fixture
Annual Maintenance Savings	$15.16	$21.22	$21.22	/fixture
Payback and Financing				
Simple Payback[2]	12.7	12.8	12.0	yrs
Energy Cost Escalation	3.0%	3.0%	3.0%	/yr
Maintenance Cost Escalation	3.0%	3.0%	3.0%	/yr
Discount Rate[3]	4.5%	4.5%	4.5%	/yr
Term of Analysis	15	15	15	yrs

[1] LED Luminaire Cost + Installation Cost

[2] Incremental Cost / [Annual Maintenance Savings + Annual Energy Savings]

[3] Rate used in this analysis is an estimated cost of capital for municipal efficiency investments. Discount rate and escalation rates are highly variable.

Table XLVI: End-of-Useful Life/New Construction Economic Assumptions, 200W HPS Base Case



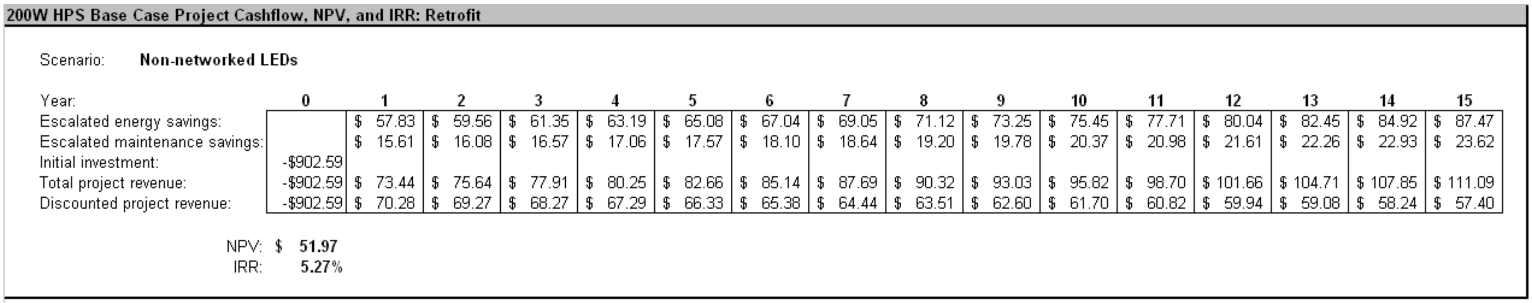
Scenario:	Non-networked LEDs	Networked LEDs	Adaptive Networked LEDs	
Costs and Savings				
Incremental Cost[1]	$573.78	$642.77	$697.52	/fixture
Annual Energy Savings	$56.14	$54.74	$63.98	/fixture
Annual Maintenance Savings	$15.16	$21.22	$21.22	/fixture
Payback and Financing				
Simple Payback[2]	8.0	8.5	8.2	yrs
Energy Cost Escalation	3.0%	3.0%	3.0%	/yr
Maintenance Cost Escalation	3.0%	3.0%	3.0%	/yr
Discount Rate[3]	4.5%	4.5%	4.5%	/yr
Term of Analysis	15	15	15	yrs

[1] LED Luminaire Cost - HPS Luminaire Cost

[2] Incremental Cost / [Annual Maintenance Savings + Annual Energy Savings]

[3] Rate used in this analysis is an estimated cost of capital for municipal efficiency investments. Discount rate and escalation rates are highly variable.

Table XLVII: Retrofit Cash Flow Scenarios, 200W HPS Base Case

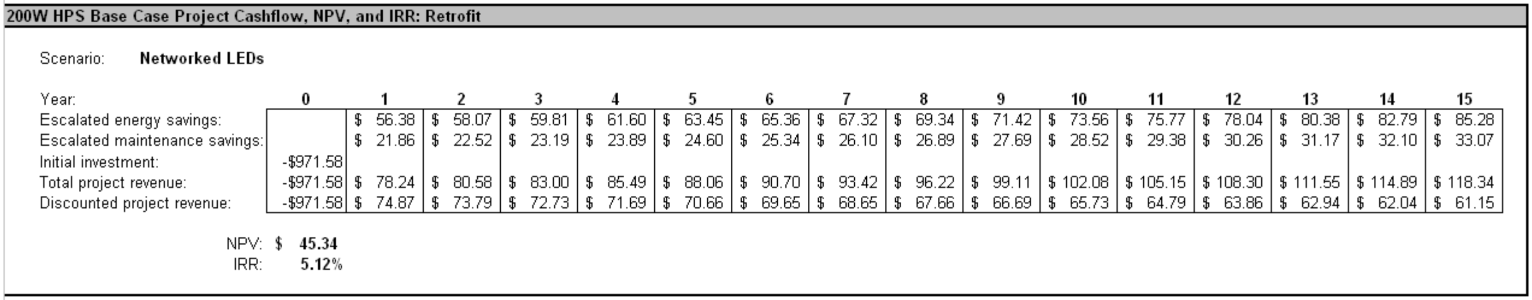


200W HPS Base Case Project Cashflow, NPV, and IRR: Retrofit

Scenario: **Non-networked LEDs**

Year:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Escalated energy savings:		$ 57.83	$ 59.56	$ 61.35	$ 63.19	$ 65.08	$ 67.04	$ 69.05	$ 71.12	$ 73.25	$ 75.45	$ 77.71	$ 80.04	$ 82.45	$ 84.92	$ 87.47
Escalated maintenance savings:		$ 15.61	$ 16.08	$ 16.57	$ 17.06	$ 17.57	$ 18.10	$ 18.64	$ 19.20	$ 19.78	$ 20.37	$ 20.98	$ 21.61	$ 22.26	$ 22.93	$ 23.62
Initial investment:	-$902.59															
Total project revenue:	-$902.59	$ 73.44	$ 75.64	$ 77.91	$ 80.25	$ 82.66	$ 85.14	$ 87.69	$ 90.32	$ 93.03	$ 95.82	$ 98.70	$ 101.66	$ 104.71	$ 107.85	$ 111.09
Discounted project revenue:	-$902.59	$ 70.28	$ 69.27	$ 68.27	$ 67.29	$ 66.33	$ 65.38	$ 64.44	$ 63.51	$ 62.60	$ 61.70	$ 60.82	$ 59.94	$ 59.08	$ 58.24	$ 57.40

NPV: $ **51.97**
IRR: **5.27%**

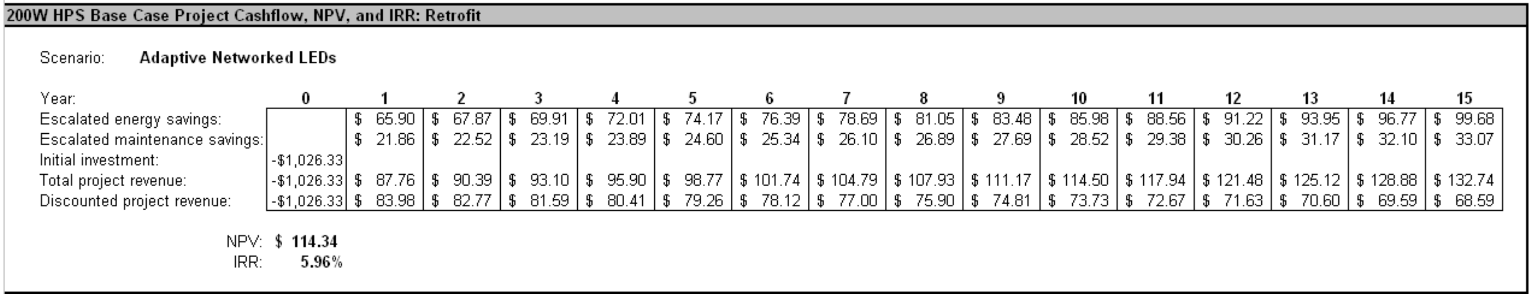


200W HPS Base Case Project Cashflow, NPV, and IRR: Retrofit

Scenario: **Networked LEDs**

Year:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Escalated energy savings:		$ 56.38	$ 58.07	$ 59.81	$ 61.60	$ 63.45	$ 65.36	$ 67.32	$ 69.34	$ 71.42	$ 73.56	$ 75.77	$ 78.04	$ 80.38	$ 82.79	$ 85.28
Escalated maintenance savings:		$ 21.86	$ 22.52	$ 23.19	$ 23.89	$ 24.60	$ 25.34	$ 26.10	$ 26.89	$ 27.69	$ 28.52	$ 29.38	$ 30.26	$ 31.17	$ 32.10	$ 33.07
Initial investment:	-$971.58															
Total project revenue:	-$971.58	$ 78.24	$ 80.58	$ 83.00	$ 85.49	$ 88.06	$ 90.70	$ 93.42	$ 96.22	$ 99.11	$ 102.08	$ 105.15	$ 108.30	$ 111.55	$ 114.89	$ 118.34
Discounted project revenue:	-$971.58	$ 74.87	$ 73.79	$ 72.73	$ 71.69	$ 70.66	$ 69.65	$ 68.65	$ 67.66	$ 66.69	$ 65.73	$ 64.79	$ 63.86	$ 62.94	$ 62.04	$ 61.15

NPV: $ **45.34**
IRR: **5.12%**



200W HPS Base Case Project Cashflow, NPV, and IRR: Retrofit

Scenario: **Adaptive Networked LEDs**

Year:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Escalated energy savings:		$ 65.90	$ 67.87	$ 69.91	$ 72.01	$ 74.17	$ 76.39	$ 78.69	$ 81.05	$ 83.48	$ 85.98	$ 88.56	$ 91.22	$ 93.95	$ 96.77	$ 99.68
Escalated maintenance savings:		$ 21.86	$ 22.52	$ 23.19	$ 23.89	$ 24.60	$ 25.34	$ 26.10	$ 26.89	$ 27.69	$ 28.52	$ 29.38	$ 30.26	$ 31.17	$ 32.10	$ 33.07
Initial investment:	-$1,026.33															
Total project revenue:	-$1,026.33	$ 87.76	$ 90.39	$ 93.10	$ 95.90	$ 98.77	$ 101.74	$ 104.79	$ 107.93	$ 111.17	$ 114.50	$ 117.94	$ 121.48	$ 125.12	$ 128.88	$ 132.74
Discounted project revenue:	-$1,026.33	$ 83.98	$ 82.77	$ 81.59	$ 80.41	$ 79.26	$ 78.12	$ 77.00	$ 75.90	$ 74.81	$ 73.73	$ 72.67	$ 71.63	$ 70.60	$ 69.59	$ 68.59

NPV: $ **114.34**
IRR: **5.96%**

Table XLVIII: End-of-Useful Life/New Construction Cash Flow Scenarios, 200W HPS Base Case

200W HPS Base Case Project Cashflow, NPV, and IRR: Replacement at End-of-Useful Life / New Construction

Scenario: **Non-networked LEDs**

Year:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Escalated energy savings:		$ 57.83	$ 59.56	$ 61.35	$ 63.19	$ 65.08	$ 67.04	$ 69.05	$ 71.12	$ 73.25	$ 75.45	$ 77.71	$ 80.04	$ 82.45	$ 84.92	$ 87.47
Escalated maintenance savings:		$ 15.61	$ 16.08	$ 16.57	$ 17.06	$ 17.57	$ 18.10	$ 18.64	$ 19.20	$ 19.78	$ 20.37	$ 20.98	$ 21.61	$ 22.26	$ 22.93	$ 23.62
Initial investment:	-$573.78															
Total project revenue:	-$573.78	$ 73.44	$ 75.64	$ 77.91	$ 80.25	$ 82.66	$ 85.14	$ 87.69	$ 90.32	$ 93.03	$ 95.82	$ 98.70	$ 101.66	$ 104.71	$ 107.85	$ 111.09
Discounted project revenue:	-$573.78	$ 70.28	$ 69.27	$ 68.27	$ 67.29	$ 66.33	$ 65.38	$ 64.44	$ 63.51	$ 62.60	$ 61.70	$ 60.82	$ 59.94	$ 59.08	$ 58.24	$ 57.40

NPV: **$ 380.78**
IRR: **12.30%**

200W HPS Base Case Project Cashflow, NPV, and IRR: Replacement at End-of-Useful Life / New Construction

Scenario: **Networked LEDs**

Year:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Escalated energy savings:		$ 56.38	$ 58.07	$ 59.81	$ 61.60	$ 63.45	$ 65.36	$ 67.32	$ 69.34	$ 71.42	$ 73.56	$ 75.77	$ 78.04	$ 80.38	$ 82.79	$ 85.28
Escalated maintenance savings:		$ 21.86	$ 22.52	$ 23.19	$ 23.89	$ 24.60	$ 25.34	$ 26.10	$ 26.89	$ 27.69	$ 28.52	$ 29.38	$ 30.26	$ 31.17	$ 32.10	$ 33.07
Initial investment:	-$642.77															
Total project revenue:	-$642.77	$ 78.24	$ 80.58	$ 83.00	$ 85.49	$ 88.06	$ 90.70	$ 93.42	$ 96.22	$ 99.11	$ 102.08	$ 105.15	$ 108.30	$ 111.55	$ 114.89	$ 118.34
Discounted project revenue:	-$642.77	$ 74.87	$ 73.79	$ 72.73	$ 71.69	$ 70.66	$ 69.65	$ 68.65	$ 67.66	$ 66.69	$ 65.73	$ 64.79	$ 63.86	$ 62.94	$ 62.04	$ 61.15

NPV: **$ 374.15**
IRR: **11.43%**

200W HPS Base Case Project Cashflow, NPV, and IRR: Replacement at End-of-Useful Life / New Construction

Scenario: **Adaptive Networked LEDs**

Year:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Escalated energy savings:		$ 65.90	$ 67.87	$ 69.91	$ 72.01	$ 74.17	$ 76.39	$ 78.69	$ 81.05	$ 83.48	$ 85.98	$ 88.56	$ 91.22	$ 93.95	$ 96.77	$ 99.68
Escalated maintenance savings:		$ 21.86	$ 22.52	$ 23.19	$ 23.89	$ 24.60	$ 25.34	$ 26.10	$ 26.89	$ 27.69	$ 28.52	$ 29.38	$ 30.26	$ 31.17	$ 32.10	$ 33.07
Initial investment:	-$697.52															
Total project revenue:	-$697.52	$ 87.76	$ 90.39	$ 93.10	$ 95.90	$ 98.77	$ 101.74	$ 104.79	$ 107.93	$ 111.17	$ 114.50	$ 117.94	$ 121.48	$ 125.12	$ 128.88	$ 132.74
Discounted project revenue:	-$697.52	$ 83.98	$ 82.77	$ 81.59	$ 80.41	$ 79.26	$ 78.12	$ 77.00	$ 75.90	$ 74.81	$ 73.73	$ 72.67	$ 71.63	$ 70.60	$ 69.59	$ 68.59

NPV: **$ 443.15**
IRR: **12.00%**

Appendix E: PG&E Rate Schedule

ELECTRIC SCHEDULE LS-2

Sheet 1

CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

APPLICABILITY: This schedule is applicable to services for lighting installations which illuminate streets, highways, and other outdoor ways and places where the Customer is a Governmental Agency (Agency) and owns the lighting fixtures, poles and interconnecting circuits. This schedule is also applicable for service to those installations where service is initially established in the name of a developer who has installed such systems as required by an Agency and, where ownership of facilities and responsibility for service will be transferred to an Agency. Where the Agency does not accept facilities or where no transfer is intended, service will be provided under an otherwise appropriate rate schedule and rule. Class C is closed to new installations and additional lamps in existing accounts. (D)

TERRITORY: The entirety of PG&E's service territory.

RATES: The total monthly charge per lamp is equal to the sum of the facility charge and the energy charge. The monthly charge per lamp used for billing is calculated using unrounded facility and energy charges.

Monthly facility charges include the costs of owning, operating and maintaining the various lamp types and size. Monthly energy charges are based on the kWh usage of each lamp.

Monthly energy charges per lamp are calculated using the following formula: (Lamp wattage + ballast wattage) x 4,100 hours/12 months/1000 x streetlight energy rate per kilowatt hour (kWh). Ballast wattage = ballast factor x lamp wattage.

Total bundled monthly facility and energy charges are shown below.

The various ballast wattages used in the monthly energy charge calculations can be found in the Ballast Factor table following the monthly energy charges. Ballast factors are averaged within each grouping (range of wattages). The same ballast factor is applied to all of the lamps that fall within its watt range. Applicant or Customer must provide third party documentation where manufacturer's information is not available for rated wattage consumption before PG&E will accept lamps for this schedule.

Direct Access (DA) and Community Choice Aggregation (CCA) charges shall be calculated in accordance with Condition 13, Billing, below.

(Continued)

ELECTRIC SCHEDULE LS-2
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

Sheet 2

RATES: (Cont'd.)

Facilities Charge Per Lamp Per Month

CLASS:	A	C**
	PG&E supplies energy and service only.	PG&E supplies the energy and maintenance service as described in Special Condition 8
	$0.187	$2.688

Energy Charge Per Lamp Per Month
All Night Rates

Nominal Lamp Rating:

			Per Lamp Per Month			
LAMP WATTS	kWh per MONTH	AVERAGE INITIAL LUMENS*	All Classes			Half-Hour Adjustment
INCANDESCENT LAMPS:						
58	20	600	$2.441			$0.111
92	31	1,000	$3.784			$0.172
189	65	2,500	$7.934			$0.361
295	101	4,000**	$12.328			$0.560
405	139	6,000**	$16.966			$0.771
620	212	10,000**	$25.877			$1.176
860	294	15,000**	$35.886			$1.631
MERCURY VAPOR LAMPS:						
40	18	1,300	$2.197			$0.100
50	22	1,650	$2.685			$0.122
100	40	3,500	$4.882			$0.222
175	68	7,500	$8.300			$0.377
250	97	11,000	$11.840			$0.538
400	152	21,000	$18.553			$0.843
700	266	37,000	$32.468			$1.476
1,000	377	57,000	$46.017			$2.092

(D)

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* Latest published information should be consulted on best available lumens.

** Service for incandescent lamps over 2,500 lumens will be closed to new installations after September 11, 1978.

*** Closed to new installations and new lamps on existing circuits, see Condition 8A.

(Continued)

ELECTRIC SCHEDULE LS-2
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

Sheet 3

RATES: (Cont'd.)

HIGH PRESSURE SODIUM VAPOR LAMPS AT:
120 VOLTS

35	15	2,150	$1.831	$0.083
50	21	3,800	$2.563	$0.117
70	29	5,800	$3.540	$0.161
100	41	9,500	$5.004	$0.227
150	60	16,000	$7.324	$0.333
200	80	22,000	$9.765	$0.444
250	100	26,000	$12.206	$0.555
400	154	46,000	$18.797	$0.854

HIGH PRESSURE SODIUM VAPOR LAMPS AT:
240 VOLTS

50	24	3,800	$2.929	$0.133
70	34	5,800	$4.150	$0.189
100	47	9,500	$5.737	$0.261
150	69	16,000	$8.422	$0.383
200	81	22,000	$9.887	$0.449
250	100	25,500	$12.206	$0.555
310	119	37,000	$14.525	$0.660
360	144	45,000	$17.577	$0.799
400	154	46,000	$18.797	$0.854

LOW PRESSURE SODIUM VAPOR LAMPS:

35	21	4,800	$2.563	$0.117
55	29	8,000	$3.540	$0.161
90	45	13,500	$5.493	$0.250
135	62	21,500	$7.568	$0.344
180	78	33,000	$9.521	$0.433

METAL HALIDE LAMPS:

70	30	5,500	$3.662	$0.166
100	41	8,500	$5.004	$0.227
150	63	13,500	$7.690	$0.350
175	72	14,000	$8.788	$0.399
250	105	20,500	$12.816	$0.583
400	162	30,000	$19.774	$0.899
1,000	387	90,000	$47.237	$2.147

INDUCTION LAMPS:

40	14	2,200	$1.709	$0.078
55	19	3,000	$2.319	$0.105
80	27	4,500	$3.296	$0.150
85	30	4,800	$3.662	$0.166
120	42	8,500	$5.067	$0.230
150	51	10,900	$6.225	$0.283
165	58	12,000	$7.079	$0.322

(Continued)

ELECTRIC SCHEDULE LS-2

CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

Sheet 4

RATES: (Cont'd.)

LIGHT EMITTING DIODE (LED) LAMPS: 120-240 VOLTS

(N)

LAMP WATTS****	kWh per MONTH*****	A Only		Half-Hour Adjustment	
0.00-5.00	0.9	$0.110	(N)	$0.005	(N)
5.01-10.00	2.6	$0.317	(N)	$0.014	(N)
10.01-15.00	4.3	$0.525	(N)	$0.024	(N)
15.01-20.00	6.0	$0.732	(N)	$0.033	(N)
20.01-25.00	7.7	$0.940	(N)	$0.043	(N)
25.01-30.00	9.4	$1.147	(N)	$0.052	(N)
30.01-35.00	11.1	$1.355	(N)	$0.062	(N)
35.01-.40.00	12.8	$1.562	(N)	$0.071	(N)
40.01-45.00	14.5	$1.770	(N)	$0.080	(N)
45.01-50.00	16.2	$1.977	(N)	$0.090	(N)
50.01-55.00	17.9	$2.185	(N)	$0.099	(N)
55.01-60.00	19.6	$2.392	(N)	$0.109	(N)
60.01-65.00	21.4	$2.612	(N)	$0.119	(N)
65.01-70.00	23.1	$2.820	(N)	$0.128	(N)
70.01-75.00	24.8	$3.027	(N)	$0.138	(N)
75.01-80.00	26.5	$3.235	(N)	$0.147	(N)
80.01-85.00	28.2	$3.442	(N)	$0.156	(N)
85.01-90.00	29.9	$3.650	(N)	$0.166	(N)
90.01-95.00	31.6	$3.857	(N)	$0.175	(N)
95.01-100.00	33.3	$4.065	(N)	$0.185	(N)
100.01-105.00	35.0	$4.272	(N)	$0.194	(N)
105.01-110.00	36.7	$4.480	(N)	$0.204	(N)
110.01-115.00	38.4	$4.687	(N)	$0.213	(N)
115.01-120.00	40.1	$4.895	(N)	$0.223	(N)
120.01-125.00	41.9	$5.114	(N)	$0.232	(N)
125.01-130.00	43.6	$5.322	(N)	$0.242	(N)
130.01-135.00	45.3	$5.529	(N)	$0.251	(N)
135.01-140.00	47.0	$5.737	(N)	$0.261	(N)
140.01-145.00	48.7	$5.944	(N)	$0.270	(N)

(N)

(Continued)

ELECTRIC SCHEDULE LS-2

CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

RATES: (Cont'd.)

LIGHT EMITTING DIODE (LED) LAMPS: 120-240 VOLTS (Cont'd.)

(N)

LAMP WATTS****	kWh per MONTH*****	A Only		Half-Hour Adjustment	
145.01-150.00	50.4	$6.152	(N)	$0.280	(N)
150.01-155.00	52.1	$6.359	(N)	$0.289	(N)
155.01-160.00	53.8	$6.567	(N)	$0.299	(N)
160.01-165.00	55.5	$6.774	(N)	$0.308	(N)
165.01-170.00	57.2	$6.982	(N)	$0.317	(N)
170.01-175.00	58.9	$7.189	(N)	$0.327	(N)
175.01-180.00	60.6	$7.397	(N)	$0.336	(N)
180.01-185.00	62.4	$7.617	(N)	$0.346	(N)
185.01-190.00	64.1	$7.824	(N)	$0.356	(N)
190.01-195.00	65.8	$8.032	(N)	$0.365	(N)
195.01-200.00	67.5	$8.239	(N)	$0.375	(N)
200.01-205.00	69.2	$8.447	(N)	$0.384	(N)
205.01-210.00	70.9	$8.654	(N)	$0.393	(N)
210.01-215.00	72.6	$8.862	(N)	$0.403	(N)
215.01-220.00	74.3	$9.069	(N)	$0.412	(N)
220.01-225.00	76.0	$9.277	(N)	$0.422	(N)
225.01-230.00	77.7	$9.484	(N)	$0.431	(N)
230.01-235.00	79.4	$9.692	(N)	$0.441	(N)
235.01-240.00	81.1	$9.899	(N)	$0.450	(N)
240.01-245.00	82.9	$10.119	(N)	$0.460	(N)
245.01-250.00	84.6	$10.326	(N)	$0.469	(N)
250.01-255.00	86.3	$10.534	(N)	$0.479	(N)
255.01-260.00	88.0	$10.741	(N)	$0.488	(N)
260.01-265.00	89.7	$10.949	(N)	$0.498	(N)
265.01-270.00	91.4	$11.156	(N)	$0.507	(N)
270.01-275.00	93.1	$11.364	(N)	$0.517	(N)
275.01-280.00	94.8	$11.571	(N)	$0.526	(N)
280.01-285.00	96.5	$11.779	(N)	$0.535	(N)

(N)

(Continued)

ELECTRIC SCHEDULE LS-2

Sheet 6

CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

RATES: (Cont'd.)

LIGHT EMITTING DIODE (LED) LAMPS: 120-240 VOLTS (Cont'd.)

(N)

LAMP WATTS****	kWh per MONTH*****	A Only		Half-Hour Adjustment	
285.01-290.00	98.2	$11.986	(N)	$0.545	(N)
290.01-295.00	99.9	$12.194	(N)	$0.554	(N)
295.01-300.00	101.6	$12.401	(N)	$0.564	(N)
300.01-305.00	103.4	$12.621	(N)	$0.574	(N)
305.01-310.00	105.1	$12.829	(N)	$0.583	(N)
310.01-315.00	106.8	$13.036	(N)	$0.593	(N)
315.01-320.00	108.5	$13.244	(N)	$0.602	(N)
320.01-325.00	110.2	$13.451	(N)	$0.611	(N)
325.01-330.00	111.9	$13.659	(N)	$0.621	(N)
330.01-335.00	113.6	$13.866	(N)	$0.630	(N)
335.01-340.00	115.3	$14.074	(N)	$0.640	(N)
340.01-345.00	117.0	$14.281	(N)	$0.649	(N)
345.01-350.00	118.7	$14.489	(N)	$0.659	(N)
350.01-355.00	120.4	$14.696	(N)	$0.668	(N)
355.01-360.00	122.1	$14.904	(N)	$0.677	(N)
360.01-365.00	123.9	$15.123	(N)	$0.687	(N)
365.01-370.00	125.6	$15.331	(N)	$0.697	(N)
370.01-375.00	127.3	$15.538	(N)	$0.706	(N)
375.01-380.00	129.0	$15.746	(N)	$0.716	(N)
380.01-385.00	130.7	$15.953	(N)	$0.725	(N)
385.01-390.00	132.4	$16.161	(N)	$0.735	(N)
390.01-395.00	134.1	$16.368	(N)	$0.744	(N)
395.01-400.00	135.8	$16.576	(N)	$0.753	(N)

(N)

**** Wattage based on total consumption of lamp and driver. Customer may be required to provide verification of total energy consumption of lamp and driver upon request by PG&E.

***** Assumptions consistent with tariff, based on 4100 hours of operation for a full year; mid-point in range established by deducting 2.5 watts from highest wattage in range. The energy use calculation is: (high wattage in range-2.5 watts)x(4,100 hours/12 months/1000)

(Continued)

ELECTRIC SCHEDULE LS-2

Sheet 7

CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

RATES: (Cont'd.)

Ballast Factors by Lamp Type and Wattage Range (L)

Watt Range			Ballast Factor
MERCURY VAPOR			
1	to	75	31.00%
76	to	125	17.07%
126	to	325	13.69%
326	to	800	11.22%
801	+		10.34%
LOW PRESSURE SODIUM VAPOR			
1	to	40	75.61%
41	to	75	54.32%
76	to	110	46.34%
111	to	160	34.42%
161	+		26.83%
METAL HALIDE			
1	to	85	25.44%
86	to	200	20.39%
201	to	375	22.93%
376	to	700	18.54%
701	+		13.27%

Watt Range			Ballast Factor
HIGH PRESSURE SODIUM VAPOR			
120 Volts			
1	to	40	25.44%
41	to	60	22.93%
61	to	85	21.25%
86	to	125	20.00%
126	+		17.07%
240 Volts			
1	to	60	40.49%
61	to	85	42.16%
86	to	125	37.56%
126	to	175	34.63%
176	to	225	18.54%
226	to	280	17.07%
281	to	380	12.35%
381	+		12.68%

(Continued)

ELECTRIC SCHEDULE LS-2
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

Sheet 8

RATES: (Cont'd.)

(L)

TOTAL ENERGY RATES

Total Energy Charge Rate ($ per kWh)	$0.12206

UNBUNDLING OF TOTAL ENERGY CHARGES

The total energy charge is unbundled according to the component rates shown below.

Energy Rate by Components ($ per kWh)	
Generation	$0.08032
Distribution	$0.02507
Transmission*	$0.00650
Transmission Rate Adjustments*	($0.00096)
Reliability Services*	$0.00027
Public Purpose Programs	$0.00270
Nuclear Decommissioning	$0.00028
Competition Transition Charge	$0.00066
Energy Cost Recovery Amount	$0.00231
DWR Bond	$0.00491

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* Transmission, Transmission Rate Adjustments, and Reliability Service charges are combined for presentation on customer bills.

(Continued)

ELECTRIC SCHEDULE LS-2

CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

SPECIAL CONDITIONS:

1. **TYPE OF SERVICE**: This schedule is applicable to multiple lighting systems to which PG&E will deliver current at secondary voltage. Multiple current will normally be supplied at 120/240 Volt, single-phase. In certain localities PG&E may supply service from 120/208 Volt, wye-systems, polyphase lines in place of 240 Volt service. Unless otherwise agreed, existing series current will be delivered at 6.6 amperes. Single-phase service from 480 Volt sources and series circuits will be available in certain areas at the option of PG&E when this type of service is practical from PG&E's engineering standpoint. All currents and voltages stated herein are nominal, reasonable variations being permitted. (L)

   New lights will normally be supplied as multiple systems. Series service to new lights will be made only when it is practical from PG&E's engineering standpoint to supply them from existing series systems.

2. **SERVICE REQUIREMENTS**:

   a) **PHOTO CONTROLS**

   This rate schedule is predicated on an electronic type photo controls meeting ANSI standard C136.10, with a turn on value of 1.0 foot-candles and a turn off value of 1.5 foot-candles. Electro-mechanical or thermal type photo controls are not acceptable for this rate schedule.

   b) **LIGHT or POLE NUMBERING**

   As agreed upon by the parties, pole number sequencing and coding for single lights or multiple lights on a single pole, shall be provided by either party and must conform to PG&E's billing system. Customer will provide physical numbering on lights or poles for LS-2 installations in order to facilitate accurate billing and inventory reporting. Numbering is required prior to energizing facilities. Numbering must be legible from the ground.

   c) **SERVICE REQUESTS**

   Service request shall include form 79-1007 for installation and energizing, and form 79-1008 for removing or de-energizing Customer's facilities.

(Continued)

ELECTRIC SCHEDULE LS-2
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

SPECIAL CONDITIONS: (Cont'd.)

3. **SERVICE INSTALLATION** (L)

PG&E will establish service delivery points within close proximity to its distribution system.

a) **Overhead:** In an overhead area, a single drop will be installed. For an overhead to underground system, service will be established in a PG&E box at the base of the riser pole or other agreed upon location within close proximity. PG&E will connect Customer's conductors at the service delivery point.

b) **Underground:** In an underground area, service will be established at the nearest existing secondary box. Where no secondary facilities exist, a new service, transformer and secondary splice box, as required, will be installed in the shortest most practical configuration from the connection on the distribution line source. Customer shall install and own all facilities from the service delivery point on PG&E's system.

c) **Customer Installation Responsibility:** Customer shall install, own and maintain all facilities beyond the service delivery point. For PG&E's serving facilities, Customer or Applicant, at its expense, shall perform all necessary trenching, backfill and paving, and shall furnish and install all necessary conduit and substructures (including substructures for transformer installations, if necessary, for street lights only) in accordance with PG&E's specifications. Riser material shall be installed by PG&E at the Customer's expense. Upon acceptance by PG&E, ownership of the conduit and substructures shall vest in PG&E. Customer shall provide rights of way as provided in electric Rule 16.

d) **PG&E Installation Responsibility:** PG&E shall furnish and install the underground or overhead service conductor, transformers and necessary facilities to complete the service to the distribution line source, subject to the payment provisions of Special Condition 4. Only duly authorized employees of PG&E shall connect Customer's loads to, or disconnect the same from, PG&E's electrical distribution facilities.

e) **Rearrangements:** Customer or Applicant shall pay, in advance, PG&E's estimated cost for any relocation or rearrangement of PG&E's existing street light or service facilities requested by Customer or Applicant and agreed to by PG&E.

f) **Non-Conforming Load:** Applicant or Customer must be a governmental agency. Any load, other then the lighting loads listed in the Rate table above, is non conforming load. Non conforming load may be connected to customer circuits not to exceed 150 watts per circuit, or light for individually connected lights. Loads will conform to the requirements of Agreement form 79-1048 available on PG&E's web site, http://www.pge.com/tariffs/EF.SHTML#EF for electric forms. All other non conforming load connected to unmetered LS-2 facilities exceeding this limitation requires metering of the Customer's system at PG&E's service delivery point.

(Continued)

ELECTRIC SCHEDULE LS-2
Sheet 11

CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

SPECIAL CONDITIONS: (Cont'd.)

4. **NON REFUNDABLE PAYMENT FOR SERVICE INSTALLATION**: (L)

   a) Customer or Applicant shall pay in advance the estimated installed cost necessary to establish a service delivery point. A one-time revenue allowance will be provided based on Customer's kWh usage and the distribution component of the energy rate posted in the Rate Schedule for the lamps installed. The total allowance shall be determined by taking the annual equivalent kWh times the Distribution component of this rate divided by the cost of service factor shown in Electric Rule 15.C.

   b) The allowance will only be provided where PG&E must install capital assets to connect load. No allowance will be provided where a simple connection is required. Only lights on a minimum 11 hour All Night (AN) schedule for permanent service shall be granted an allowance. Where Applicant received allowances based upon 11 hour AN operation, no billing adjustments, as otherwise provided for in Special Condition 7, shall be made for the first three (3) years following commencement of service.

   Line or service extensions in excess of the above shall be installed under special condition 9.

5. **TEMPORARY SERVICE:** Temporary services will be installed under electric Rule 13.

6. **ANNUAL OPERATING SCHEDULES**: The above rates for AN service assume 11 hours operation per night and apply to lamps which will be turned on and off once each night in accordance with a regular operating schedule selected by the Customer but not exceeding 4,100 hours per year.

(Continued)

ELECTRIC SCHEDULE LS-2

Sheet 12

CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

SPECIAL CONDITIONS: (Cont'd.)

7. **OPERATING SCHEDULES OTHER THAN ALL-NIGHT:** Rates for regular operating schedules other than full all-night will be the AN rate, plus or minus, respectively, the half-hour adjustment for each half-hour more or less than an average of 11 hours per night. This adjustment will apply only to lamps on regular operating schedules of not less than 1,095 hours per year, or 3 hours per night, and may be applied for 24-hour operation. Photo control devices used for more or less than AN must be approved by PG&E prior to adjustments in billing. (L)

8. **MAINTENANCE, ACCESS, CLEARANCES**

   a) Maintenance

      The C rates include all labor and material necessary for the inspection, cleaning, or replacement by PG&E of lamps and glassware. Replacement is limited to certain glassware such as is commonly used and manufactured in reasonably large quantities. A commensurate extra charge will be made for maintenance of glassware of a type entailing unusual expense. The Class C rate also includes all labor and material necessary for replacement by PG&E of photoelectric controls. Class C rates are closed to new installations and to additional lamps in existing accounts as of March 1, 2006. (T) (T)

   b) Under the grand fathered Class C rates, the following shall apply: (T)

      1) At Customer's request, where PG&E's resources permit, PG&E will paint poles for Customer on a time and material basis. This service will only be offered for poles that have been designed to be painted.

      2) PG&E will Isolate any trouble in the Customer's system which has resulted in an outage or diminished light output.

      3) PG&E will make necessary repairs which do not require wiring replacement on accessible wiring between poles and on equipment and wiring in and on poles to keep the system in operating condition.

      4) PG&E will provide labor for the replacement of material such as ballasts, relays, fixtures, individual cable runs between poles where such runs are in conduit, and other individual parts of the system that are not capital items.

      5) Customer shall compensate PG&E for any material furnished by PG&E not included in 8.A. above. Customer must have been on Class C for this service. (D)

      6) PG&E shall not be responsible for excavation or any major replacement of circuits, conduits, poles, or fixtures owned by the Customer.

      7) Tree trimming is the responsibility of the Customer for installation of new lights or for maintaining lighting patterns of existing lights.

(Continued)

ELECTRIC SCHEDULE LS-2
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

SPECIAL CONDITIONS: (Cont'd.)

8. **MAINTENANCE, ACCESS, CLEARANCES** (Cont'd.): (L)

c) Access

Customer will maintain adequate access for PG&E's standard equipment used in maintaining facilities and for installation of its facilities. PG&E reserves the right to collect additional maintenance costs due to obstructed access or other conditions preventing PG&E from maintaining its equipment with standard operating procedures. Applicant or Customer shall be responsible for rearrangement charges as provided for in Special Condition 3.e.

d) Clearances

Customer applicant shall, at its expense, correct all access or clearance infractions, or pay PG&E its total estimated cost for PG&E to relocate facilities to a new location which is acceptable to PG&E. Failure to comply with corrective measures within a reasonable time may result in discontinuance of service in accordance with electric Rule 11. Applicant or Customer shall be responsible for tree trimming to maintain lighting patterns of existing lights.

(Continued)

ELECTRIC SCHEDULE LS-2
CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

SPECIAL CONDITIONS: (Cont'd.)

9. **LINE EXTENSIONS** (L)

   A. Where PG&E extends its facilities to street light installations in advance of subdivision projects where subdivision maps have been approved by local authorities, extensions will be installed under the provisions of electric Rule 15, except as noted below.

   B. Where PG&E extends its facilities to street light installations in the absence of any approved subdivision maps, applicant shall pay PG&E's estimated cost, plus cost of ownership and applicable tax. Standard form contract 62-4527, Agreement to Perform Tariff Schedule Related Work, shall be used for these installations.

10. **STREET LIGHT LAMPS – STANDARD AND NONSTANDARD RATINGS:** The rates under Classes B and C are applicable to both standard and group replacement street lamps. Standard and group replacement street lamps have reference only to street lamps having wattage and operating life ratings within three percent of those specified in the EEI-NEMA Standards for Filament Lamps Used in Street Lighting. Where Class A service is supplied to lamps of other ratings than those specified in EEI-NEMA Standards an adjustment will be made in the lamp rates proportionate to the difference between the wattage of the lamps and the standard lamps of the same lumen rating.

11. **ENERGY EFFICIENT STREET LIGHTS:** Where Customer permanently installs energy efficient street lights and total energy use cannot be verified through industry standard test results and customer requests that the energy efficient street lights be added to this tariff, customer may be required to provide specific performance data on the total energy consumption of the fixture (which includes controls, lamp and ballast or driver) as requested by PG&E. (N)

12. **CONTRACT:** Except as otherwise provided in this rate schedule, or where lighting service is installed in conjunction with facilities installed under the provisions of Rules 15 or 16, standard form contract 62-4527, Agreement to Perform Tariff Schedule Related Work shall be used for installations, rearrangements or relocations. (T)

13. **POLE CONTACT AGREEMENT:** Where Customer requests to have a portion or all Customer owned street lighting facilities in contact with PG&E's distribution poles, a Customer-Owned Streetlights PG&E Pole Contact Agreement (Form 79 938) will be required. (T)

(Continued)

ELECTRIC SCHEDULE LS-2

Sheet 15

CUSTOMER-OWNED STREET AND HIGHWAY LIGHTING

SPECIAL CONDITIONS: (Cont'd.)

14. **BILLING:** This Rate Schedule is subject to PG&E's other rules governing billing issues, as may be applicable. PG&E performs regular auditing as part of this rate schedule. (T) (L)

Limited testing of Energy Efficient Street Light Technology will be allowed under this Rate Schedule where a light of the type and wattage of the fixture and lamp to be tested are not presently included in the rate tables. Such test installations are subject to approval by PG&E. Following approval, test installations will be billed at the customer's currently billed rate. Customer will provide a monthly inventory of streetlights that will be tested. The format and content of the inventory must be approved by PG&E. The Company reserves the right to audit customer. PG&E also reserves the right to collect the cost of any such audit from the customer. Testing is limited to existing street light fixtures and the total energy consumption per fixture must not exceed current energy use per fixture. Additional energy efficient street light fixtures installed will also be subject to billing under the current rate upon the approval of PG&E. The test period will not exceed 12 months.

Bundled Service Customers receive supply and delivery service solely from PG&E. The Customer's bill is based on the Total Rate set forth above.

Transitional Bundled Service Customers take transitional bundled service as prescribed in Rules 22.1 and 23.1, or take bundled service prior to the end of the six (6) month advance notice period required to elect bundled portfolio service as prescribed in Rules 22.1 and 23.1. These customers shall pay charges for transmission, transmission rate adjustments, reliability services, distribution, nuclear decommissioning, public purpose programs, the FTA (where applicable), the RRBMA (where applicable), the applicable Cost Responsibility Surcharge (CRS) pursuant to Schedule DA CRS or Schedule CCA CRS, and short-term commodity prices as set forth in Schedule TBCC.

Direct Access (DA) and Community Choice Aggregation (CCA) Customers purchase energy from their non-utility provider and continue receiving delivery services from PG&E. Bills are equal to the sum of charges for transmission, transmission rate adjustments, reliability services, distribution, public purpose programs, nuclear decommissioning, the FTA (where applicable), the RRBMA (where applicable), the franchise fee surcharge, and the applicable CRS. The CRS is equal to the sum of the individual charges set forth below. Exemptions to the CRS are set forth in Schedules DA CRS and CCA CRS.

	DA CRS	CCA CRS
Energy Cost Recovery Amount Charge (per kWh)	$0.00231	$0.00231
Power Charge Indifference Adjustment (per kWh)	($0.00062)	$0.01934
DWR Bond Charge (per kWh)	$0.00491	$0.00491
CTC Charge (per kWh)	$0.00066	$0.00066
Total CRS (per kWh)	$0.00726	$0.02722

15. **DWR BOND CHARGE:** The Department of Water Resources (DWR) Bond Charge was imposed by California Public Utilities Commission Decision 02-10-063, as modified by Decision 02-12-082, and is property of DWR for all purposes under California law. The Bond Charge applies to all retail sales, excluding CARE and Medical Baseline sales. The DWR Bond Charge (where applicable) is included in customers' total billed amounts. (T)