

GATEWAY

Demonstrations



Philadelphia International Airport Apron Lighting: LED System Performance in a Trial Installation

October 2015

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Philadelphia International Airport Apron Lighting LED System Performance in a Trial Installation

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Preface

The GATEWAY Program

This document is a report of observations and results obtained from a lighting evaluation project conducted under the U.S. Department of Energy (DOE) GATEWAY Program. The program supports field evaluations of high-performance solid-state lighting products in order to develop empirical data and experience with in-the-field applications of this advanced lighting technology. The DOE GATEWAY Program provides independent, third-party data for use in decision-making by lighting manufacturers, users, and other professionals. Though products used in the GATEWAY Program may have been prescreened for performance, DOE does not endorse any commercial product or in any way provide assurance that other users will achieve similar results through use of these products.

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Executive Summary

The adoption of light emitting diode (LED) lighting products has accelerated rapidly in many exterior applications in recent years. For a few exterior applications, however, LED luminaires have not yet been able to match the photometric and economic performance of incumbent high-intensity discharge (HID) systems. Area-lighting applications with mounting heights of 65 ft and higher (often called high-mast lighting) generally require light output levels that are provided by 750 or 1000 W HID lamps; these light outputs exceed those provided by most LED luminaires available for exterior applications.

This report describes a trial LED installation for the apron lighting at Philadelphia International Airport (PHL), where lighting is the single largest user of energy when considering the entire airport, representing 25% of the total energy usage in 2012. Airport apron lighting is one of the contributors, with the incumbent HPS lighting system using an estimated 1,758,450 kWh per year. The apron lighting is critical to airport operations because it provides task lighting for baggage loading and off-loading in the aircraft belly, tow tractor hookup, fueling operations, pre-flight check by the pilots and minor maintenance at the gate. This application poses an especially difficult lighting challenge, with the following application requirements and limitations:

- **High light levels** are required due to the demanding visual task needs,
- **Luminaire locations** are limited to one side of perimeter zones, unlike other large-area lighting applications where light poles can be placed throughout the area,
- **Long throws** are needed to provide the light required for visual tasks that extend the entire length of aircraft that are parked at airport gates.

Luminaires with very high lumen packages and good optical control are required to satisfy these requirements.

In the summer of 2013, PHL airport staff began examining ways to reduce the energy consumption of their apron lighting, and contacted the DOE SSL GATEWAY Program for assistance. In addition to reducing energy, PHL also hoped to reduce required maintenance, reduce light pollution, and increase safety with an improved lighting system. To minimize the complexity and cost of installing the new lighting system, PHL staff chose to pursue replacing the existing HPS luminaires on a one-for-one basis. After reviewing many alternative products and approaches, PHL selected an LED luminaire for a trial installation in the apron area at one of their seven terminals. An evaluation of an initial trial installation of three luminaires was conducted in October 2014; this evaluation led to recommended improvements in the system design and evaluation procedures. Consequently, a second trial installation was evaluated in May 2015 and provided a better solution.

This type of high-mast application remains challenging for LED technology. The following lessons learned from this project may help facility managers and LED product manufacturers better meet the challenges.

- *Need to establish clear design criteria and constraints for the LED project.* The only way to fairly evaluate the many options available for a large-scale LED project is to establish clear criteria at the project outset.
- *Importance of trial installations and mock-ups.* While detailed computer analyses can help to assess illuminances in different areas of an application, they cannot replace the experience of viewing a trial installation under realistic conditions.
- *Careful review of calculations of photometric quantities.* PHL staff received many inquiries from luminaire manufacturers and sales agencies, who often provided computer analyses that failed to

accurately reflect the system requirements in an attempt to improve the apparent suitability of the proposed solution.

Acronyms and Abbreviations

CCT	correlated color temperature
CRI	color rendering index
DOE	U.S. Department of Energy
FAA	Federal Aviation Administration
HID	high-intensity discharge
HPS	high pressure sodium
IES	Illuminating Engineering Society
K	kelvin
LED	light emitting diode
lm	lumen(s)
lx	lux
MH	metal halide
PHL	Philadelphia International Airport
PNNL	Pacific Northwest National Laboratory
SPD	spectral power distribution
SSL	solid-state lighting
W	Watt(s)

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1. Introduction

The adoption of light emitting diode (LED) lighting products has accelerated rapidly in many exterior applications in recent years. For example, the U.S. Department of Energy (DOE) estimates that in area and roadway applications, 5.7 million LED luminaires had been installed in the U.S. through 2014, representing 13% of the products used in those applications; a market penetration rate increase of 10% since 2012. Similarly, the market penetration of LED products for parking lot applications grew from 1% in 2012 to 10% in 2014, with an estimated 2.8 million LED units installed in parking lots as of 2014.¹ Compared to the incumbent lighting systems that typically use 250 and 400 W high intensity discharge (HID) lamps, LED systems offer similar light output with longer expected lifetimes and potentially higher luminaire efficacy, providing opportunities for energy and maintenance savings.

For a few exterior applications, however, LED luminaires have not yet been able to match the photometric and economic performance of incumbent HID systems. Area-lighting applications with mounting heights of 65 ft and higher (often called high-mast lighting) generally require light output levels that are provided by 750 or 1000 W HID lamps; these light outputs exceed those provided by most LED luminaires available for exterior applications. The high drive currents often used in these higher output LED luminaires can reduce the luminaire efficacy, due in part to thermal effects related to the higher drive current. Examples of high-mast exterior lighting applications include major roadway interchanges, prisons, military and other high-security installations, large parking lots, sports stadiums, and the apron areas at major airports.

This report describes a trial LED installation for the apron lighting at Philadelphia International Airport (PHL). Airport apron lighting provides task lighting for baggage loading and off-loading in the aircraft belly, tow tractor hookup, fueling operations, pre-flight check by the pilots and minor maintenance at the gate. This application poses an especially difficult lighting challenge, with the following application requirements and limitations:

- **High light levels** are required due to the demanding visual task needs.
- **Luminaire locations** are limited to one side of perimeter zones, unlike other large-area lighting applications where light poles can be placed throughout the area.
- **Long throws** are needed to provide the light required for visual tasks that extend the entire length of aircraft that are parked at airport gates.

Luminaires with very high lumen packages and good optical control are required to satisfy these requirements.

In the summer of 2013, PHL airport staff began examining ways to reduce the energy consumption of their apron lighting, and contacted the DOE Solid State Lighting (SSL) GATEWAY Program for assistance. In addition to reducing energy, PHL also hoped to reduce maintenance and light pollution, and increase safety with an improved lighting system. To minimize the complexity and cost of installing the new lighting system, PHL staff chose to pursue replacing the existing high pressure sodium (HPS) luminaires on a one-for-one basis. After reviewing many alternative products and approaches, PHL selected an LED luminaire for a trial installation in the apron area at one of their seven terminals. An evaluation of an initial trial installation (Trial 1) of three luminaires was conducted in October 2014 which led to recommended improvements to the system design and evaluation procedures. A second trial installation (Trial 2) was evaluated in May 2015. This report describes the processes used to select and evaluate the LED luminaires and the results of the trial installations.

¹ *Adoption of Light-Emitting Diodes in Common Lighting Applications*, July 2015, available with other similar studies at <http://energy.gov/eere/ssl/market-studies>.

2. Background

2.1 Philadelphia International Airport

PHL is the only major airport serving Philadelphia, the sixth largest metropolitan area in the U.S. The airport is owned and operated by the City of Philadelphia, and is located seven miles from downtown Philadelphia. It is one of the busiest airports in the northeastern United States, serving more than 30 million passengers in 2014 (about 84,000 per day), of which 4.5 million were international passengers. PHL ranks tenth in the nation and fifteenth in the world in total number of takeoffs and landings.

PHL covers 2,394 acres and has four runways, ranging in length from 5,000 to 10,500 ft, and seven terminals: A-West, A-East, B, C, D, E and F. Expansion of the terminal complex since 2001 has more than doubled the area, with the seven terminals now occupying more than 3.2 million square feet. The airport has more than 18,000 employees and nearly 19,000 public parking spaces.

At this sizable airport, lighting is the single largest use of energy, representing 25% of the total energy usage in 2012. Energy conservation efforts have been implemented in recent years in interior and exterior lighting applications, including installations of LED systems. An evaluation of the apron lighting system was initiated as part of a facility-wide energy conservation program.

2.2 Incumbent Apron Lighting System

The incumbent lighting system for the PHL apron areas use 390 Sterner Infranor™ 876 luminaires, each with one 1000 Watt (W) HPS lamp. These lamps are rated to produce 130,000 initial lumens (lm), and based on published photometric data the luminaire efficiency is about 49%, so approximately 64,000 lm exit the luminaire. The power draw for the lamp and ballast combination is rated at 1100 W, producing a luminaire efficacy for the incumbent system of 58 lm/W. The system has 51 poles with two luminaires, 82 poles with three luminaires, and eight poles with four luminaires. The original design documents specify that the luminaires were to be tilted up 60 degrees (with 0-degree tilt meaning the luminaire aperture is horizontal); however, the luminaires are not all titled at 60 degrees due to field adjustments during installation, possible movement during routine maintenance, and some spot adjustments to reduce glare.

The 390 luminaires have a combined power draw of 429,000 W (429 kW). Photocells and timeclocks are used to switch the luminaires on and off (dusk to dawn), so that the luminaires average 11.23 daily operating hours over the course of a year. The annual energy use for the incumbent HPS lighting system is therefore estimated to be 1,758,450 kWh.

Wall-pack luminaires with 100 and 150 W HPS lamps are mounted on the exterior walls of the terminal building in some areas, and in other areas similar luminaires are ceiling-mounted from an overhang. The primary purpose of these luminaires is to provide supplemental lighting on the sidewalks and other areas immediately adjacent to the terminal. Although they contribute light to the apron area near the building, these luminaires were not considered as part of the apron lighting upgrade evaluation.

3. Trial Installation Design Process

Prior to selecting luminaires, the first priority was to understand the criteria for a new lighting system, including any issues with the current lighting system. The chief concern with the current lighting system at PHL is luminaires that stop operating, most often due to a burned-out lamp. The resulting light level decrease presents safety concerns as well as potential flight delays. Long lifetime and system reliability were therefore key criteria for a new apron lighting system. Beyond long lifetime and reliability, another primary concern was the light levels in the apron area. An LED lighting solution could address the lifetime and reliability concerns of the old system, but could it provide the desired light levels? This was a serious concern in the summer of 2013, when LED technology was just becoming potentially viable for high-mast outdoor lighting applications. Other concerns with the use of LED technology at PHL included glare and flicker, as it was very important to avoid any deleterious impact to airport operations and personnel including air traffic controllers, pilots, and the ground crew.

3.1 Design Criteria

This apron lighting application was challenging because the visual tasks at PHL require high illuminances, which are difficult to achieve given the long throws from luminaire locations that are limited to one side of a perimeter zone. Establishing realistic design criteria was important to better understanding and addressing these challenges.

It was difficult to determine the target illuminance levels and uniformity for PHL's apron area for several reasons. First, PHL had existing criteria for the average and the average to minimum ratio of the horizontal illuminance on the pavement, but the current lighting system did not meet the criteria (based on both computer modeling and spot measurements). PHL airport staff wanted to make sure Federal Aviation Administration (FAA) criteria were met; however, the FAA Advisory Circular for airport design² references Illuminating Engineering Society (IES) RP-14-87 for illuminance requirements, which has been withdrawn by the IES³. Therefore, recommendations for illuminance levels and uniformity from FAA and IES appear to be in transition, with no guidance as to how any new recommendations may change from the past recommendations.

When there are no recommendations for a particular application, the target criterion for a new system often becomes to meet or exceed the performance of the existing lighting system. The area where the light levels are of concern on the apron usually extends from a given terminal building to the end of the aircraft being served at each gate. Lighting is needed at the end of the plane because the pilot walks around the entire plane prior to departure, looking for damage or other issues of concern. Because the maximum plane size that can be accommodated varies by gate area, so do the distance requirements for illuminance. The area of concern for the PHL Terminal A-West gates extends outward to a distance of 250 ft due the larger size of the planes arriving and departing from these gates.

3.2 Luminaire Selection

To minimize the complexity and cost of installing the new lighting system, PHL staff chose to pursue replacing the existing HPS luminaires on a one-for-one basis. Initial computer modeling showed that if the illuminance levels of the new LED lighting system were going to meet or exceed the incumbent apron lighting system with a

² FAA Advisory Circular 150/5300-13A Airport Design. 2014.

³ As of the writing of this report there is no replacement, although the IES is working on the replacement document, IES RP-37.

one-to-one replacement, the LED luminaires would most likely require a minimum lumen output of 60,000 lm, with appropriate optics to control the light distribution without much errant light. Many LED luminaires were available with light output ranging between 20,000 and 40,000 lm, but in the fall of 2013 only one manufacturer offered several distribution options with lumen output above 60,000 lm. As of the writing of this report, only five manufacturers listed on LED Lighting Facts offered an outdoor area/roadway luminaire with a lumen output above 60,000 lm and a correlated color temperature (CCT) less than 4500 K.⁴

The specified minimum LED luminaire output was less than that of the incumbent HPS luminaire because the optical control made possible with LEDs can create the opportunity to maintain a minimum illuminance level with less overlighting than a typical HPS system. For HPS systems, overlighting certain areas (such as right underneath the pole) is often necessary to ensure that the darkest point in the lighted area stays above the minimum illuminance required. Overlighting increases the average illuminance, but adds little to the overall visibility and lighting quality of the site. LEDs can often achieve minimum illuminances with lower average illumination levels than the incumbent system. If overlighting can be avoided while meeting the minimum illuminance level, the lumen output does not need to be as high. To better understand the actual target illuminances needed at PHL, an initial mock-up was completed in Terminal A-West in October 2014.

⁴ More luminaires are available at higher CCT, but CCT above 4500K was not considered for this project based on PHL's criteria. Visit www.lightingfacts.com/products to search for listed products.

4. Trial Installation: Procedure and Results

4.1 Procedure for the Initial Trial Installation (Trial 1)

The trial installation focused on the apron area directly in front of pole 16 at PHL Terminal A-West, between gates A15 and A16. Figure 1 is an aerial view of Terminal A-West showing several key features. This area was selected because the international flights using these gates have the largest aircraft that arrive at and depart from PHL, and thus require the longest throws for delivering the target illuminances. The largest passenger jet used at PHL at the time of this study was the Boeing 777-300ER, which is 240 ft long with a wingspan of 213 ft. PHL maintenance and engineering staff wanted to assess the appropriateness of an LED luminaire in this critical area of the application, assuming that if the proposed luminaire worked at pole 16, other luminaires from the same family could work for the apron lighting system in other areas of the facility.

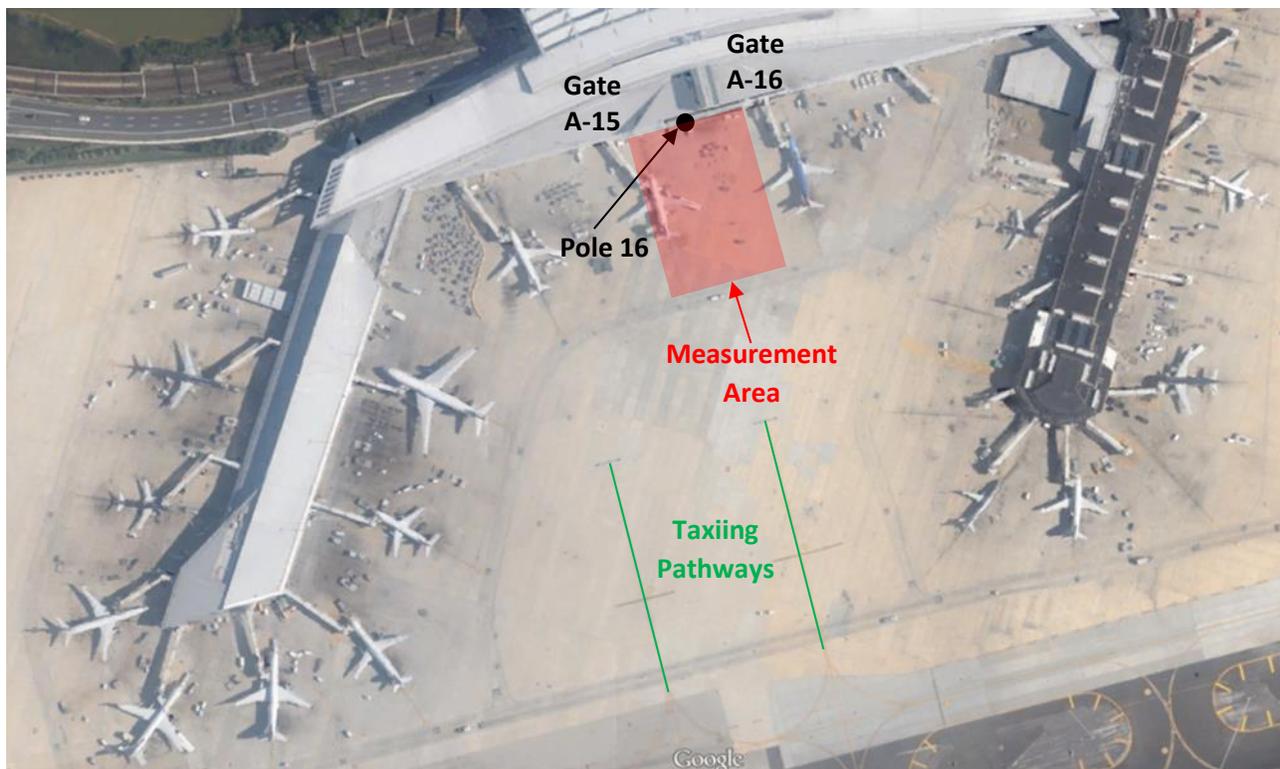


Figure 1. Aerial view of PHL Terminal A, where the trial LED installation took place. Location of lighting pole 16 and gates A15 and A16 are shown. The trial installation evaluation took place in the apron area immediately in front of pole 16. Note the marked taxiing pathways that have direct views of the luminaires in the study area as the pilots move their aircraft towards the gates. (Photo Source: Google Maps)

The mounting heights of luminaires in Terminal A range from 50 to 70 ft above the apron surface, with most poles having three luminaires. The aiming of each luminaire is described by a tilt angle, which specifies the aiming in the vertical plane, and an orientation angle, which specifies the rotation of the luminaire in the horizontal plane. All of the incumbent luminaires in this area were tilted approximately 60° up from horizontal. The center luminaire on each pole was aimed straight out from the terminal building, defined as an orientation of 0° , while the two side luminaires had orientations of about 45° and 315° (or -45°). Figure 2 is a photograph of the study area showing the incumbent HPS system.



Figure 2. Photograph of the HPS system in the trial installation area. Pole 16 is at the center of the photo, with pole 15 to the left (west) and pole 17 to the right (east). The passenger boarding bridge serving gate A15 can be seen between poles 15 and 16.

For the initial trial installation, PHL staff installed three LED luminaires on pole 16 as recommended by the luminaire manufacturer, Cree. The center luminaire was model ARE-EHO-4M (Type IV Medium distribution); this luminaire was not tilted (i.e., with a 0° tilt) and had an orientation angle of 0° . The two side luminaires were model FLD-EHO-25-AA (25° flood distribution) and were tilted 70° with the same orientation angle as the incumbent luminaires, with one aimed towards the apron area in front of pole 15 and one towards the apron area in front of pole 17. All of the luminaires had 240 LEDs and 1000 mA drive current in order to meet the minimum desired light output. Figure 3 is a photograph of the initial LED installation.

One of the PHL electricians who installed the fixtures noted that the new luminaires were large and awkward to handle, requiring two people in the bucket truck. The center luminaire was the most difficult to install because its horizontal orientation made it more difficult to support the weight of the luminaire during installation.



Figure 3. Photo of the initial trial installation of LED luminaires on pole 16. The difference in CCT (2200 K for the HPS vs. 4000 K for the LED) is apparent. The center LED luminaire was mounted horizontally (0° tilt) while the two side luminaires were installed with a 70° tilt.

DOE SSL GATEWAY Program staff visited the site in late October 2014 to collect data on two consecutive nights, first for the existing HPS system and then for the trial LED system, which was installed on the same day that measurements were taken. Measurements did not begin until at least 90 minutes after civil twilight. Weather conditions were similar on both nights, with partly to mostly cloudy skies, no precipitation, and temperatures during the measurement periods between 49 and 55 °F. The HPS luminaires in the study area (including poles

15, 16 and 17) were cleaned and re-lamped the week before the initial trial installation, so that the new lamps had at least 100 hours of operation before the measurements.

To evaluate the photometric performance of the trial installation, horizontal illuminance was measured on a 15 ft by 15 ft grid with a primary grid line beginning at pole 16 and extending 255 ft south (straight out from the terminal building) from the pole location. The grid also extended 90 ft to the east of pole 16 (past the mid-point to pole 17) and 75 ft to the west of pole 16 (past the mid-point to pole 15) for a total distance of 165 ft along the east-west direction. This encompassed the entire apron area where baggage handlers and other grounds crew operate, from the terminal building to the marked apron service road. A diagram of the measurement grid is provided in Figure 4. Horizontal illuminances were measured throughout the grid, while vertical illuminances were measured at the 15 ft spacing in the measurement rows at 75 ft and at 255 ft from the pole.

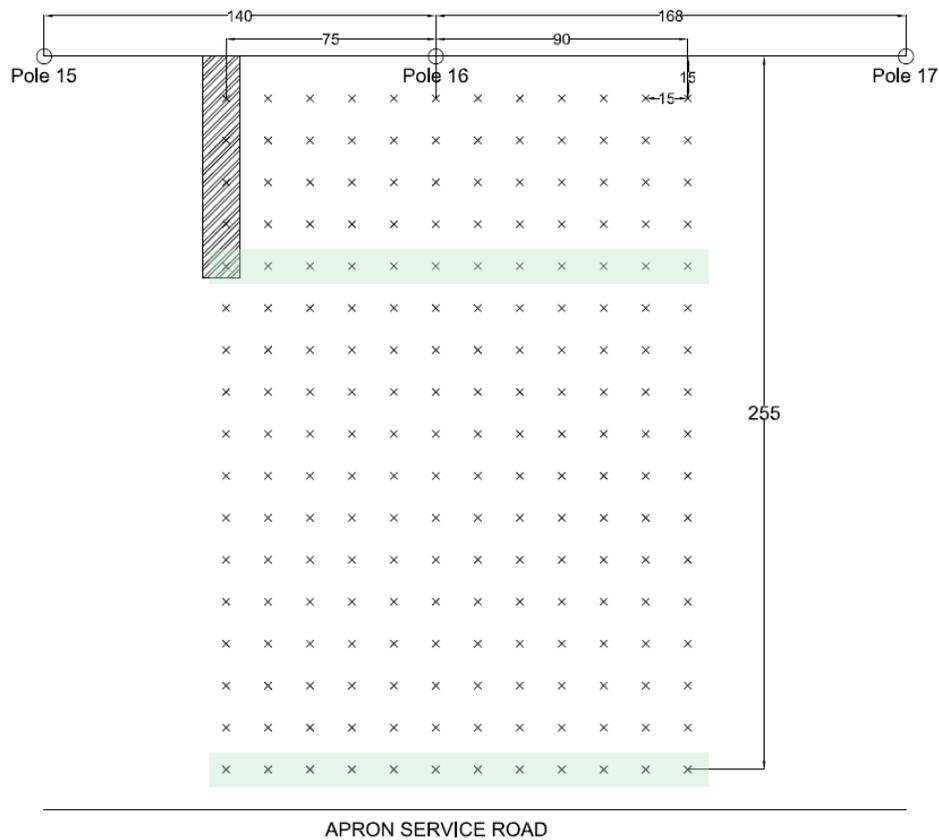


Figure 4. Diagram of pole locations and measurement grid. Horizontal illuminance was measured on a 15 ft by 15 ft grid with a primary grid line beginning at pole 16 and extending 255 ft out from the pole. Vertical illuminance was measured at the grid points in the rows 75 ft and 255 ft from the pole, highlighted in green. The striped box indicates where the jet bridge partially or completely prevented the light from reaching the measurement points.

The illuminance meter⁵ was mounted on a tripod head in a small wagon, and illuminance measurements were taken about 9.5 in. above ground. A tripod head attached to the illuminance meter was used to level the meter head near the building where the pavement sloped away from the building slightly; leveling of the meter beyond the 90 ft row was typically not necessary since the pavement was level in that region. A tripod was used to take

⁵ T-10A Konica Minolta illuminance meter, serial number 30011584/20011162, calibrated 4/14/14.

the vertical illuminance and color measurements,⁶ and was adjusted so that the center of the meter head was at a height of 4 ft. For these measurements, the meters were mounted in a vertical orientation with the detector facing directly toward the terminal building.

4.2 Illuminance Results for Trial 1

The average horizontal illuminance measured for the HPS system was 33.7 lx with a maximum (max) to minimum (min) illuminance ratio of 8.7, and for the initial LED trial system (LED-1), the average horizontal illuminance was 35.1 lx and the max-to-min illuminance ratio was 9.8. The complete set of data for the HPS system and the LED-1 system is provided in Appendix A.

Although the overall average illuminance of the LED system exceeded that of the HPS system, a detailed review of the data showed that the LED-1 system did not provide acceptable lighting for the apron area being studied. Table 1 provides the average illuminance and the illuminance ratio for each measurement row for both the HPS and the LED-1 systems, and Table 2 summarizes the vertical illuminance data. Although the average illuminance of the LED-1 system exceeded that of the HPS system in rows 45 through 135, the values for the LED-1 system decreased sharply beginning at row 150. Furthermore, the LED-1 average values beginning at row 180 dropped below 20 lx. PHL staff considered rows 15 and 30 relatively unimportant for this analysis, since most of the grounds crew work and pilot inspections occur in the areas beyond those rows.

In addition to the average illuminance in each row, Table 1 also shows that the light distribution within each row changed with the LED-1 system compared to the HPS system, as indicated by the increase in max-to-min illuminance ratios in many rows. Specifically, the illuminances at the measurement points in the center of the grid, in front of pole 16, were much less for the LED-1 system than they were for the HPS system. This change in distribution is illustrated in Figure 5, which plots the percentage difference in illuminance between the LED-1 and the HPS systems. This plot demonstrates that the LED-1 system was producing higher illuminances than the HPS system along the sides of the grid area from rows 45 to 150, but was producing lower illuminances throughout the center of the grid area and at almost all points in row 150 and beyond.

⁶ CL-500A Konica Minolta Illuminance Spectrophotometer, serial number 10002008, factory calibrated when purchased in late 2013 and within calibration when tested by a National Voluntary Laboratory Accreditation Program accredited testing lab in June 2015.

Table 1. Horizontal illuminance measurements for the HPS system and the initial LED trial installation (LED-1).

Row (ft from pole)	HPS		LED-1	
	Average illuminance (lx)	Max : Min illuminance	Average illuminance (lx)	Max : Min illuminance
15	66.3	3.6	47.3	1.9
30	67.4	4.0	53.3	2.1
45	57.4	2.9	64.6	2.2
60	47.1	2.1	70.1	2.5
75	40.6	1.9	65.6	2.9
90	32.0	1.7	59.2	2.6
105	26.3	1.4	45.7	2.6
120	25.2	1.3	37.1	2.7
135	27.0	1.2	29.0	2.5
150	28.9	1.3	23.8	2.6
165	27.3	1.1	20.8	1.9
180	25.9	1.1	18.0	1.7
195	24.5	1.1	16.2	1.6
210	23.6	1.1	14.6	1.5
225	21.9	1.2	13.2	1.4
240	19.3	1.2	12.1	1.3
255	15.5	1.3	11.2	1.3
OVERALL	33.7	8.7	35.1	9.8

Table 2. Vertical illuminance measurements for the HPS system and the initial LED trial installation (LED-1).

Row (ft from pole)	HPS		LED-1	
	Average illuminance (lx)	Max:Min illuminance ratio	Average illuminance (lx)	Max:Min illuminance ratio
75	65.3	1.9	100	2.3
255	57.1	1.3	42.3	1.3

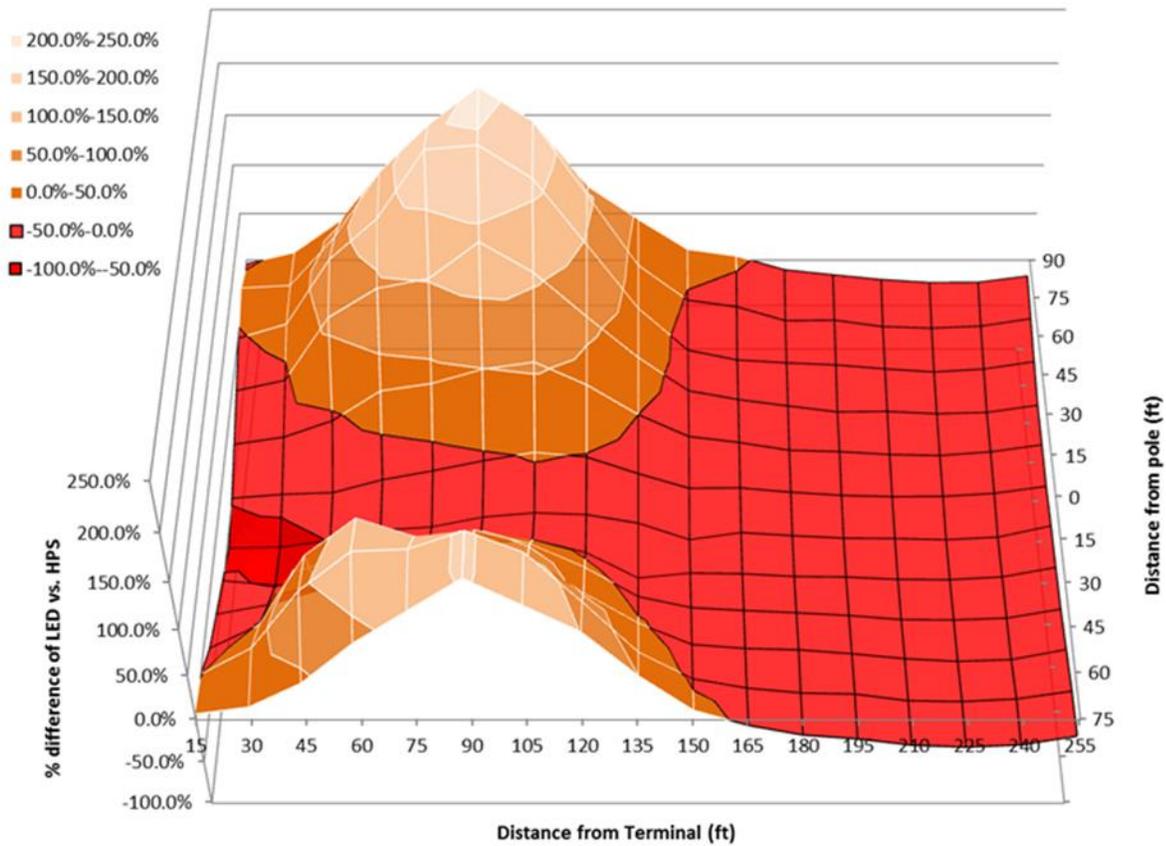


Figure 5. Surface plot of the percentage difference in illuminance for the initial LED trial installation (LED-1) versus the incumbent HPS system. Areas in red illustrate the measurement points where the LED system produced less illuminance than the HPS system, while the areas in orange show the measurement points where the LED system produced greater illuminance. The terminal building and pole location are at the left of this diagram to better show the distribution effects; refer to Figure 4 for details on the measurement grid.

Based on these results from the initial LED trial installation, and in consultation with DOE and the manufacturer's representatives, PHL decided to proceed with a second trial with the following changes:

1. Replace the center luminaire on pole 16 with the same type as used in the other two locations (model FLD-EHO-25), with the luminaire tilted at 70°, similar to the other LED luminaires and the HPS luminaire that had been replaced. The reduced illuminances throughout the central area of the measurement grid were assumed to have resulted in part because of the luminaire type and aiming of the initial center luminaire. One reason that the initial luminaire was horizontal rather than tilted was concern about glare for the pilots using the taxiways that face the lighting poles in this area.
2. Replace the east-facing HPS luminaire on pole 15 and the west-facing HPS luminaire on pole 17 with LED luminaires of the same type and tilt as used on pole 16. This step was recommended because the evaluation of the initial trial installation found that those luminaires from the adjacent poles were contributing light to the measurement area, especially to the rows farther away from the terminal building, so a complete evaluation of the LED system required that those luminaires also be included in the trial installation.

4.3 Procedure for the Second Trial Installation (Trial 2)

The second LED trial installation was completed and evaluated in May 2015. For this trial, three new LED luminaires were installed (model FLD-EHO-25). The LED luminaire from the initial trial that was in the center position on pole 16 was replaced with one of the new LED luminaires. This new luminaire was tilted to the same angle (70°) as the others on pole 16. The rotation of the center luminaire was 0°; that is, it was aimed straight out from the building. The east-facing HPS luminaire on pole 15 was replaced with a new LED luminaire that was tilted to 70° and was rotated to about 45°, roughly matching the rotation of the HPS luminaire it replaced. The west-facing HPS luminaire on pole 17 was replaced with a new LED luminaire that was tilted to 70° and was rotated to about 315°, again roughly matching the rotation of the HPS luminaire it replaced.

After installation it was discovered that the LED luminaire installed on pole 17 was not fully functional. Attempts to resolve this issue in the field, including switching components with the luminaire on pole 15, were unsuccessful, with the result that four of the eight LED arrays were not functioning in the luminaire on pole 15 and two of the eight LED arrays were not functioning in the luminaire on pole 17. Correcting the problems and re-scheduling the evaluation would have introduced lengthy delays; therefore, the evaluation of the second LED trial installation proceeded on the planned date of May 7, 2015, with the inoperable LED arrays remaining in place in the two affected luminaires. Figure 6 shows the setup for the second trial installation.

Measurement protocols during the second LED trial installation (LED-2) were similar to those for the HPS and LED-1 evaluations, except that no color measurements were recorded, and a different unit of the same model of illuminance meter was used.⁷

⁷ T-10A Konica Minolta illuminance meter, serial number 54931049/35921004, calibrated 12/10/14.



Figure 6. Photo of the second trial installation of LED luminaires on pole 16. The difference in CCT (2200 K for the HPS vs. 4000 K for the LED) is apparent, particularly on poles 15 and 17. All LED luminaires were mounted at a 70° tilt.

4.4 Illuminance Results for Trial 2

As shown in Table 3 and Table 4, the LED-2 system performed much better than the LED-1 system, even with the non-functioning LED arrays. The overall average illuminance increased from 35.1 lx to 48.2 lx (compared to 33.7 lx for the HPS system) with the same input power, partially due to the slightly higher efficacy and tilting of the center luminaire on pole 15. More importantly, the distribution of light across the measurement grid was much more uniform, with the max-to-min illuminance ratio at each measurement row less than 2.0 for all rows from 30 to 255 ft. The LED-2 system exceeded the average illuminances produced by the HPS system for all rows from 45 through 180, and provided 20 lx illuminance past 195 feet.

Table 3. Horizontal illuminance data for the HPS system and the second LED trial installation (LED-2). The LED-2 system was measured as installed, with two of the five LED luminaires not producing their full light output – see the accompanying text for details.

Row (ft from pole)	HPS		LED-2	
	Average illuminance (lx)	Max : Min illuminance	Average illuminance (lx)	Max : Min illuminance
15	66.3	3.6	26.2	2.1
30	67.4	4.0	35.9	1.8
45	57.4	2.9	60.9	1.6
60	47.1	2.1	83.8	1.4
75	40.6	1.9	92.3	1.6
90	32.0	1.7	88.7	1.6
105	26.3	1.4	75.8	1.7
120	25.2	1.3	62.3	1.7
135	27.0	1.2	50.3	1.8
150	28.9	1.3	40.3	1.7
165	27.3	1.1	33.3	1.7
180	25.9	1.1	27.2	1.6
195	24.5	1.1	22.9	1.5
210	23.6	1.1	19.3	1.4
225	21.9	1.2	16.6	1.2
240	19.3	1.2	14.3	1.2
255	15.5	1.3	12.7	1.1
OVERALL	33.7	8.7	48.2	9.3

Table 4. Vertical illuminance data for the HPS system and the second LED trial installation (LED-2). The LED-2 system was measured as installed, with two of the five LED luminaires not producing their full light output – see the accompanying text for details.

	HPS		LED-2	
Row (ft from pole)	Average illuminance (lx)	Max:Min illuminance	Average illuminance (lx)	Max:Min illuminance
75	65.3	1.9	147	1.6
255	57.1	1.3	48.2	1.1

Figure 7 shows the percentage difference in the illuminances produced by the LED-2 system relative to those produced by the HPS system. This figure illustrates that the LED-2 system illuminances exceed those of the HPS system throughout the apron areas from 45 through 180 ft (where many of the grounds crew and baggage handling tasks occur), falling below the HPS illuminances beyond 180 ft and at less than about 45 ft. The LED-2 performance would be further improved with all of the LED arrays in the luminaires functioning.

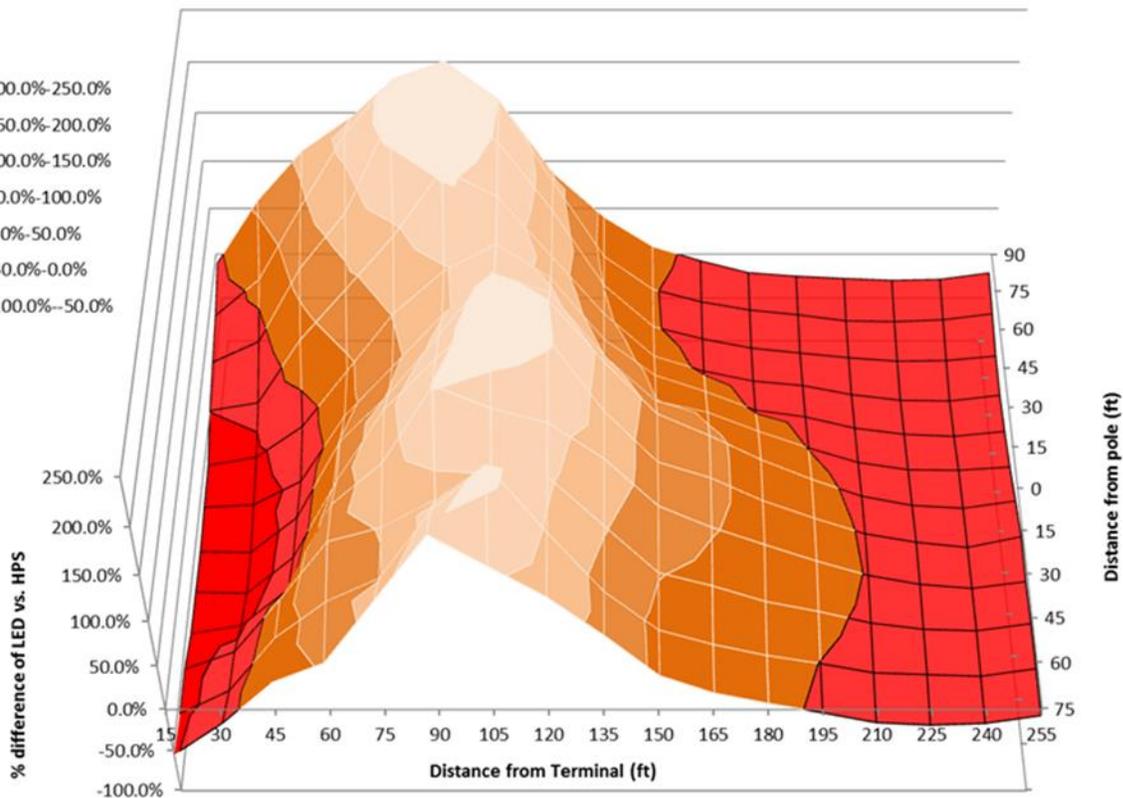


Figure 7. Surface plot of the percentage difference in illuminance for the second LED trial installation (LED-2) versus the incumbent HPS system. Areas in red illustrate the measurement points where the LED system produced less illuminance than the HPS system, while the areas in orange show the measurement points where the LED system produced greater illuminance. The

terminal building and pole location are at the left of this diagram to better show the distribution effects; refer to **Figure 4** for details on the measurement grid.

4.5 User Response

A formal survey of the pilots, air traffic controllers, and ground crew regarding the new LED lighting system was not feasible; however, pole 16 was near one of the ground crew break rooms and provided the opportunity to informally get feedback. There were no negative comments about the new LED lighting system for either trial installations.

One ground crew member described having difficulty reading luggage tags when transitioning between the interior of the plane and the exterior, and noted that typically the crew uses their mobile phones to provide enough light to read the tags. This individual commented that it would be easier for the baggage handlers to read the luggage tags under the new lighting because the color and amount of light was similar to the lighting in the cargo section of the airplane. For interior applications, the IES 10th Edition Handbook recommends an illuminance level of 300 lx for reading 10 point size font. Exterior illuminance requirements are lower than interior due in part to the adaptation of the visual system, but this highlights the difficulty of reading small font sizes while trying to quickly retrieve luggage from the interior of a plane –which happens every time a passenger checks a bag but does not board the plane on time. The difference between the yellow color of the HPS and white color of the interior plane lighting as well as supplemental lighting is illustrated in Figure 8.



Figure 8. Airplane interior lighting compared to PHL HPS apron lighting. The cargo hatch of the airplane is raised, revealing the white color of the interior lighting as well as the supplemental lighting on the cargo loader. The yellow color of the PHL HPS apron lighting system can be seen below and on top of the plane.

No measurements of the interior plane lighting or any equipment were recorded, but color measurements were taken during the initial LED measurements to help characterize the visual difference between the HPS and LED lighting systems. The color measurements were taken at 15 ft spacing in row 75, at a height of 4 ft facing the terminal building, to simulate what a crew member might experience while working on the apron. The measurements did not characterize a single luminaire or type of luminaire (the terminal building had ceiling-mounted HPS luminaires), but did capture the effect of the luminaires on the visual environment near the terminal building. The average CCT measured for the HPS system was 2058 K, in contrast to 3316 K for the LED-1 system. The color rendering index (CRI) was 30 for the HPS system and 69 for the LED-1 system. The increase in CCT and improvement in CRI likely contributed to the positive response from the ground crew, as well as the increase in light levels.

4.6 HID Retrofit Solution

PHL evaluated a possible solution that did not require new luminaires, installing a retrofit solution in which the incumbent HPS lamp and ballast was replaced by a metal halide (MH) lamp operated on a high-frequency electronic ballast. This retrofit solution was installed in three luminaires mounted on pole 141 west of terminal A-West, a perimeter area away from terminal gates. For this trial, 320 W Venture Lighting pulse-start MH lamps (rated 22,500 lm) replaced the 1000 W HPS lamps (rated 130,000 lm), and Genesys electronic MH ballasts replaced the HPS ballasts. The luminaires were located at a height of 60 ft and illuminated the plane taxi area. Additional lighting in this area came from three incumbent HPS luminaires on pole 140 and from other HPS luminaires along the west side of Terminal A-West (see Figure 9).

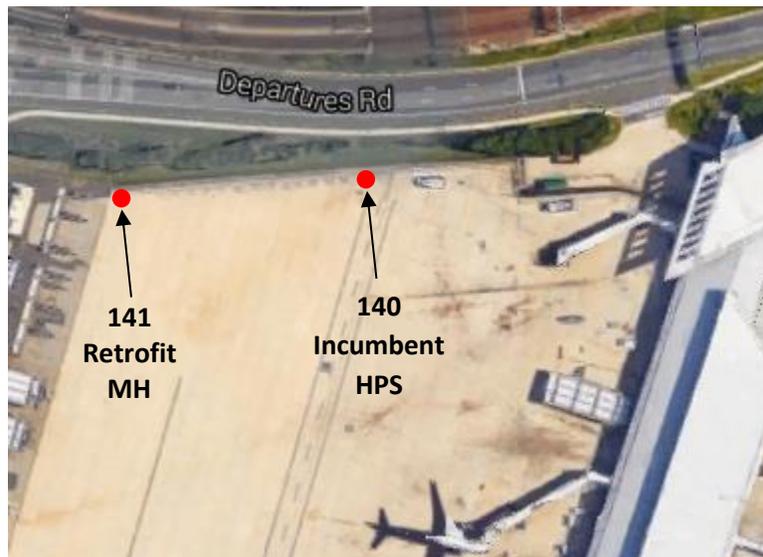


Figure 9. Area of metal halide retrofit. To the east is the A-West Terminal, and to the west is a vehicle battery recharging station for electric Ground Support Equipment (eGSE), with minor activity in the area of the retrofit.

Illuminance levels were measured in this area; however, there was a considerable amount of spill light from the surrounding areas that was impossible to eliminate, especially farther away from the two poles of interest, and the exact aiming of the luminaires was not known. As a result, the illuminance measurements were not considered a viable comparison of the two systems. Consequently, both the incumbent HPS luminaire and the MH retrofit lamp and ballast components were sent to a testing laboratory for further analysis.

The manufacturer of the retrofit solution provides no information on luminaire lumens with the retrofit installed, but states on its website that the 320 W HID lamp-ballast retrofit (noted as a 320 W replacement, rated at 295 W) typically replaces HID lamps up to 1000 W. The results from the laboratory testing (Table 5) show that this is only viable for applications where a substantial decrease in lumen output is considered acceptable – the luminaire lumens decreased from nearly 60,000 for the HPS luminaire to less than 9,000 for the same luminaire with the MH lamp-ballast retrofit.

Table 5. Summary of sphere testing of incumbent HPS luminaire and same luminaire with MH lamp-ballast retrofit.

	Incumbent HPS Luminaire	Retrofit MH Luminaire
Rated lamp output (lm)	130,000	22,500
Luminaire light output (lm)	59,800	8627
Luminaire efficiency	46%	38%
Luminaire input power (W)	1103	274.2
Luminaire efficacy (lm/W)	54.2	31.5
CCT (kelvin; K)	2127	5728
CRI or R _a	28.2	90
Duv ⁸	0.0025	0.0098

Key observations based on these test results are as follows:

- The MH retrofit operated at much lower power than the HPS, reducing the input power by 75%.
- The MH retrofit produced much lower light output than the HPS, with the MH luminaire producing less than 15% of the light output of the HPS luminaire. This is not surprising since the MH lamp itself only produces about 17% of the HPS lamp’s rated light output.
- The MH retrofit reduced the luminaire efficiency and efficacy.
- The MH retrofit has much higher CCT⁹ and CRI than the HPS.

From these findings it was concluded that the resulting illuminances would not meet the target illuminance levels for the apron lighting at PHL, and the retrofit solution was not considered further.

⁸ Duv expresses the distance of the chromaticity coordinates from the blackbody curve. See the DOE SSL Technology Fact Sheet, “LED Color Characteristics,” at <http://energy.gov/eere/ssl/technology-fact-sheets>.

⁹ In certain low-light situations, higher CCT sources may provide more visually effective lighting than indicated by normal light output data. This effectiveness is sometimes expressed in terms of the S/P (scotopic/photopic) ratio. The S/P ratio was calculated based on the spectral power distribution (SPD) measurements provided by the testing laboratory. The S/P ratio was 0.668 for the HPS system and 2.209 for the MH system. However, the S/P ratio is not relevant for this application, because the light levels and related adaptation luminances are relatively high, and photopic quantities are therefore appropriate. A detailed discussion of S/P ratios and their application is provided in IES TM-12-12, “Spectral Effects of Lighting on Visual Performance at Mesopic Lighting Levels.”

5. Discussion

As previously discussed, the motivations for PHL to evaluate options for their apron lighting system included energy savings, reduced maintenance, and possibly increased safety through better illuminance distribution and reduced frequency of lamp or luminaire failures. In a July 2013 report to Congress on injuries and fatalities of workers struck by vehicles on airport aprons, the FAA noted that lighting conditions may have been a factor in six of the nine fatal accidents on airport aprons between 1985 and 2000. Many of the possible solutions that were initially evaluated held the potential for substantial energy savings, but resulted in lower illuminance levels, which was not considered acceptable by PHL given the importance of lighting in maintaining a safe working environment. PHL was committed to at least maintaining their existing illuminance levels, and there were very few viable options for achieving this.

5.1 Energy Savings

With LED systems, multiple light output levels are often available from the same luminaire by varying the drive current provided to the LED arrays (and thus varying the input power to the luminaire). Numerous manufacturers also provide the ability to scale the lumen output of their luminaires by adjusting the number of LED arrays (i.e., packages or modules) in a luminaire. Different intensity distribution options are also available, and can be varied by the manufacturer even within the same luminaire. Advances in LED technology now allow for a single outdoor luminaire model to be used for all locations for a particular lighting application, even when the characteristics of the locations vary, helping avoid under-lighting or over-lighting. These features provide some flexibility for applications such as the PHL apron, where the throw distances at a few gates may be quite long, while at many other gates the throws are shorter and areas narrower. Higher light output (and higher power) luminaires can be used for longer throws, and lower light output (and lower power) luminaires with varying optics can be used in other smaller areas with shorter throws, potentially saving energy.

The luminaires used for the trial installation at PHL were operating with a 1000 mA drive current (831 W and 73,303 lm), but a 700 mA drive current (533 W and 54,588 lm) was also available (in addition to different array and optics options). Because the trial installation was conducted in an apron area where the largest aircraft may be present, the 831 W option was specified. But in many of the other apron areas at PHL, the 533 W luminaires may be suitable for meeting the target illuminance criteria. The final solution is expected to be a mixture 533 and 831 W luminaires, with the estimated energy savings depending on the proportion of each type used.

Table 6 shows the estimated annual energy use for the PHL apron lighting system for each terminal, comparing the incumbent HPS system to an LED system that uses high output luminaires and an LED system that uses medium output luminaires. Overall, an LED system using all high output luminaires would save an estimated 430,021 kWh (24.5%), and an LED system using all medium output luminaires would save an estimated 906,401 kWh (51.5%).

Table 6. Annual energy use for apron lighting system at PHL, assuming dusk-to-dawn operation (11.2 hours per day on average). Luminaire power draw values are from photometric test reports and include ballast / driver power.

TERMINAL	NO. OF LUMINAIRES	ANNUAL ENERGY USE (kWh)		
		HPS (1100 W)	HIGH OUTPUT LED (831 W)	MED OUTPUT LED (533 W)
A	106	477,938	361,060	231,582
B	37	166,827	126,030	80,835
C	32	144,283	108,999	69,912
D	48	216,425	163,499	104,868
E	69	311,110	235,030	150,747
F	98	441,867	333,810	214,105
TOTAL	390	1,758,450	1,328,429	852,049

The actual savings realized by a full implementation of LED luminaires will fall somewhere between 24.5% and 51.5%, depending on the mix of high and medium output LED luminaires installed. Figure 10 plots the linear relationship between the annual energy savings and the percentage of medium output LED luminaires used. Although the exact number of each type needed depends on a careful analysis of the apron lighting needs served by each pole, the majority of the gate areas have shorter required throws than the area used for the trial installation. If the final mix of luminaire types is 80% medium output and 20% high output, for example, the energy savings realized will be 46.1%.

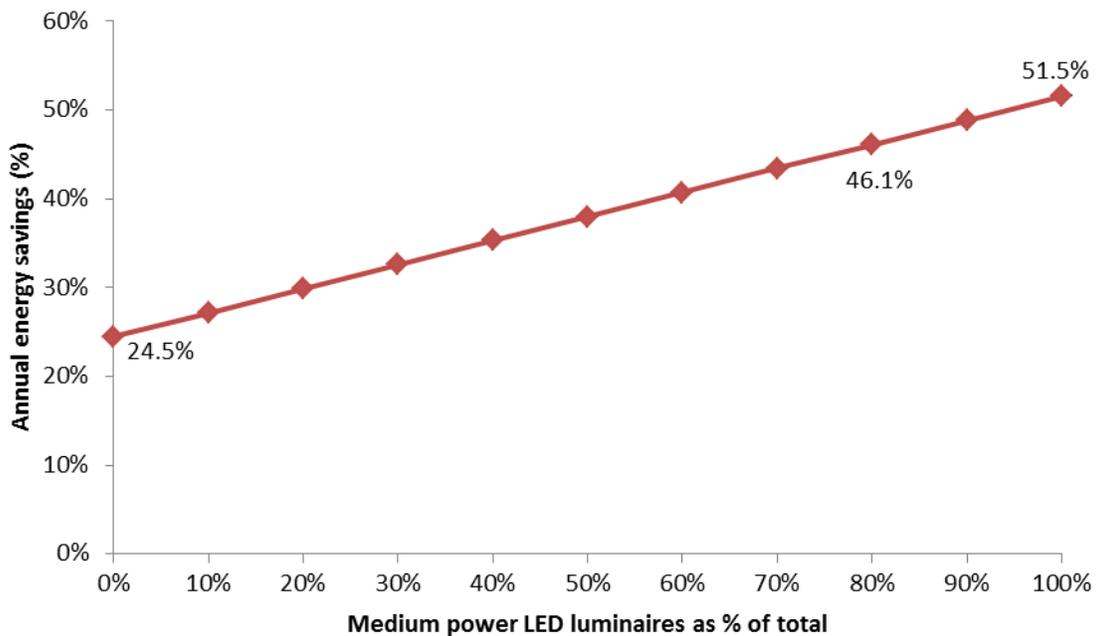


Figure 10. Annual energy savings of LED system vs. HPS system for the PHL apron areas, based on the different combinations of medium-power (533 W) and high-power (831 W) LED luminaires implemented.

The analysis above is limited to comparing the two different light output (input power) options available for the 240-LED FLD-EHO-25-AA (25° flood distribution) luminaires used in the Trial 2 installation. However, the manufacturer offers many other options in this same luminaire style, including different numbers of LED arrays, different optical packages and beam patterns, and different drive currents (resulting in different power and light output levels). A comprehensive, optimized design for the PHL apron lighting system could result in a combination of several other luminaire types that may further vary in their input power to meet the specific lighting needs in different sections of the airport. A complete energy and economic analysis for this application therefore depends on the detailed design that is yet to be completed. Furthermore, LED technology continues to evolve, and luminaire manufacturers frequently release updated products with higher luminaire efficacy, often at lower costs. Large-scale projects such as this often require several re-designs and re-assessments of the energy and economic analyses during the months that the project is under consideration before implementation.

5.2 Illuminances and Lighting Distribution

Although the average illuminance initially calculated for the Trial 1 demonstration exceeded the target illuminance, the measured data during the Trial 1 evaluation showed that the distribution of illuminance was not acceptable, with many measurement points having lower illuminance than the HPS system produced. This finding reinforces the limitations of using the average illuminance to characterize complex distributions such as those for this installation.

The Trial 2 evaluation demonstrated that the LED solution provided higher illuminances than the incumbent HPS system throughout the key task area from 45 to 180 ft from the terminal building, which encompasses the work areas for baggage handlers and other grounds crew members for the various plane sizes at PHL. In fact, from 60 to 135 ft the LED system produced illuminances that were more than 100% higher than those from the HPS system (Figure 7), even with two of the five LED luminaires functioning below their full output. This demonstrates the potential for greater energy savings with medium-output LED luminaires for the majority of gates with smaller apron areas, rather than the high-output luminaires used in the Trial 2 installation.

At most throw distances beyond 195 ft, the LED system produced lower illuminances than the HPS system. While the luminaires that were functioning at less than full output during the trial are expected to contribute additional illuminance to these points when operating at full output, it is unlikely that even a fully functioning LED system would equal or exceed the HPS system at all of the grid points with these longer throws. Since there are few if any demanding visual tasks occurring at these throw distances, the illuminances provided are expected to be considered acceptable by PHL. One possible exception is for gate areas where longer planes are expected, where high-output LED luminaires may be necessary to ensure adequate illuminances along the entire length of the plane.

Part of the difficulty in assessing the adequacy of the illuminances throughout the evaluation area comes from the lack of any established design criteria for apron areas at airports. Until FAA provides new guidance or the IES publishes the new Recommended Practice, airport facility managers and designers must rely on their own experiences and judgment to establish lighting performance criteria for airport aprons. However, this leaves many airport facility managers in a predicament given liability and safety concerns.

The trial evaluations at PHL illustrate that opportunities exist in this application for lighting system optimization that could produce substantial additional savings in energy use by leveraging inherent advantages of LEDs. First, the conventional approach to this application is to flood the entire apron area with relatively high and uniform

illuminances. This approach makes sense for HPS and other HID systems, where each luminaire has a single, high lumen lamp. For these luminaires, precise control of the light is difficult, and there are no opportunities to direct portions of the luminaire's light output to different parts of the target area. Because LED luminaires use many smaller sources, each of which can have its own discrete optics, the possibility exists to optimize the distribution of light from the lighting system to address specific task needs. For example, the demanding task areas within an airport apron are relatively localized to the vicinity of the gates and jetways, with large portions of the apron having no demanding visual task needs. As a result, lower illuminances may be adequate throughout much of the apron, with higher illuminances required only where necessary to address visual task needs. LED systems potentially provide greater flexibility for achieving this type of variable criteria in an application such as airport apron lighting.

The second opportunity for additional energy savings with LED apron lighting systems involves the use of lighting controls. Incumbent HID systems such as the one at PHL typically operate at full output throughout the entire apron area from dusk to dawn, regardless of activity level. The inherent dimmability of LEDs provides opportunities to reduce the illuminances in the areas around certain gates where no activity is scheduled, resulting not only in greater energy savings but also in a reduction in any contributions from the apron lighting system to light pollution. An apron lighting control system with some combination of motion detection, time scheduling, and manual override capability could provide substantial benefits in these areas.

6. Lessons Learned

The discussion above focused on the results of the trial installations and the expected energy savings and photometric performance of an LED lighting system for the PHL apron areas. As shown, this type of high-mast application with demanding visual needs (and the corresponding high illuminances) remains challenging for LED technology. The following lessons learned from this project may help facility managers and LED product manufacturers better meet the challenges for these applications.

- *Need to establish clear design criteria and constraints for the LED project.* The only way to fairly evaluate the many options available for a large-scale LED project is to establish clear criteria at the project outset. For example, early in the PHL project the facilities staff established guidelines such as the following:
 - One-for-one luminaire replacement to eliminate the need for additional pole locations and power distribution wiring.
 - CCT in the range of 4000-4500 K.
 - Minimum luminaire light output of 60,000 lm. (This requirement coupled with the CCT requirement actually eliminated many options from further consideration, saving review time for the PHL staff as they vetted different proposals.)
 - Illuminance levels that equaled or exceeded the existing system.
 - No increase in complaints from pilots about glare or from grounds crew members about visibility, glare, color, or other lighting attributes.
 - Product warranty of at least five years.
- *Importance of trial installations and mock-ups.* While detailed computer analyses can help to assess illuminances in different areas of an application, they cannot replace the experience of viewing a trial installation under realistic conditions. For example, calculated illuminance ratios provide some insight into illuminance uniformity, but the visual experience of uniformity depends on variables beyond the ratios such as the distances between points of high and low illuminance, the relative brightness of the surrounding areas, and other factors that cannot be fully assessed through simple illuminance calculations. Similarly, human response factors such as glare, color quality, and satisfaction can only be assessed through one or more trial installations. Finally, a trial installation is an important vehicle for verifying the actual installed performance relative to the predicted performance through calculations.
- *Careful review of calculations of photometric quantities.* PHL staff received many inquiries from luminaire manufacturers and sales agencies, who often provided computer analyses of their proposed solutions for the apron lighting areas. Unfortunately, some of these sales efforts failed to accurately reflect the system requirements in an attempt to improve the apparent suitability of the proposed solution. The following apparent ploys were seen from different companies as part of the product vetting and selection process:
 - Use of photometric data for a higher CCT LED luminaire than desired, resulting in higher lumen output and efficacy than the desired CCT would provide.

- Use of unreasonably high light loss factors (or even ignoring light loss factors) instead of factoring in the expected system depreciations due to LED lumen degradation and luminaire dirt depreciation.
- Unrealistic optimization of the system by specifying aiming angles that were not practically achievable in the field. For example, at least one manufacturer specified luminaire tilt angles to the third decimal place for luminaires which could only be adjusted in five-degree increments.
- Addition of luminaires in locations where there were no incumbent luminaires or poles, or re-aiming nearby luminaires into an area being calculated (thereby compromising other areas) to increase the apparent performance of the system.
- Use of average illuminance as a single metric for comparison, without adequately characterizing distribution differences between options. The risk of this type of over-simplified analysis was shown by the Trial 1 installation for this project, where the LED system produced a higher average illuminance than the HPS system, while a more thorough review of the distributions produced showed that the LED system was not adequate.

Appendix A: Illuminance Measurements

Full set of HPS measurements. The color in each square represents the relative measured illuminance quantity: Red – high horizontal; Yellow – medium horizontal; Green – low horizontal and vertical; Purple – high vertical.

	75	60	45	30	15	Pole	15	30	45	60	75	90
15	44.8	41.0	79.9	96.3		116	116	78.9	48.1	41.0	32.5	34.3
30	54.1	46.9	66.6	80.2	103	120	92.1	71.1	59.2	47.2	37.6	30.1
45	54.0	44.9	50.6	70.8	81.4	84.7	74.6	64.2	53.2	44.1	36.3	29.6
60	42.6	41.1	40.8	53.8	60.6	61.3	62.0	57.0	47.3	39.5	30.3	29.1
75		41.3	40.2	47.0	47.7	51.5	52.0	45.6	37.2	29.5	27.5	27.4
90	31.1	30.4	33.4	32.0	38.3	39.1	40.5	35.1	27.6	25.7	24.1	26.1
105		27.8	26.6	27.1	30.8	30.2	29.6	25.6	23.4	22.6	21.8	24.2
120	28.3	27.3	27.0	24.2	24.6	27.6	26.3	23.6	22.5	21.7	23.3	25.9
135	27.5	28.5	27.7	25.3	29.1	27.7	27.4	26.1	25.1	25.3	26.8	27.1
150	28.3	29.4	30.0	29.9	29.8	24.7	28.8	27.8	28.2	31.2	30.1	29.1
165	27.0	27.4	27.5	27.4	26.9	25.5	25.6	26.9	28.6	29.0	28.5	27.2
180	25.1	25.4	25.1	25.3	24.9	24.8	25.0	27.0	27.0	27.9	27.0	26.6
195	23.1	24.0	23.6	23.1	23.8	23.9	24.3	25.2	25.7	26.5	25.6	24.8
210	22.4	22.2	22.3	22.4	22.6	23.7	24.6	24.7	25.1	25.2	24.5	23.5
225	20.4	20.0	20.5	20.5	20.9	22.0	22.4	23.9	24.5	23.3	23.0	21.5
240	17.5	18.1	17.3	17.9	18.5	19.7	20	21	21.6	21.3	19.9	18.5
255	13.8	14	13.9	14.4	14.5	15.3	16.3	17.1	17.6	17.4	16.7	15.5
Illuminance Vertical												
75			66.9	72	76.7	83.6	84.2	76.2	57.7	47.1	44.2	44.3
255	48.5	51.5	52.6	53.1	53.9	56.1	60.6	64	64.8	63	60.4	56.6

Full set of LED-1 measurements. The color in each square represents the relative measured illuminance quantity: Red – high horizontal; Yellow – medium horizontal; Green – low horizontal and vertical; Purple – high vertical.

	75	60	45	30	15	Pole	15	30	45	60	75	90
15	47.8	40.6	61.0	61.9		48.3	59.8	52.7	39.6	39.9	35.8	32.9
30	62.1	60.3	68.6	60.2	48.8	51.0	51.5	53.2	55.6	53.2	42.5	32.5
45	76.6	86.1	90.9	65.4	42.1	42.8	43.2	59.9	86.0	80.1	59.7	42.0
60	79.1	95.7	89.4	75.3	45.1	38.2	45.0	71.8	90.9	88.1	69.9	52.1
75		97.2	80.4	67.2	42.5	34.0	43.0	61.1	75.2	85.8	76.1	59.1
90	79.1	77.3	63.8	50.8	36.9	30.2	38.1	52.4	66.0	75.9	75.5	64.6
105		64.5	46.6	38.9	30.7	24.8	30.6	40.2	48.8	59.4	61.2	56.8
120	56.1	49.0	37.5	28.5	21.0	22.1	25.8	31.3	36.6	42.7	48.5	46.0
135	41.3	35.3	29.1	21.4	16.3	19.5	21.8	26.1	29.8	32.8	36.1	38.9
150	31.4	27.5	24.2	21.5	18.4	12.7	18.1	21.0	23.2	26.2	29.2	32.5
165	25.3	22.7	20.9	18.8	16.4	15.2	16.2	18.5	20.7	21.2	25.6	28.4
180	20.7	19.6	18.7	16.7	14.4	13.9	14.6	16.2	17.6	19.5	20.1	23.8
195	18.0	18.2	16.5	14.5	13.6	12.7	13.3	14.7	15.0	17.9	19.2	20.8
210	15.8	15.1	14.3	13.0	12.3	12.5	13.1	13.6	14.8	15.9	16.6	18.5
225	13.9	13.4	12.5	11.8	11.3	11.3	12.0	12.9	13.8	13.9	15.2	16.2
240	12.4	12.7	10.9	10.7	10.6	10.7	11.4	12.2	12.5	13.4	13.6	14.0
255	11.2	11.1	10.4	10.1	9.9	10.3	10.6	11.3	11.6	12.4	12.8	12.8
Illuminance Vertical												
75			127	104	70.6	57.8	73.1	101	125	135	119	88.9
255	41.6	42.2	39.2	37.7	37.1	38	39.9	42.2	44.7	46.6	48.4	49.9

Full set of LED-2 measurements. The color in each square represents the relative measured illuminance quantity:
 Red – high horizontal; Yellow – medium horizontal; Green – low horizontal and vertical; Purple – high vertical.

	75	60	45	30	15	Pole	15	30	45	60	75	90
15	20.3	16.1	30.9	27.5		30.1	34.6	25.2	24.3	25.4	23.4	30.7
30	45.3	31.5	39.9	31.1	26.7	29.7	30.3	29.8	35.3	40.4	42.5	47.7
45	70.9	58.2	61.5	58.2	56.1	56.3	45.3	49.9	69.7	73.3	69.4	62.3
60		70.0	76.1	95.9	94.5	93.7	83.7	79.9	87.9	88.8	80.4	71.0
75		81.0	81.1	105	111	105	98.1	92.3	89.7	94.3	87.9	70.5
90	91.1	81.4	77.3	96.8	109	104	98.3	86.4	84.9	84.9	81.2	69.0
105	70.2	87.7	63.0	75.8	103	98.8	84.3	70.0	65.7	66.9	65.3	59.8
120	64.4	67.1	69.2	64.1	75.3	82.9	69.8	56.3	49.5	49.4	50.7	48.3
135	51.0	51.8	56.4	57.6	67.3	66.0	54.9	45.6	40.0	37.5	37.1	38.1
150	39.5	40.7	45.6	52.8	52.7	45.2	43.6	37.6	31.7	31.9	30.6	31.5
165	32.2	33.4	37.7	41.9	42.9	40.6	35.6	31.5	27.4	25.7	25.0	25.1
180	26.9	27.7	29.9	33.8	33.4	32.9	29.5	26.0	22.8	21.8	21.2	21.0
195	22.2	23.9	25.4	26.5	27.2	26.4	24.1	22.3	20.4	19.2	18.7	18.6
210	18.9	19.7	21.0	22.0	21.8	21.6	20.3	18.7	17.3	16.9	16.2	17.0
225	16.6	17.3	17.8	18.0	18.1	17.7	16.6	16.4	15.3	14.7	15.0	15.1
240	14.6	15.3	14.7	14.8	14.9	15.2	14.7	13.9	13.3	13.6	13.4	13.2
255	12.8	13.1	13.0	13.1	13.5	13.1	12.6	12.3	12.0	12.0	12.4	12.2
Illuminance Vertical												
75			133	159	175	163	154	145	145	149	140	110
255	47.8	49.4	50.2	50.4	50.1	49.8	48.9	47	45.5	45.9	46.3	46.7