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GATEWAY Demonstrations

Exterior LED Lighting Projects at Princeton University

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Prepared by:

Pacific Northwest National Laboratory

Exterior LED Lighting Projects at Princeton University

Final Report prepared in support of the DOE Solid-State Lighting Technology GATEWAY Demonstration Program

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Preface

This report has a broader scope than previous GATEWAY reports in that it covers a series of projects at Princeton University that have been implemented since 2008. Most GATEWAY projects take an in-depth look at a single project at a host site, in many cases carefully documenting the before and after conditions as the host organization transitioned from conventional lighting technology to solid-state lighting (SSL). Detailed photometric and energy measurements are often collected at the site and analysis of those data included in the project report. But for this report, the U.S. Department of Energy (DOE) studied a series of past projects at Princeton, in order to document Princeton's experiences with SSL and the lessons learned along the way, and to show how their approach to SSL projects evolved as their own learning expanded and as the products available improved in performance and sophistication.

In covering a broader scope in both time and in the number of SSL projects, the data collection and analysis does not have the depth that is typical of other GATEWAY projects. Energy savings are estimated based on product ratings and different assumed scenarios for operating conditions; power levels, operating hours, and photometric performance were not independently verified. While the details of each project are documented herein, the main value for the GATEWAY audience comes from the overall principles and lessons learned along the way.

This project also differs in its communication approach. In order to support the broader scope and the focus on overall principles and lessons, this document is composed of a series of graphics displaying the important features of each individual SSL implementation project at Princeton. After an overview of Princeton's efforts in Section 1, each of the following four sections (Sections 2 through 5) features a specific SSL project. These sections begin with a brief project synopsis, after which the story for each project is presented through a series of figures and accompanying text, concluding with a summary of the estimated energy savings from the project and the key lessons learned. The report concludes with an overall summary of the early Princeton experiences with SSL, in Section 6.

Contents

1.0 Introduction

1.1 Princeton background and sustainability initiatives

"In the Nation's Service and in the Service of All Nations."

This unofficial motto reflects Princeton University's commitment to providing its students with the resources needed for leadership and service to the nation and the world. Chartered in 1746, Princeton is the fourth-oldest college in the US, and part of the Ivy League system. As of the 2013-2014 academic year, Princeton was home to 7,910 students and 6,323 employees, with 98% of the undergraduate students living on campus.[5] Annually, the University attracts 790,000 visitors and generates approximately $2 billion in economic activity to the region.

Former President Shirley M. Tilghman claimed, "Princeton University's campus is one of its most precious assets."[6] With 180 buildings occupying 12-13 million square-feet on 500 acres, the architecture at Princeton spans four centuries and represents a variety of styles, including Colonial, Collegiate Gothic, Italianate, Romanesque, and Modern.[7]. Princeton strives to integrate the principles of sustainability across all campus systems, and to lead by accelerating implementation of sustainable solutions locally and globally. By engaging the campus as a living laboratory for sustainability, students are actively engaged with the local ecological, social and economic environment, which serves as a microcosm of global challenges and possible solutions.

To further these efforts, Princeton adopted a comprehensive Sustainability Plan in 2008. The Sustainability Plan identifies three priority areas — greenhouse gas emissions reduction; resource conservation; and research, education and civic engagement. As a key feature, Princeton has committed to reducing its greenhouse gas emissions to 1990 levels by 2020 without the purchase of market offsets. In the next decade, the sustainability plan will inform the further development of the campus as almost two million square feet of additional building space is anticipated. Figure 1 shows that Princeton has been able to reduce CO_2 emissions even during a time when the campus was growing.

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5 *About Princeton University*: http://www.princeton.edu/pub/profile/about/.

6 *A Sustainability Plan for Princeton*: http://sustain.princeton.edu/sites/sustainability/files/Sustainability%20Plan.pdf.

7 *Buildings & Architects*: http://www.princeton.edu/main/about/facts/buildings/.

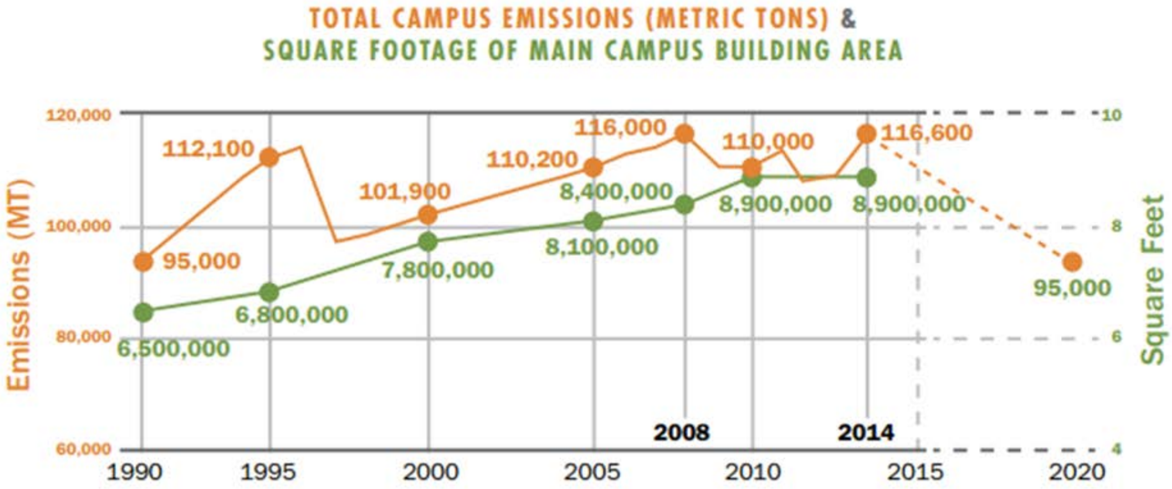

Figure 1: Carbon reductions during campus expansion at Princeton.[8]

1.2 Princeton's experiences with solid-state lighting

Princeton views lighting as playing a major role in its commitment to large reductions in energy use and to a reduced carbon footprint, and the Princeton facilities staff recognized the potential benefits of SSL from the early days of the technology. According to Art Murphy, Energy Project Manager in Princeton's facilities group, "We started learning about LED lighting back in 2006-2007, and realized that its higher efficacy and easier controllability presented new opportunities for our campus in upgrading some of our older lighting systems." In 2008, Princeton installed its first LED exterior lighting system.

Princeton's experiences with SSL parallel the evolution of the GATEWAY program in many ways. In 2008, as the SSL technology was rapidly evolving and becoming viable for replacing high-intensity discharge (HID) street and roadway lighting, the first GATEWAY reports were published on small-scale SSL implementations. Similarly, Princeton's first SSL project occurred in 2008, and involved upgrading the seven HID luminaires lighting a pedestrian path along a main entrance road to the campus. From that small initial step, Princeton then began similar small-scale lamp replacement projects in some interior spaces before committing to more extensive exterior applications.

This report focuses on four exterior SSL projects that have been completed at Princeton since 2008. Figure 2 shows those four projects on a general timeline, and Figure 3 shows the locations of those projects on the Princeton campus. Figure 3 also shows the locations of several major interior SSL projects, one which has been completed and two which are in progress or being evaluated for future implementation.

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8 *Sustainability at Princeton*: http://sustain.princeton.edu/progress/energy.

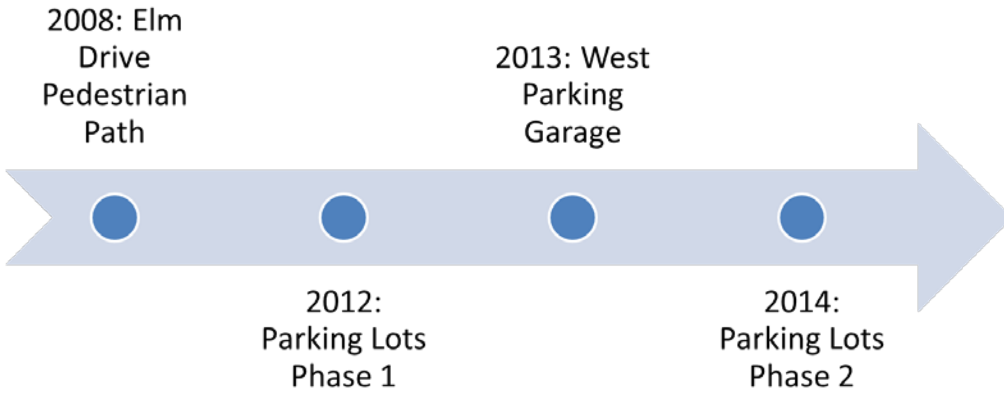

Figure 2: Sequence of Princeton exterior SSL projects. The date shown indicates the year in which each project was completed.

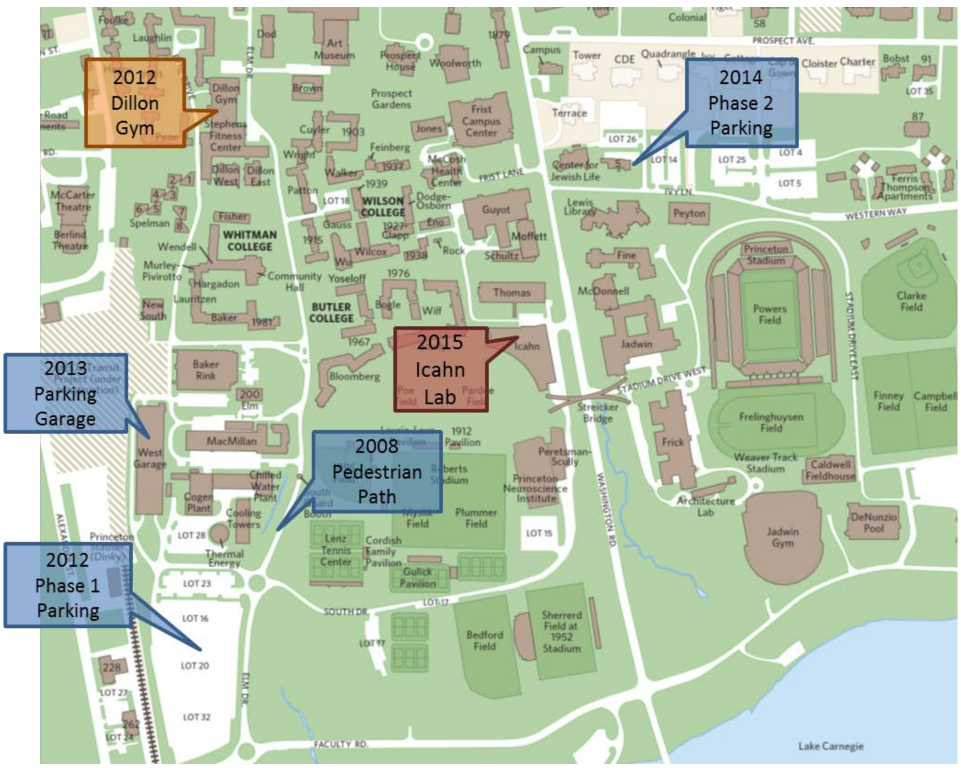

Figure 3: Locations of important SSL projects at Princeton (blue indicates completed exterior projects, yellow indicates completed major interior projects, and red indicates in-process major interior projects).

2.0 Pedestrian lighting on Elm Drive

2.1 Project synopsis

In 2008, Princeton completed their first LED exterior lighting upgrade project by replacing seven high pressure sodium (HPS) luminaires with LED luminaires. The luminaires are located along a pedestrian walkway that runs alongside of Elm Drive and connects parking areas at the perimeter of the campus to several athletic fields and the central campus. The upgrade reduced the wattage and corresponding energy use by over 60%, saving about 2500 kWh annually from just seven luminaires. Beyond the energy savings, the facilities group received anecdotal reports that more students were now using the walkway as some students who previously did not feel comfortable using the path, despite its convenience, reported that they now felt it was a safer area.

2.2 Project story

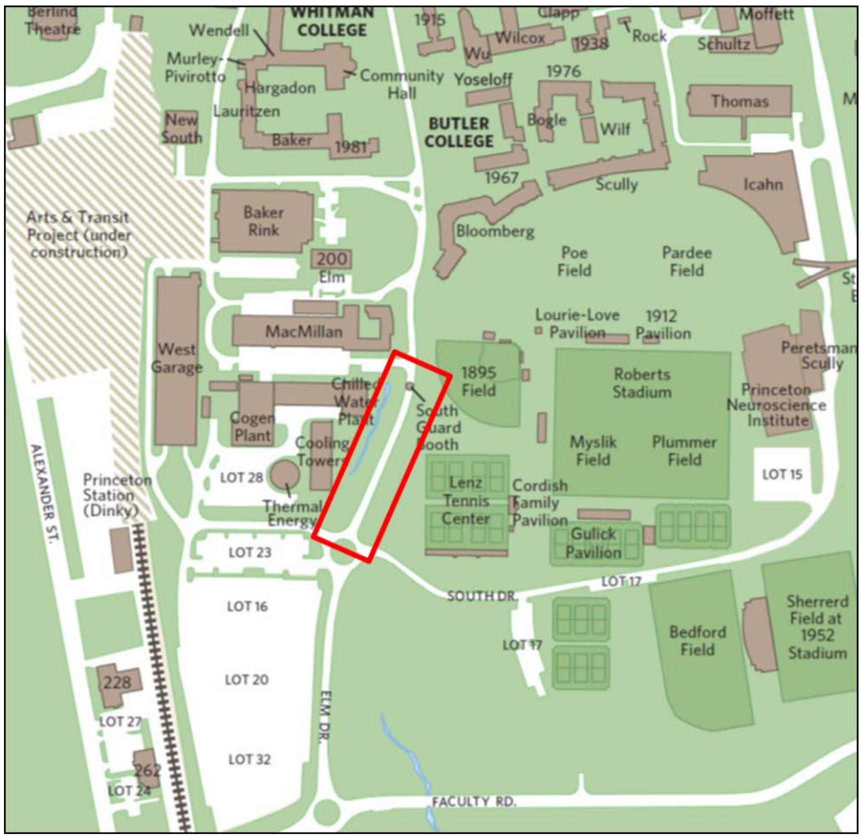

Figure 4: Location of Elm Drive pedestrian lighting project.

The red box in Figure 4 indicates the section of Elm Drive where seven HPS luminaires were replaced with LED luminaires. The pedestrian walkway on the west side of Elm Drive extends from the South Guard Booth campus entrance to the traffic circle near the remote parking lots, and serves as the primary pathway for pedestrians going to and from the main campus and athletic fields to the parking lots.

Figure 5: Elm Drive in the center of campus (left) and near the south end of campus (right).

As shown in the left image of Figure 5, Elm Drive in the center of campus has pedestrian-style HPS luminaires that are closely spaced to provide uniform lighting and good vertical illumination for facial recognition, which is related to perceived safety. The sidewalks are separated from the roadway and bordered by open areas. As Elm Drive approaches the edge of campus (the right image), the pedestrian walkway is close to the roadway and has thick vegetation immediately adjacent to it. The lighting provided by the HPS shoe-box style luminaires was very non-uniform with areas of high brightness directly beneath the luminaires, and dark areas between luminaires. The combination of non-uniform lighting and adjacent areas of heavy vegetation (providing potential hiding places) can reduce the perceived safety of pedestrian pathways.

Figure 6: New LED luminaires along Elm Drive, looking north towards the Guard station at the South entrance (left) and a close-up view (right).

Figure 6 shows the pathway with the new LED luminaires, which directly replaced the prior HPS luminaires, using the same mounting height and pole locations. Although they use less than 40% of the energy of the HPS luminaires, the LED luminaires produced more uniform lighting along the pathway, eliminating the dark areas. Athletic coaches and public safety personnel reported that after the new lighting was installed, more students began using the walkway, presumably because they now felt safer than with the old lighting. They previously used alternate (and longer) routes to avoid walking on the Elm Drive path. The image on the right provides a close-up view of the Edge luminaire from Cree BetaLED®, configured with 40 LEDs and rated for 53 W at an LED drive current of 325 mA. The incumbent HPS luminaires used a 100 W lamp, with total luminaire power (including the ballast) of 135 W. Converting the seven luminaires from HPS to LED reduced Princeton's energy use by more than 2,500 kWh per year.

2.3 Project savings and lessons

The seven incumbent luminaires along Elm Drive operated on dusk-to-dawn photocell controls, which were maintained after the upgrade. So for this application, the savings are entirely due to the reduced power of the LED luminaires relative to the HPS luminaires. The luminaires operate for about 4,304 hours per year, based on dusk-to-dawn operation.[9] Table 1 summarizes the energy savings.

Table 1: Energy savings for the Elm Drive project.

	Incumbent HPS System		New LED System		
No. of Luminaires	Power (W)	Annual Energy Use (kWh)	Power (W)	Annual Energy Use (kWh)	Annual Energy Savings (kWh)
7	135	4,067	53	1,597	2,470

This early project allowed the Princeton facilities staff to test the new LED technology in a small-scale, real-world installation. The positive lessons learned from this installation include:

- Substantial energy savings are possible with LED lighting systems through reduced input power relative to the incumbent luminaires.
- Higher efficacy of LED luminaires make the reduced power possible without compromising light levels.
- Improved optical performance of LED luminaires compared to HPS enable better distribution of light in the application.
- Users within the campus community are aware of the upgrade and apparently have changed their behavior in a positive way as a result.

The Elm Drive installation also posed some implementation challenges at Princeton, which resulted in important lessons for future LED projects.

- The campus uses a 480 V electrical distribution system for its exterior lighting, and at the time of this installation, 480 V LED drivers were not available. So a transformer was added at each luminaire to reduce the voltage supplied to the luminaire to 277 V, from the incoming 480 V. Drivers designed for 480 V operation have since become available, and have been used in newer Princeton exterior LED installations.
- The luminaires installed did not have surge suppression, and several luminaires experienced early failure as a result of electrical surges. Surge suppression is now integral in LED luminaires used at Princeton.
- The change from 2,200 K CCT HPS lamps to 5,400 K CCT LED sources caused some initial concerns, with a few stakeholders concerned that the much higher CCT sources would seem overly bright. Those concerns were resolved through demonstrations and did not arise after the installation. Since the Elm

[9] Based on data available from the National Oceanographic and Atmospheric Administration (http://www.esrl.noaa.gov/gmd/grad/solcalc/)

Drive installation, lower CCT LED sources with high efficacy have become more common, and were used in subsequent projects discussed in the following sections.

3.0 Parking lot lighting, Phase 1 (Lots 16, 20, 23 & 28)

3.1 Project synopsis

The initial parking lot re-lighting project in mid-2012 addressed the existing HID lighting in four adjacent lots on the southwest corner of campus. In these parking lots, 68 HPS luminaires were directly replaced with LED luminaires from BetaLED's Edge family. In addition to the standard dusk-to-dawn control that keeps the luminaires turned off during daylight hours, each LED luminaire also has an integral passive infrared motion detector. Whenever there is motion in the area of detection for a particular luminaire, that luminaire remains on at full output. When no motion is detected during a four-minute period, the luminaire dims to 20% power. The project resulted in over 60% energy savings from the reduced wattage of the LED luminaires, with further savings from the bi-level control based on motion detection, further explained in Section 3.3. Princeton has taken a similar approach with several other parking lot projects since 2012, and they have implemented a different control strategy in some as explained in Section 5.0.

3.2 Project story

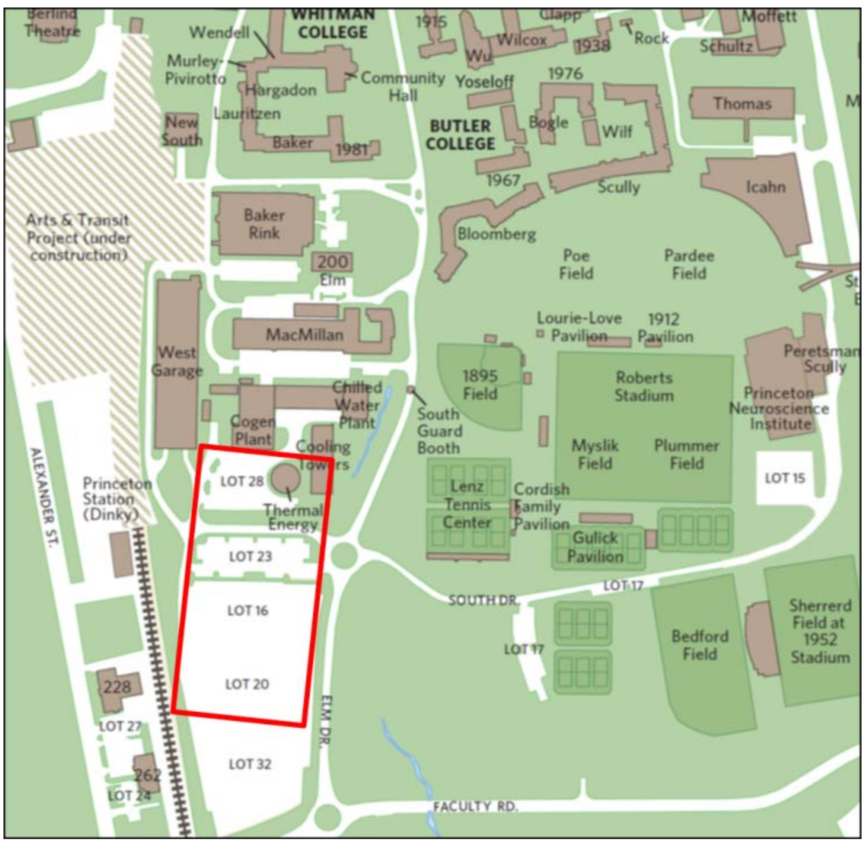

Figure 7: The first surface parking lots upgraded to LED are located in the SW corner of campus.

The first surface parking lots that were upgraded to LED are located in the southwest corner of the Princeton campus, near the main commuter access roads, as shown in Figure 7. Commuters parking in these lots are connected to other parts of the campus by the Tiger Transit campus bus service.

Figure 8: 15' poles with 100 W HPS lamps and 20' poles with 150 W HPS lamps.

Figure 8 shows these parking lots, which had a mix of 15' poles with 100 W HPS lamps (135 W with ballast) and 20' poles with 150 W HPS lamps (189 W with ballast). Each pole is mounted on a 2' concrete base. The HPS luminaires were directly replaced by BetaLED Edge luminaires on the existing poles.

Figure 9: Cree® Edge LED luminaire.

The left photo in Figure 9 shows a typical luminaire used in these parking lots. The Edge LED luminaires have a square or rectangular cross-section, depending on the number of LEDs used, which in turn depends on the desired wattage and light output. The luminaires have an integrated photosensor to enable dusk-to-dawn control, and they offer bi-level control through a passive infrared motion detector, integrated into the mounting arm. The 135 W HPS luminaires were replaced by 47 W LED luminaires; an example pole with two luminaires is shown in the center photo of Figure 9. The luminaires are 18" long (extending 27" in total away from the pole) and 14" wide. Each luminaire has 60 LEDs each, arranged in a 10 x 6 array. The 189 W HPS luminaires were replaced by 68 W LED luminaires shown in the right photo in Figure 9. Each luminaire has 200 LEDs arranged in a 10 x 20 array; these luminaires are 18" long (extending 27" in total away from the pole) and 14" wide. An integrated photosensor and passive infrared motion detector are located on the mounting arm of each luminaire.

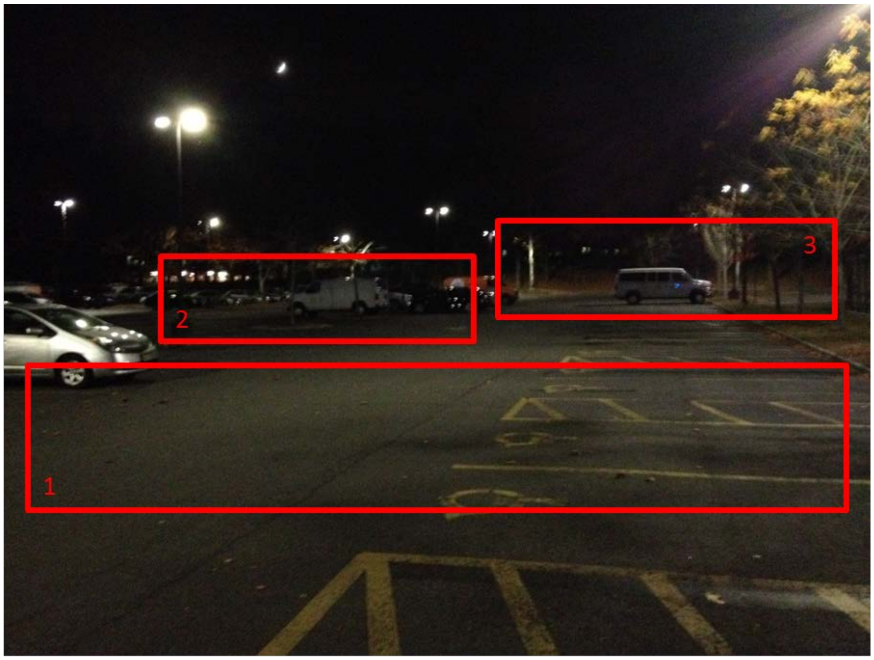

Figure 10: Zones of luminaires at different light output depending on occupancy.

The luminaires lighting the foreground (box 1 in Figure 10) are at full output since they recently detected motion, perhaps from the photographer as he approached. Some luminaires in the distance (zone 2) are at 20% output since there has not been recent motion. Those in zone 3 are at full power, as they sit along the main egress road where there is frequent motion. Princeton found that the factory-default setting of four minutes delay for the motion detectors worked well for this application.

3.3 Project savings and lessons

The incumbent HID system in these parking lots consisted of 48 luminaires on 20' poles with 150 W HPS lamps and 20 luminaires on 15' poles with 100 W HPS lamps. Annual nighttime hours for the dusk-to-dawn operation were estimated to be 4304 hours, and the resultant annual energy use of the HID system was estimated to be 50,666 kWh.

The 150 W HPS lamp luminaires were replaced by 68 W LED luminaires, and the 100 W HPS luminaires were replaced by 47 W LED luminaires. For the same dusk-to-dawn control, the annual energy use of the LED system was estimated to be 18,094 kWh. The estimated reduction in annual energy use for the LED luminaire relative to the HPS system was 32,572 kWh, a savings of 64%. Table 2 summarizes the analysis, without considering the bi-level dimming based on motion detection.

Table 2: Phase 1 parking lot analysis, without bi-level dimming.

	Incumbent HPS System		New LED System		
No. of Luminaires	Power (W)	Annual Energy Use (kWh)	Power (W)	Annual Energy Use (kWh)	Annual Energy Savings (kWh)
48	189	39,046	68	14,048	24,997
20	135	11,621	47	4,046	7,575
TOTALS		50,666		18,094	32,572

Additional savings are realized through the integral motion detectors included in the LED system, which reduce the power to the luminaires to 20% of the full rated power whenever motion is not detected. To estimate the range of potential savings, GATEWAY compared the energy use of the lighting system based on several assumptions regarding the total amount of time that luminaires in the system would be operating at the 20% level rather than 100%. The actual percentage of luminaires operating at 100% or 20% power at any point in time varies widely. For example, during peak access hours all of the luminaires can be assumed to be operating at 100% power, while during late night and early morning hours there are likely to be hours when all of the luminaires are operating at 20% power. At many times it is likely that some of the luminaires will be operating at 100% power while others are operating at 20% power. Princeton has not monitored actual hours of operation at 100% and 20% output levels, but the savings under a likely operation scenario are estimated below.

Figure 11 illustrates the further energy reductions possible through implementation of the bi-level dimming determined by motion detection. For example, considering that there is likely to be little activity in these parking lots during the hours from 2:00 AM to 6:00 AM, and only intermittent activity at some other time periods, an assumption that the overall operation may result in 50% operation at 100% power and 50% operation at 20% power seems reasonable. In this situation, the bi-level dimming reduces the annual energy use to 9,952 kWh, a reduction of 80% relative to the original HID system.

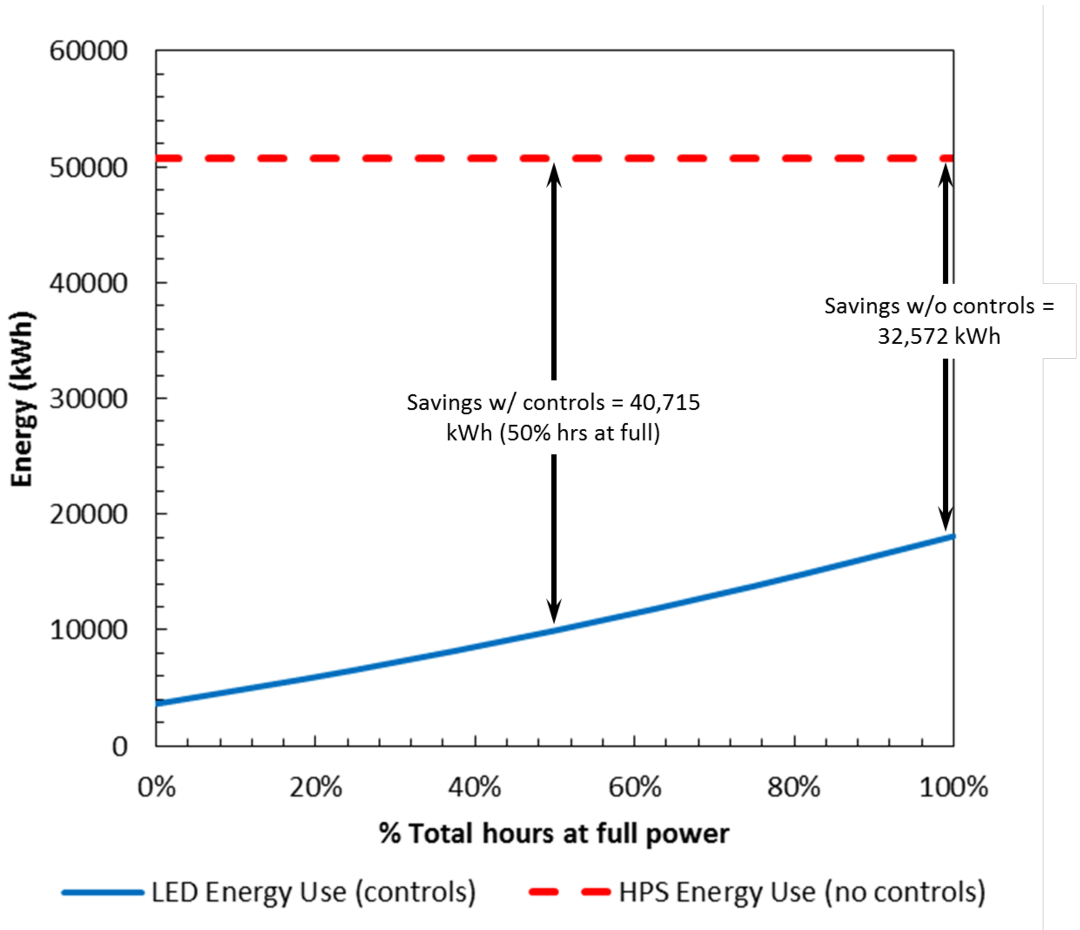

Figure 11: Impact of bi-level dimming controls for Phase 1 parking lots. The right vertical axis illustrates the energy performance of the system when all the luminaires are continuously operating at 100% power during the dusk-to-dawn hours, without any bi-level dimming. The blue curve shows the energy use for the LED system at various assumed reductions in the hours when luminaires are operating at full power; these reductions are produced by the bi-level dimming controls reducing the output to 20% during hours when no motion is detected. Energy savings are indicated for the 100% condition (no bi-level dimming) and for the 50% condition (50% of the time at full power and 50% of the time at 20% power).

The Phase 1 parking lot project broadened Princeton's experience with LED technology with a larger application that entailed several different luminaire wattages and sizes, different pole heights, and the use of motion detection in addition to dusk-to-dawn photosensors for controlling the luminaires. The positive lessons learned from this installation included:

- Relative to the incumbent HPS luminaires, LED luminaires with reduced operating power of 50% or more are viable options for a large-scale parking lot installation,
- The ability to dim LEDs without the complications related to dimming of HPS lamps (e.g. color shift, warm-up time when restored to full power) enable a reduction in power to 20% of the maximum (full) power during times when an integral motion detector on each luminaire does not detect motion nearby, and
- Overall energy savings are greatly increased through the use of motion-based dimming, especially for parking lots with little activity during long periods of the nighttime operating hours.
- The color characteristics of the LED luminaires were much better than those of the HPS lamps, with the LEDs providing higher CCT and much higher CRI. This resulted in improved visibility at night in the parking lot.

Several areas of concern arose with these Phase 1 parking lots, which helped inform future projects.

- While dimming the luminaires to 20% of maximum when no motion has been detected enables substantial energy savings, that technique raised concerns before the installation about the perceived adequacy of the lighting as a person approached the area. In practice, this concern did not seem to affect users, probably because the luminaires still remain on (at 20% output) in an otherwise dark area. Furthermore, since these parking lots are primarily used by students and staff familiar with the area, and the users experienced the increasing light levels as soon as they approached, they soon learned to expect that function upon repeat visits.
- In this installation, each luminaire has its own integral motion detector which only controls the luminaire to which it is attached. So each luminaire individually raises and lowers its output based on motion detection from its own sensor. As a result, a person entering their vehicle may be in a well illuminated area based on their movements but have dimmed areas nearby where no movement has been detected. Although the Princeton facility engineers have not received any complaints related to this functionality, it did cause them to search for and evaluate ways to network their parking area lighting systems into zones rather than depending on individual control. Section 5.0 describes the Phase 2 parking lot installation at Princeton, where a zoned network control system was implemented.

4.0 West (MacMillan) parking garage

4.1 Project synopsis

Following the successful LED implementation project in the surface parking lots on the SW corner of campus, Princeton next upgraded the lighting system in the nearby West Parking Garage (also known as the MacMillan Garage). This garage is the primary parking facility used by faculty and staff. The incumbent lighting in the garage combined 252 metal halide (MH) luminaires that operated during hours of darkness with fluorescent luminaires that operated during daylight hours. In early 2013, the metal halide luminaires were replaced on a one-for-one basis with LED luminaires, and the new LED luminaires were configured to provide lighting both during the day and at night. The LED system saves over 143,000 kWh annually from the reduction in power during nighttime operation alone – over 60% savings compared to the metal halide system – and additional savings are achieved through the use of controls. Each LED luminaire has an integral motion detector and daylight sensor (photocontrol), and the maximum output of each LED luminaire was set to 90% initially. The photocontrol limits the output of the LED luminaire to 50% of its maximum whenever daylight is present, and the motion detector dims the luminaire to 20% power whenever there is no movement detected nearby. The estimated additional savings at night from these controls is about 40,000 kWh annually.

4.2 Project story

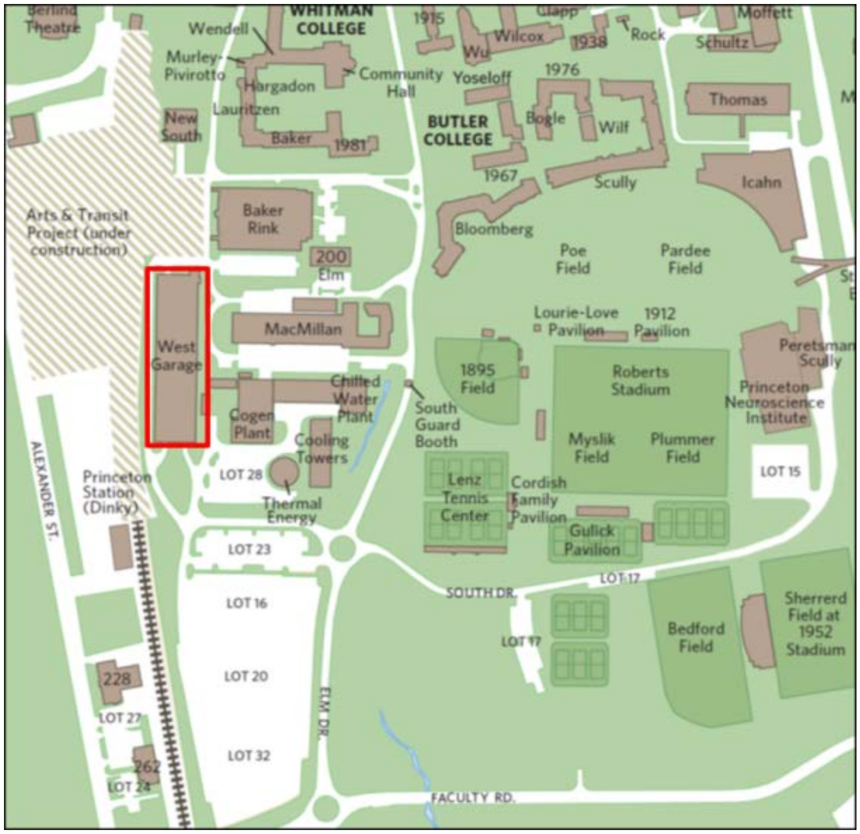

Figure 12: The West Garage is on the SW corner of campus, near the main commuter access roads.

As shown in Figure 12, the West Garage is located in the southwest corner of the Princeton campus, near the main commuter access roads. The garage is adjacent to the largest surface parking lots on campus. With three levels of parking, the garage provides faculty / staff parking that is relatively close to the core campus.

Figure 13: LED luminaires installed in the West Garage.

Princeton installed LED luminaires in the West Parking Garage in early 2013; Figure 13 shows some of these luminaires. The 68 W LED luminaires directly replaced 252 200 W metal halide luminaires. The metal halide luminaires operated continuously at full power during hours of darkness. The output of the LED luminaires was such that the full output setting on the control system was set to 90%, further reducing the lighting energy. This level can be increased as needed later in the life of the LED system as the LED light output depreciates.

Figure 14: An existing fluorescent luminaire (shown in OFF condition), still used for emergency lighting.

During daylight hours with the original system, fluorescent luminaires operated continuously at full power. With the new system, the LED luminaires operate around the clock – at 90% output during darkness and at 50% output during daylight hours, controlled by an integral photocontrol. The fluorescent luminaires remained in place after the LED conversions and provide emergency lighting for the garage in case of a power outage. A fluorescent luminaire is marked by the red oval in Figure 14.

Figure 15: Close-up view of an LED luminaire, with the photocontrol and motion detector in the center of the luminaire.

As shown in Figure 15, each LED luminaire (Beta Cree 304 Series) has an integral photocontrol and passive infrared motion detector. The photocontrol determines whether the luminaire operates at 90% power (nighttime) or 50% power (daytime) when motion is detected. The motion detector dims the luminaire to 20% power after a defined period of detecting no motion.

Figure 16: LED luminaire with widespread distribution (NEMA Type V Medium).

The LED luminaire has a widespread distribution (NEMA Type V Medium) to provide uniform illuminance on the parking surface. Because the luminaires are positioned between the concrete beams, direct glare into the eyes of an approaching driver is minimized. Figure 16 shows that luminaires in the distance are typically shielded from view by the beams as the driver approaches.

4.3 Project savings and lessons[10]

The incumbent metal halide system in the West Parking Garage consisted of 252 luminaires, each drawing 200 W. Annual nighttime usage for the dusk-to-dawn operation was estimated to be 4,304 hours, and the resultant annual energy use of the incumbent system was estimated to be 216,922 kWh. The 200 W metal halide luminaires were replaced by 68 W LED luminaires. For the same dusk-to-dawn control, the annual energy use of the LED system was estimated to be 73,753 kWh. The estimated reduction in annual energy use for the LED luminaire relative to the metal halide system was 143,168 kWh, a reduction of 66%. Table 3 summarizes the analysis, without considering the effect of lighting controls beyond the dusk-to-dawn controls.

Table 3: Comparison of nighttime energy use for lighting in the West Parking Garage.

	Incumbent MH System		New LED System		
No. of Luminaires	Power (W)	Annual Energy Use (kWh)	Power (W)	Annual Energy Use (kWh)	Annual Energy Savings (kWh)
252	200	216,922	68	73,753	143,168

The controls implemented with the new LED system enabled further reductions in energy use in two ways. First, the maximum power was limited to 90% of full power, since the initial installation provided higher light levels than necessary. Second, each luminaire has an integral motion detector, and reduces the power to 20% whenever motion is not detected within a pre-set time period. As illustrated in Figure 17, the additional savings depends on the frequency with which luminaires are assumed to be operating at reduced power (i.e. no motion detected). Given that the garage is primarily used by faculty and staff, there is likely very limited use between the hours of 11:00 PM and 6:00 AM, and the usage is likely even more limited during semester breaks and the summer months. If these times of low usage result in luminaires operating at reduced power for a total of 50% of the overall operating hours, then the total annual energy savings including the controls is estimated to be over 183,000 kWh.

[10] This analysis focuses on the savings at night from the one-for-one replacement of the MH luminaires with LED luminaires. Additional savings during daylight hours relative to the fluorescent system are not included.

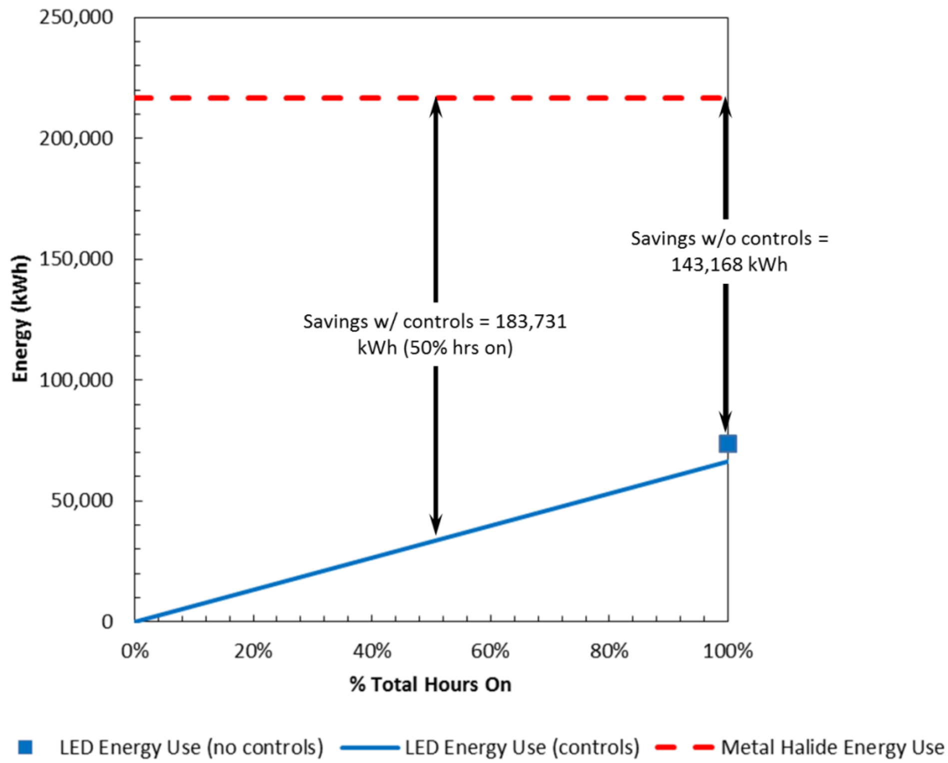

Figure 17: Energy savings from controls. Even at 100%total hours on, the LED energy use with controls is 10% lower than the "no controls" condition since the control system limited the maximum LED power to 90% of the full rated power.

The West Parking Garage project allowed Princeton to use a single LED lighting system for both nighttime and daytime use, along with more sophisticated controls to automatically adjust the lighting to the different application needs during those times. The positive results from this installation included:

- The inherent controllability of LEDs provides opportunities for multiple levels of control during daytime and nighttime hours in a parking garage, allowing the LED system to replace two different incumbent systems that served the application needs at different times.
- Additional energy savings are possible by limiting the input power for a new system to 90% of the maximum, since a new system often provides more light than needed initially. The power limit can be increased over time as the light output depreciates.
- LED parking garage luminaires can be dimmed during times when no motion is detected, since (unlike MH luminaires) they immediately return to full power when motion is detected.

Challenges faced during this project included:

- Emergency lighting for LED systems must be carefully planned and (at the time of this installation) may be overly complicated due to the limited availability of suitable emergency drivers. In this installation, the existing fluorescent system remained in place to provide emergency lighting, due to the lack of availability of suitable emergency lighting options for the LED system.
- As shown in Figure 16, having the luminaires mounted between the concrete beams helps to reduce glare for approaching drivers. However, the beams can interfere with the field of view for the motion detectors, so there is a trade-off between optimal placement of the luminaires for glare control and for

motion detection. Because the LED luminaires were lower profile than the incumbent HID luminaires, the LED luminaires were mounted at a lower height to ensure adequate coverage for the motion detectors, without introducing too much direct glare.

- As noted for the Phase 1 parking lots, the individual motion detection control of the luminaires in this parking garage can create areas of high illuminance surrounded by areas of reduced illuminance. A zoned, network approach for motion detection control, such as that implemented in the Phase 2 parking lots described in Section 5.0, may provide a more favorable solution for users, even though it would likely use more energy than the individual controls.

5.0 Parking lot lighting, Phase 2 (Lots 14 & 26)

5.1 Project synopsis

Early in 2014, 41 new LED luminaires (some 40 W and some 68 W) were installed in parking lots 14 and 26 as part of a major renovation to those areas. The new LED lighting system saved over 60% of the energy that would have been used by a conventional HPS system such as those used in other Princeton parking lots, with additional savings achieved through the use of controls. Each LED luminaire has an integral photocontrol and motion detector, but rather than individual control the luminaires are grouped into zones using a wireless network. This technique allows an area of the parking lot to dim to 20% whenever no motion is detected within that area, but brings the luminaires to full output whenever motion is detected by any one of the sensors in that zone. This can increase the perceived safety in the parking lot, compared to individual control where an adjacent area to a person who is entering his or her car may remain dim. The wireless network control also enabled Princeton to implement a programmed weekly schedule and to override the motion detection system when desired.

5.2 Project story

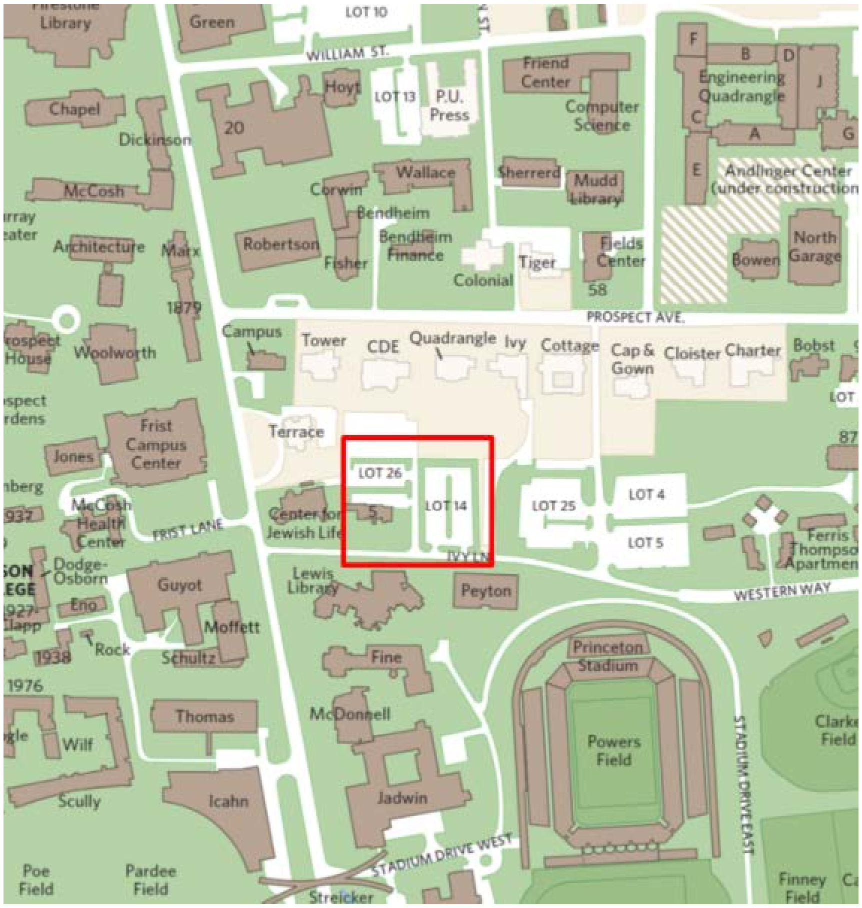

Figure 18: Location and photo of parking lots converted to LED in phase two.

Early in 2014, Princeton installed new parking lot lighting on lots 14 and 26, located in the central part of campus as shown in Figure 18. The 41 luminaires were installed on 15' poles with one or two luminaires per pole, and the system uses a combination of 40 W and 68 W LED luminaires from the Beta / Cree Edge Series. In addition to photocontrol and motion detector controls, a wireless radio frequency (RF) control system was installed to enable zone control of the luminaires.

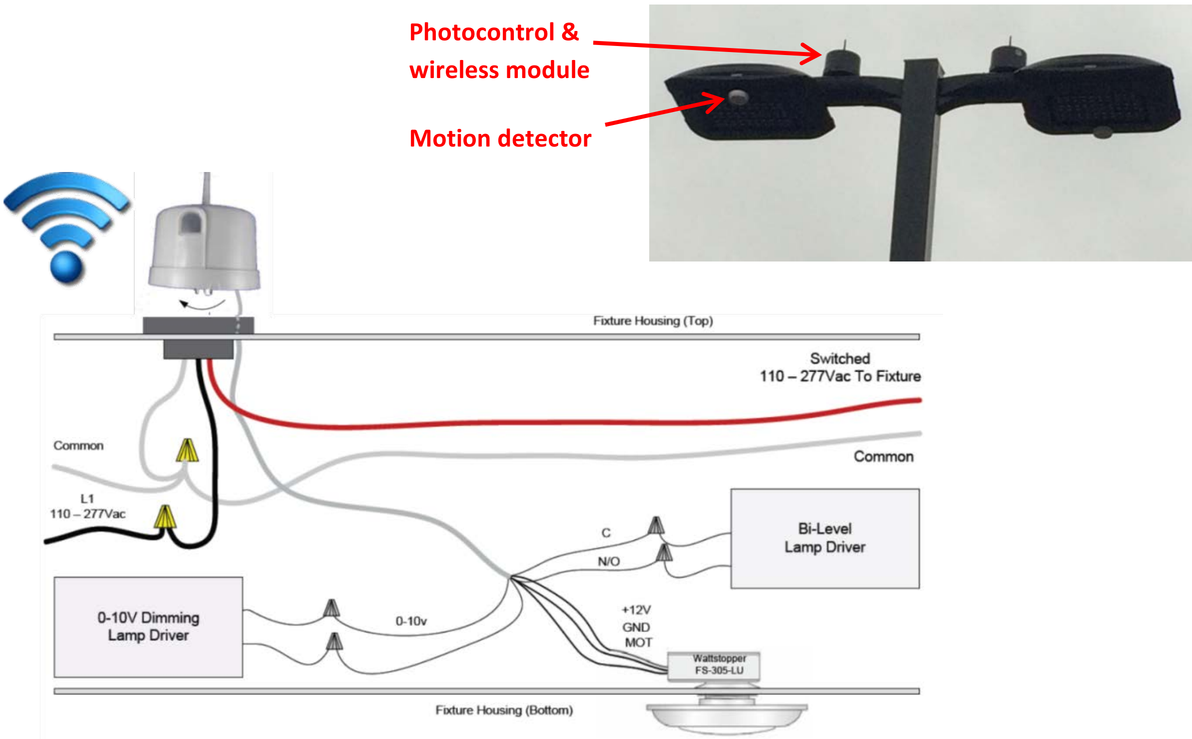

Figure 19: Wireless control module schematic, with photo of two luminaires from the Phase 2 lots. (Schematic diagram from Echelon Lumewave product literature.)

Figure 19 illustrates that the Echelon Lumewave wireless control module fits into the same receptacle as a standard photosensor, but enables RF communication between luminaires. The wireless system can enable bi-level or 0-10 V dimming control, and allows for networking of motion detectors. The motion detector is shown on the bottom of the fixture housing, and sends its control signal to the module. The wireless network looks for any motion detection within the defined zone, and controls all the luminaires within that zone accordingly.

Figure 20: Center for Jewish Life.

The wireless zone control also provides over-ride capabilities for the system. This was important for this phase of Princeton's LED implementation, in part because the parking lots were adjacent to the Center for Jewish Life, shown in Figure 20. Princeton can over-ride the control system so that motion sensor control is disabled during certain religious holidays and events.

5.3 Project savings and lessons

Of the 41 LED luminaires installed as part of Phase 2, 12 were 68W and 29 were 47W. Because this was a new installation, these luminaires did not replace existing HPS luminaires. To evaluate the energy savings, the LED luminaire wattages were compared with wattages of the typical HPS luminaires that Princeton used on other parts of campus and were replaced in the Phase 1 parking lots. Consequently, the 68W LED luminaires were compared to 150 W (189 W with ballast) HPS luminaires and the 47W LED luminaires were compared to 100 W (135 W with ballast) HPS luminaires. As shown in Table 4, the LED system saves more than 17,000 kWh annually relative to a comparable HPS system, based on the reduced power alone. The networked motion detection controls increase the annual savings to nearly 21,000 kWh, assuming as before that the motion detection results in luminaires being in the dim condition 50% of the time during the dusk-to-dawn operation.

Table 4: Estimated energy savings for the Phase 2 parking lots.

	Comparison HPS System		**New LED System**		
No. of Luminaires	Power (W)	Annual Energy Use (kWh)	Power (W)	Annual Energy Use (kWh)	Annual Energy Savings (kWh)
12	189	9,761	68	3,512	6,249
29	135	16,850	47	5,866	10,984
TOTALS		26,611		9,378	17,233

The Phase 2 parking lot project allowed Princeton to gain experience with controlling zones of parking lot luminaires rather than individual luminaires through a wireless network control solution. The lessons learned from this installation included:

- Networked control of parking lot luminaires provides opportunities for controlling groups or zones of luminaires rather than each luminaire being operated by its own dedicated control.
- Controlling a zone of luminaires based on motion detected anywhere in that zone provides increased illumination over a larger area than with individual luminaire control, potentially increasing the perceived safety in that area.
- Wireless control provides the opportunity to implement network controls and to revise the zoning without the complexity of re-wiring the lighting system. The Lumewave control system has since been implemented in several other parking lots at Princeton and the reliability of these early installations has been very good.

Challenges faced during this project included:

- The campus uses a 480 V electrical distribution system for its exterior lighting, and at the time of this installation, the Lumewave TOP900 wireless control module was available for 120 - 277 V operation. As a result, a transformer was added at each luminaire to reduce the voltage supplied to the control modules from the incoming 480 V.
- Implementing the type of irregular scheduling needed for system over-rides during special events must be performed manually as the system software available at the time of installation did not allow for this functionality. Princeton is working with the vendors involved to make this functionality easier to implement in the future.

6.0 Conclusions

Table 5 summarizes the energy savings realized by Princeton from the four exterior SSL implementation projects described in this report. The annual energy savings expected just from the reduced power of the SSL systems relative to their respective baseline HID systems is 195,445 kWh, and DOE estimates that these annual savings increase to 246,995 kWh with the controls solutions that were implemented.

Table 5: Overall summary of the early Princeton SSL projects.

	Comparison HID System		New LED System			
No. of Luminaires	**Power (W)**	**Annual Energy Use (kWh)**	**Power (W)**	**Annual Energy Use (kWh – w/o controls)**	**Annual Energy Savings (kWh) w/o controls**	**Annual Energy Savings (kWh) w/ controls**
Elm Street Pedestrian Path						
7	135	4,067	53	1,597	2,470	2,470
Phase 1 Parking Lots						
48	189	39,046	68	14,048	24,997	39,810
20	135	11,621	47	4,046	7,575	
West Parking Garage						
252	200	216,922	68	73,753	143,168	183,731
Phase 2 Parking Lots						
12	189	9,761	68	3,512	6,249	20,984
29	135	16,850	47	5,866	10,984	
TOTALS		**298,267**		**102,822**	**195,445**	**246,995**

While the economic details of the individual projects are not available to the public, each project satisfied Princeton's internal economic criteria for energy projects. Importantly, the motivating force behind these projects was not just economic. As discussed in Section 1.1, the energy initiatives at Princeton are motivated in part by a commitment to reduce the university's local greenhouse gas emissions to 1990 levels by 2020, and the energy savings from lighting upgrades count directly towards reduced CO_2 emissions from fossil-fuel power generation.

Through these initial projects, the Princeton facilities engineering staff have learned important lessons about SSL technology and have gained experience in dealing with the rapidly changing landscape of lighting manufacturers and their suppliers. These lessons and experiences continue to be applied and expanded through Princeton's ongoing commitment to SSL implementation. Several additional exterior lighting projects have been completed since those covered in this report. Additionally, a number of small and large interior SSL projects have been completed or are now underway. For example, Princeton upgraded an older lighting system using compact fluorescent lamps to an LED system in the Dillon Gymnasium, which DOE reported in a prior article and video. Also, a major lighting retrofit project at the Carl Icahn Laboratory is currently being studied by DOE, documenting the photometric and energy performance of an LED retrofit of recessed troffers that used fluorescent U-shaped lamps, cove luminaires that used linear fluorescent lamps, and downlights that used CFLS. That project will be the subject of a future report. [11]

From several small, early projects to larger-scale, full building implementations, Princeton facilities engineering has grown their internal knowledge base and adapted their lighting energy approach as SSL technology continues to mature and improve. By incorporating different types of controls in their early projects, Princeton also gained valuable experience in extending the energy savings made possible by the more efficient SSL light sources to include additional savings that are achievable because of the inherent advantages of SSL with respect to controls. Both from an economic and carbon reduction standpoint, the SSL experiences at Princeton have been highly successful and informative.

[11] These and other related resources may be accessed at http://energy.gov/eere/ssl/gateway-demonstration-university-projects.