Report on the lighting plan of the Lake Campus Development

A Introduction

Princeton University is currently planning an expansion of its campus to the rural area that lies South of Lake Carnegie and the D&R Canal State Park Trail, and is bordered by the Washington Road Elm Allée (W), Lower Harrison Road (E), and US Route 1 (S). The area presently consists of large open meadows with narrow rows of trees and bushes (Fig. 3, Fig. 4, Fig. 5). The Schenck-Covenhoven Burial Ground lies in the middle, on the Southern side of the planned development. The Northern side is bordered by a forest and the D&R Canal State Park. The entire area is an crucial refuge for wildlife, with a population of foxes, deer, rabbits, raccoons, minks, otters, beavers, raptor birds (hawks, owls), fishing birds (herons), Canada geese, among others[1] Many of these species are dominantly nocturnal. The area is currently completely unlit[2], offering a pristine night-time environment for the wildlife. The only source of illumination is the background light pollution of the New Jersey sky.

Princeton University is strongly committed to sustainability and nature conservancy. Accordingly, the development should take these principles into account. This review focuses on the lighting scheme of the planned development.

The inappropriate or excessive use of artificial light – known as light pollution – can have serious consequences for humans, wildlife, and our environment (`https://www.darksky.org/`). Light pollution includes glare (excessive brightness), skyglow (brightening of the night sky), and light trespass (light falling where it is not intended). Light pollution has been mostly overlooked, and has only attracted increased attention in recent years. This is thanks to numerous scientific studies (§ H) that document the serious negative impacts of light pollution, such as: i) disrupting the ecosystem, ii) adverse effect on human health, iii) increasing energy consumption, iv) destroying our cultural heritage, part of which is the night sky. I shall expand on each point with specific examples. To start with, the life of nocturnal animals is severely disrupted by light pollution; perhaps the best known example is that of hatching sea turtles dying due to disorientation from artificial lighting, or an estimated *one billion* birds dying every year in the USA due to light pollution, subsequent disorientation, and collision with buildings. As for human health, there is sound research indicating that artificial light at night negatively affects human health, increasing the risks for cancer, obesity, depression, sleep disorders and other ailments. To put it simply, we evolved to sleep under dark conditions. As part of the planned development is for graduate student housing, keeping this in mind is very important. Needless to say, all light emitted by light fixtures that goes "sideways", or even up in the sky, is wasted energy, squarely against sustainability. With the revolution of LEDs, the cost of lighting decreased, with the unfortunate side effect of even less attention to wasted energy. Finally, as for the "starry sky", about 70% of the USA population lives in areas from where the Milky Way can not be seen, and some of our Princeton students think that the Milky Way is a mythological creation[3]. How can they possibly understand and appreciate Van Gogh's "The Starry Night" painting?

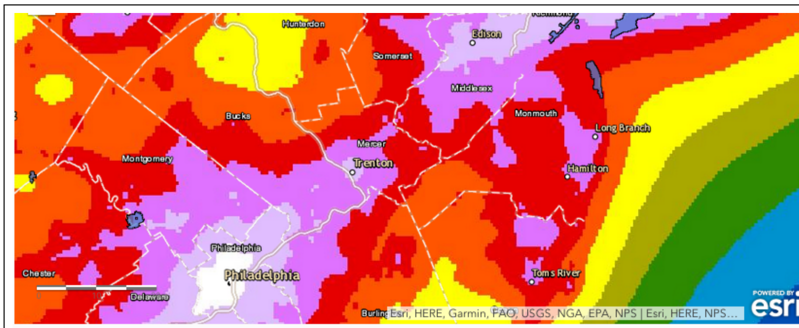
Princeton University's fusion with nature is a precious asset that should be nurtured in every possible way. An environmentally friendly campus is an attractive factor for both

[1] These species were recorded as part of Bakos' private trail camera project, an updated version of this project is now funded by the High Meadows Environmental Institute.

[2] With the exception of a single blue emergency light

[3] As based on my polls between 2011 and 2019.

students and faculty. Situated halfway between the metropolises of Philadelphia and New York, our campus offers a relatively unpolluted night sky, somewhere at the Bortle 6-7 level (Bortle 1 is an unpolluted dark sky, Bortle 10 is Manhattan). As a concrete example, the AST205 "Planets in the Universe" course has been taken by ~ 700 students so far, and all of them participated in visual observing and photography of the starry sky from the campus. All of these students have seen the basic constellations, Orion Nebula, the Andromeda Galaxy, the Pleiades, globular clusters and galaxies. This is unique among Ivy League campuses. We are on the verge of losing this. Fig. 1 and Fig. 2 show the light pollution map of central New Jersey. Princeton falls along the highly polluted corridor between Philadelphia and New York, but luckily, is situated in the dimmest "bridge" between the two cities. For reference, the summer Milky Way can not be seen from any place that is pink or white on this map, and can only be glimpsed from the red zones. With some effort, Princeton can be pushed back into "red" or "orange", representing an artificial light contribution of "only" $5-10\times$ or $2.5-5\times$ the natural night sky background. With Princeton setting an example, there is a longer-term hope that other townships would follow, turning back this runaway in light pollution that will eventually lead to completely losing the night-time environment.



View Map Legend

Ratio to natural brightness	Artificial brightness (μcd/m²)	Approximate total brightness (mcd/m²)	Color	
<0.01	<1.74	<0.176	Black	
0.01–0.02	1.74–3.48	0.176–0.177	Dark gray	
>0.02–0.04	>3.48–6.96	>0.177–0.181	Gray	
>0.04–0.08	>6.96–13.9	>0.181–0.188	Dark blue	
>0.08–0.16	>13.9–27.8	>0.188–0.202	Blue	
>0.16–0.32	>27.8–55.7	>0.202–0.230	Light blue	
>0.32–0.64	>55.7–111	>0.230–0.285	Dark green	
>0.64–1.28	>111–223	>0.285–0.397	Green	
>1.28–2.56	>223–445	>0.397–0.619	Yellow	
>2.56–5.12	>445–890	>0.619–1.065	Orange	
>5.12–10.2	>890–1780	1.07–1.96	Red	
>10.2–20.5	>1780–3560	>1.96–3.74	Magenta	
>20.5–41	>3560–7130	>3.74–7.30	Pink	
>41	>7130	>7.30	White	

Fig. 1: Map of light pollution between Philadelphia and Edison from Falchi et al. 2016. Unfortunately, Princeton already falls in the "magenta" domain, being the tiny speck above the "Mercer" label. A clear goal is to keep Princeton in the "red" range ($5-10\times$ natural brightness)

While there have been measures taken against other forms of pollution, some of which are complicated to decrease, e.g. curbing the emission of gases from combustion engines, not much has been done in decreasing light pollution. In fact, light pollution is currently under

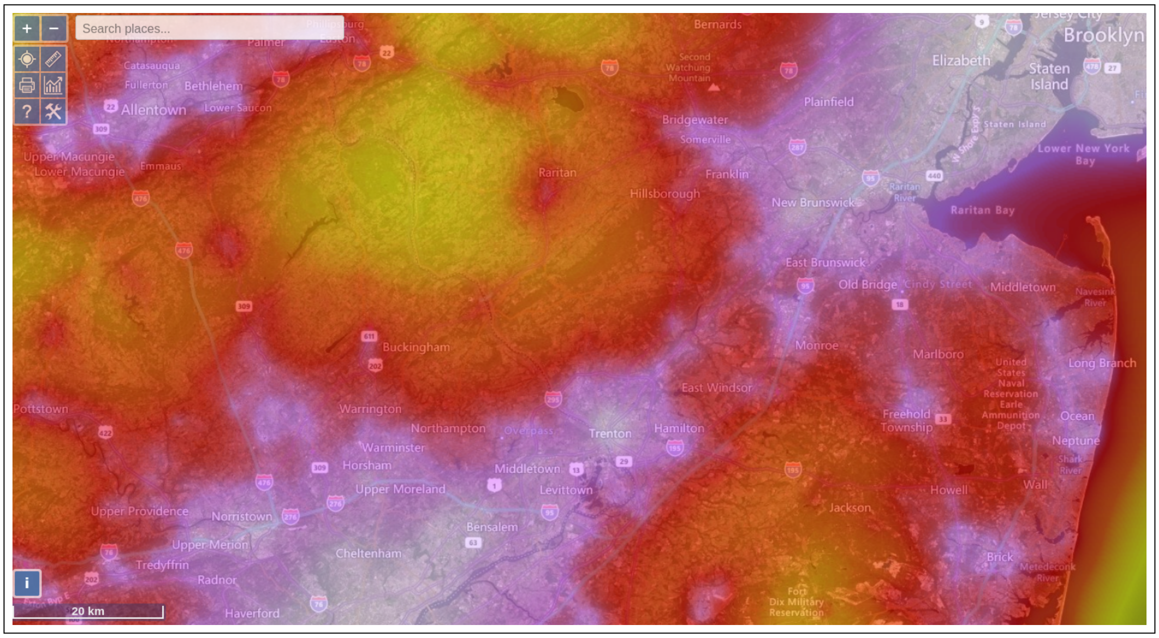


Fig. 2: Map of light pollution between Philadelphia and New York from www.lightpollutionmap.info. Princeton falls in the "darkest" area between the two megapolices, and with some effort, could be pushed back to the "red" or "orange" domains of less light pollution

an exponential growth. This is frustrating, because the solution is simple. Light pollution comes from improper shielding of light fixtures, "overlighting" of areas, and the use of lights with the wrong spectrum (white and blue). These would all be relatively easy fixes.

For centuries, Princeton University has been a world leader in a diverse range of topics, including natural sciences, humanities, social sciences, economics, and broader issues of humanity. **Princeton is in a unique position to set a positive example to the World. This could and should include the elimination of light pollution, transforming our campus to be a true dark sky haven, while maintaining safe and healthy lighting for our community.** The planned Lake Campus is a relatively small development, which is a perfect opportunity to demonstrate Princeton's willingness and capability in this respect. As a private university, the number of constraints and the amount of bureaucracy are less, enabling a pioneering effort. A dark-sky friendly campus development would be eagerly showcased by the International Dark Sky Association (IDA; `darksky.org`). In fact, IDA could provide an official certification of "Dark Sky Community[4]" to the Lake Campus, and in the longer term, to Princeton University's Campus:

> *A town, city, municipality or other legally organized community that has shown exceptional dedication to the preservation of the night sky through the implementation and enforcement of a quality outdoor lighting ordinance, dark sky education and citizen support of dark skies. Dark Sky Communities excel in their efforts to promote responsible lighting and dark sky stewardship, and set good examples for surrounding communities.*

Instead of relying on obsolete standards and technology and ignoring recent research, I am urging the University to take a bold step and spearhead the development of a dark-sky friendly campus.

[4] `https://www.darksky.org/wp-content/uploads/2018/12/IDSC-Guidelines-2018.pdf`

B The Lake Campus Area

As mentioned earlier, this is an unoccupied, unlit area, covered by fields, rows of trees, a small cemetery, and a narrow strip of forest on its Northern side adjacent to the D&R Canal and Lake Carnegie. I carried out extensive low-altitude night-time drone photography of the area as shown in Fig. 3, Fig. 4 and Fig. 5. The uniform snow cover hugely amplifies any lighting, and yet there is nothing to be seen. The fields are only lit by the ambient glow of the light polluted sky.

Monitoring of the wildlife in the D&R Canal State Park has been carried out in 2020 as a private endeavor by my three sons and myself. A wildlife track camera was placed at various locations around the proposed Lake Campus site. Over the course of about a month we observed diverse wildlife, mostly nocturnal animals: foxes, raccoons, river otters, minks, beavers, deer, rabbits, crowned night heron, grey heron, white heron, and owls. Further monitoring of the wildlife at the Lake Campus area will be carried out in 2021 funded by Princeton's High Meadows Initiative.

The proposed development will unquestionably cause damage to the wildlife and to the night-time environment. Our task is to minimize the damage.

Fig. 3: The proposed location of the Lake Campus. The only current light source is a blue emergency light. Some buildings on the very East (left) side of the area use poorly oriented floodlights. These may belong to facilities. The blue emergency light is seen from across the lake (see later Fig. 25).

Fig. 4: The proposed location of the Lake Campus. Image centered on the cemetery.

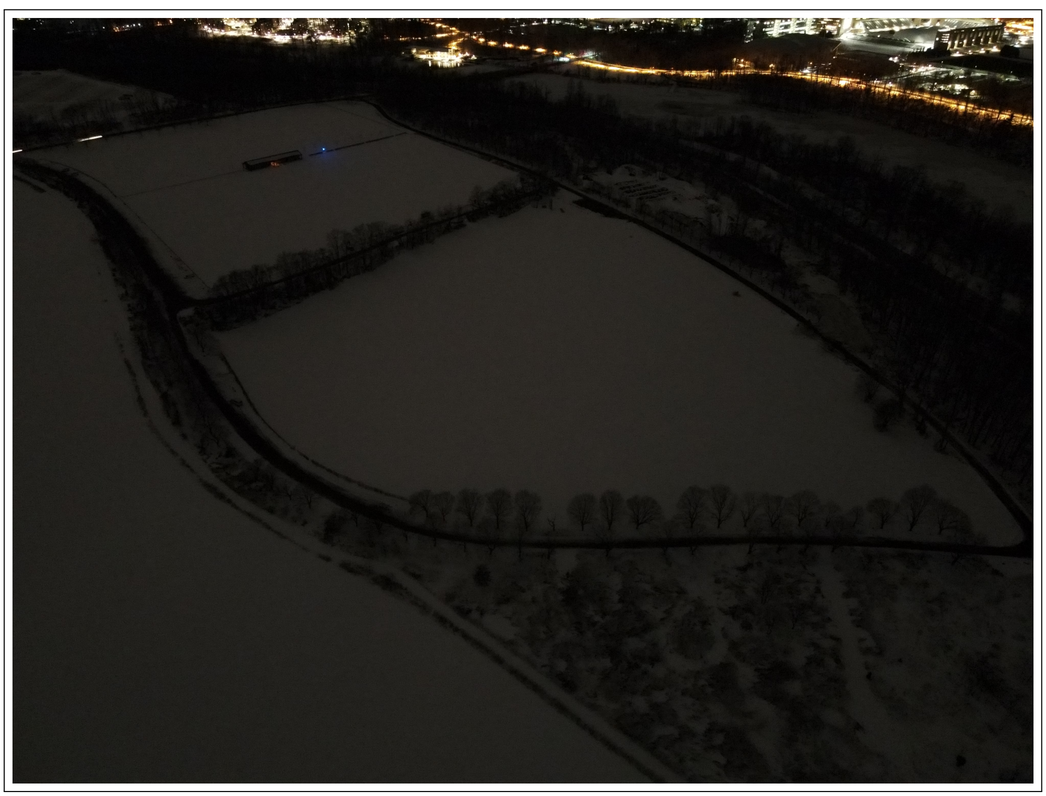


Fig. 5: The proposed location of the Lake Campus as seen from the East.

C Decreasing Light Pollution

The three most important considerations in decreasing light pollution are:

- Spectrum of light should be as red and narrow-band as possible.
- Amount of light should be kept at a minimum.
- Fixtures must be properly shielded.

I will cover each of these in the following subsections.

C.1 Spectrum, Amber LEDs

One of the most important considerations in decreasing light pollution is the use of a red (long wavelength) and narrow-band spectrum for the light emitted by the luminaires. Low pressure sodium (LPS) lamps would be ideal, because the spectrum peaks at 589 nm (orange), and is very narrow-band. Unfortunately, LPS lights are becoming rare. Low pressure sodium also has the disadvantage that it is not LED-based and can not be easily dimmed.

The longer the wavelength, the less (Rayleigh) scatter in the atmosphere, and the less unwanted brightening of the night sky background. Perhaps more importantly, especially **in our college campus setup, orange light is much less harmful for the production of melatonin, and has significant health benefits**. The underlying reason is that orange light has a smaller impact on circadian systems. In simple words, we sleep better and more if the artificial light at night is dim *and* has an orange/red spectrum[5]. Conversely, the effect of blue light and its suppression of melatonin has been linked to increased risk of breast cancer (Hansen 2001, Blask et al. 2005, Stevens 2009), obesity (Spiegel et al. 2004, Fonken et al. 2010), diabetes (Spiegel 2005) and depression (Bedrosian 2011). Also, glare from short wavelength emission cold LEDs cause veiling luminance in human eyes over the age of ~ 55 years. Due to the nature of reliable medical research on humans, it took about a decade for the medical literature to "catch up" with the sudden boom in light pollution, and to realize the serious harmful effects of such pollution on our health. **There are now numerous refereed and well-cited studies proving the link between light pollution and adverse health effects, and they can not be ignored any longer in the planning of campus lighting**. The solution is to use dimmable amber LEDs with full shielding. There is perhaps a small extra cost associated with the use of such amber LEDs, although the price gap between amber and white/blue has been steadily decreasing. Nevertheless, the additional cost is truly negligible when compared to other construction costs, and of course completely negligible in the broader context of the loss of productivity and adverse long-term health effects on our students and community.

The importance of the *narrow wavelength range* (as opposed to a broadband emission) is the ease of filtering out such an emission with astronomical filters built for the purpose, so some astronomical observations remain feasible. In simple terms, the sky background remains dark in all wavelengths other than the emission. Unfortunately, this does not hold for the naked eye viewing of the starry sky.

Our campus currently uses a variety of light sources, including "shoe-box HID lamps" (orange), yellow and white LEDs, and other HID and QL induction lamps (Fig. 9). The optimal solution with the current technology available is the use of dimmable Amber LEDs,

[5] `https://www.darksky.org/light-pollution/human-health/`

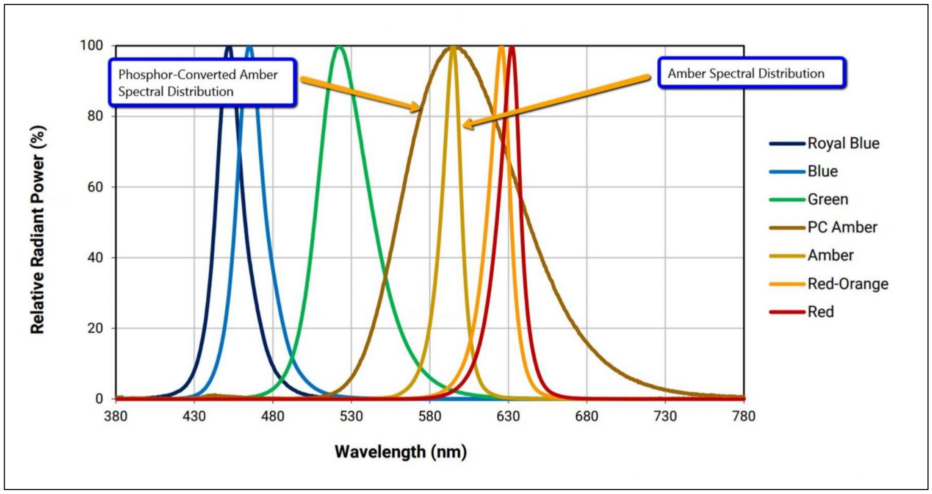
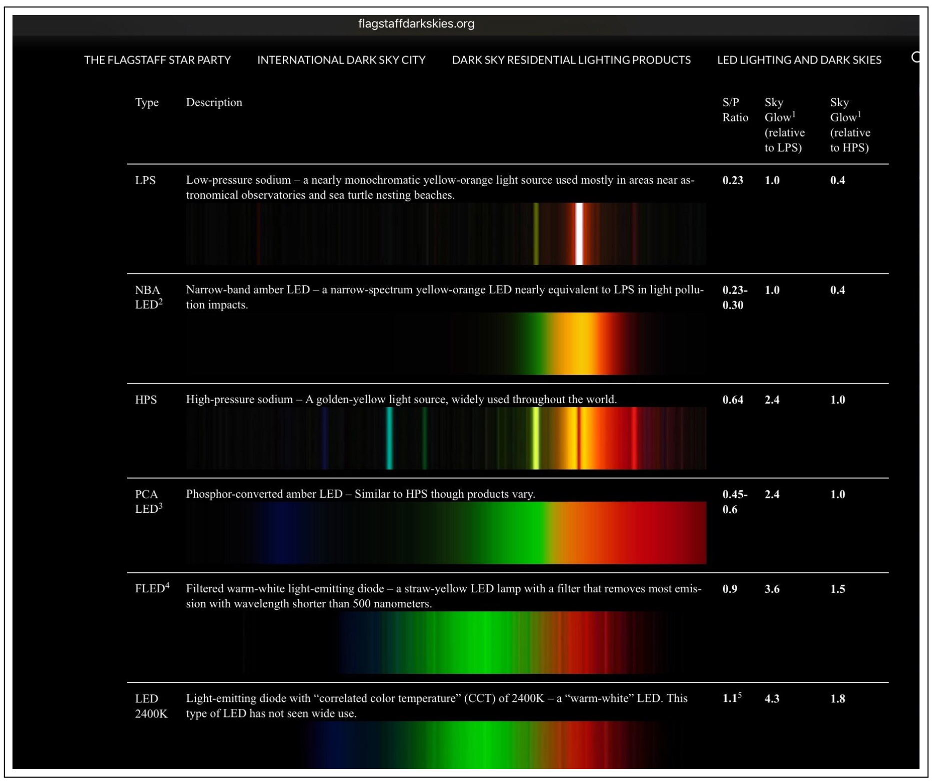


Fig. 6: The spectral distribution of amber LEDs. The peak emission is orange and relatively narrow-band.



Type	Description	S/P Ratio	Sky Glow[1] (relative to LPS)	Sky Glow[1] (relative to HPS)
LPS	Low-pressure sodium – a nearly monochromatic yellow-orange light source used mostly in areas near astronomical observatories and sea turtle nesting beaches.	**0.23**	**1.0**	**0.4**
NBA LED[2]	Narrow-band amber LED – a narrow-spectrum yellow-orange LED nearly equivalent to LPS in light pollution impacts.	**0.23-0.30**	**1.0**	**0.4**
HPS	High-pressure sodium – A golden-yellow light source, widely used throughout the world.	**0.64**	**2.4**	**1.0**
PCA LED[3]	Phosphor-converted amber LED – Similar to HPS though products vary.	**0.45-0.6**	**2.4**	**1.0**
FLED[4]	Filtered warm-white light-emitting diode – a straw-yellow LED lamp with a filter that removes most emission with wavelength shorter than 500 nanometers.	**0.9**	**3.6**	**1.5**
LED 2400K	Light-emitting diode with “correlated color temperature” (CCT) of 2400K – a “warm-white” LED. This type of LED has not seen wide use.	**1.1[5]**	**4.3**	**1.8**

Fig. 7: Comparison of the spectral distribution of various light emitting fixtures. Note the similar peak of emission for LPS and NBA LEDs. All other solutions under NBA LED are not preferred. S/P stands for scotopic to photopic ratio. An important column to observe is the “sky glow” relative to the use of LPS. Only Amber LEDs provide a sky glow that is comparable (i.e. small) to LPS. For more explanation, see Luginbuhl 2014 and Aubé 2013.

Fig. 8: A number of light fixtures from the IDA website that are available with amber LEDs. There are many more. For example, the pureform post-top matches the visual appearance of the currently planned Bega 84 121 luminaire, but the pureform is available with Amber LEDs. Photo taken from darksky.org. Not displayed in this summary image, but perhaps the most capable post-top fixture is the Lighman Macaron (see separate figure later).

with a color temperature of 2200 K or lower. According to Luginbuhl 2014, these have a scotopic to photopic ratio of 1, very similar to low pressure sodium lights. However, in comparison with sodium lights, they can be dimmed at virtually any fraction of their peak emission, and their lifetime does not depend on the number of on/off cycles. The International Dark Sky Association has a large number of light fixtures listed on their website (Fig. 8), many of them with 2200 K or 1800 K (code AMB) emission. **We must absolutely use dimmable amber LEDs throughout the new site, and nothing with a correlated color temperature in excess of 2200 K.**

Fig. 9: Aerial image of the campus, Faculty Road, Broadmead and the Stadium. The image shows the different light emission spectra, including the orange sodium shoeboxes on Faculty Road, the white "Campus standard type 1 pole top", the white/blue cobra heads (by the township). There are also three new light fixtures on Fitzrandolph, which are marked collectively as "Bega", as they are models similar to the suggested Bega.

C.2 Amount of Light

Overlighting is a major source of light pollution. As of 2016, 99% of the population of the USA and Europe can no longer experience natural light during the night. 99%! Overlighting comes from the use of an excessive amount of light, either overly bright luminaires, or too many such fixtures cluttered together. Overlighting also stems from a significant underestimate of the capabilities of normal human night-time vision. The catch-22 is that with overlit areas, night-time human vision actually deteriorates, and our dark adaptation skills are numbed.

An underlying cause for overlighting is occasionally the false impression that brightly lit areas are "safe". However, a now well-known study by Steinbach et al. 2015 ("*The effect of reduced street lighting on road casualties and crime in England and Wales: controlled interrupted time series analysis*") shows that:

> *There was no evidence that any street lighting adaptation strategy was associated with a change in collisions at night. There was significant statistical heterogeneity in the effects on crime estimated at police force level. Overall, there was no evidence for an association between the aggregate count of crime and switch off ... or part-night lighting.*

In fact, the authors found that there is a weak evidence for the "*reduction in the aggregate count of crime and dimming*". Another significant study called the "Chicago Alley Lighting" found that after a major increase in the lighting level of alleys in Chicago the crime rate <u>increased</u> by 21% (Morrow et al. 2000[6]). A report to the United State Congress entitled "*Preventing Crime: What Works, What Doesn't, What's Promising*"[7]. To quote this study:

> "*The problematic relationship between lighting and crime increases when one considers that offenders need lighting to detect potential targets and low-risk situations (Fleming and Burrows 1986). Consider lighting at outside ATM machines, for example. An ATM user might feel safer when the ATM and its immediate surrounding area are well lit. However, this same lighting makes the patron more visible to passing offenders. Who the lighting serves is unclear.*"

An obvious and definite side-effect of overlighting, however, is the waste of energy, squarely against sustainability and nature conservancy. If we look at Princeton at night, there is an enormous amount of energy wasted by light emission into the sky. The majority of lights are glowing at full capacity at 3am on a winter night. Many areas are seriously overlit (Fig. 9, Fig. 10).

It is important to note that there is no need to keep streets incessantly lit. This is especially true when a pedestrian walkway adjacent to the street is already illuminated. There are numerous examples for this in Princeton, for example Fitzrandolph Rd., Ivy Lane, Broadmead, and others (Fig. 12, Fig. 13). Conversely, Faculty Road is significantly overlit, and due to the poor shielding, much of the light spills into the nearby forest or Lake Carnegie (Fig. 9). The planned location of Princeton's Lake Campus is currently a truly dark night-time environment. The introduction of lights to this area will be a major disruption, and overlighting must be avoided.

C.3 Shielding

Proper shielding of the light fixtures is fundamental for decreasing light pollution. At the very minimum, no light should escape above the horizon. In fact, all direct light trespass must be eliminated by using a proper shield. Here, by light trespass we mean the spilling of light to areas where it is not wanted, e.g. the window of a graduate dormitory room, or the forest bordering the Lake Campus (Fig. 16).

[6] `https://www.darksky.org/wp-content/uploads/2014/09/Chicago-Alley-Lighting-Project.pdf`

[7] `https://www.ncjrs.gov/works/`

Fig. 10: Princeton Stadium at midnight. Many areas are overlit. All of the light seen in this image is leaving Earth, whereas the clear intention was to illuminate the ground.

Fig. 11: Ivy Lane, parking lots, eating clubs, Prospect Avenue. A positive feature to note, however, is the parking lot directly opposite of Peyton Hall, which is lit by LED lights that are *permanently* dimmed at 50% of their original emission, thanks to a collaboration with D. Casey and W. Evans. The parking lot has been operating as such for 4 years with no incidents to the best of my knowledge.

Fig. 12: Ivy Lane has standard Princeton walkway lights on both sides of the road, but no separate street lights. This is an excellent way of avoiding overlighting. Fitzrandolph Rd. has pedestrian walkway lights, with again no dedicated street lighting. The same holds for Broadmead, with the exception of some cobra head lights at very large spacing.

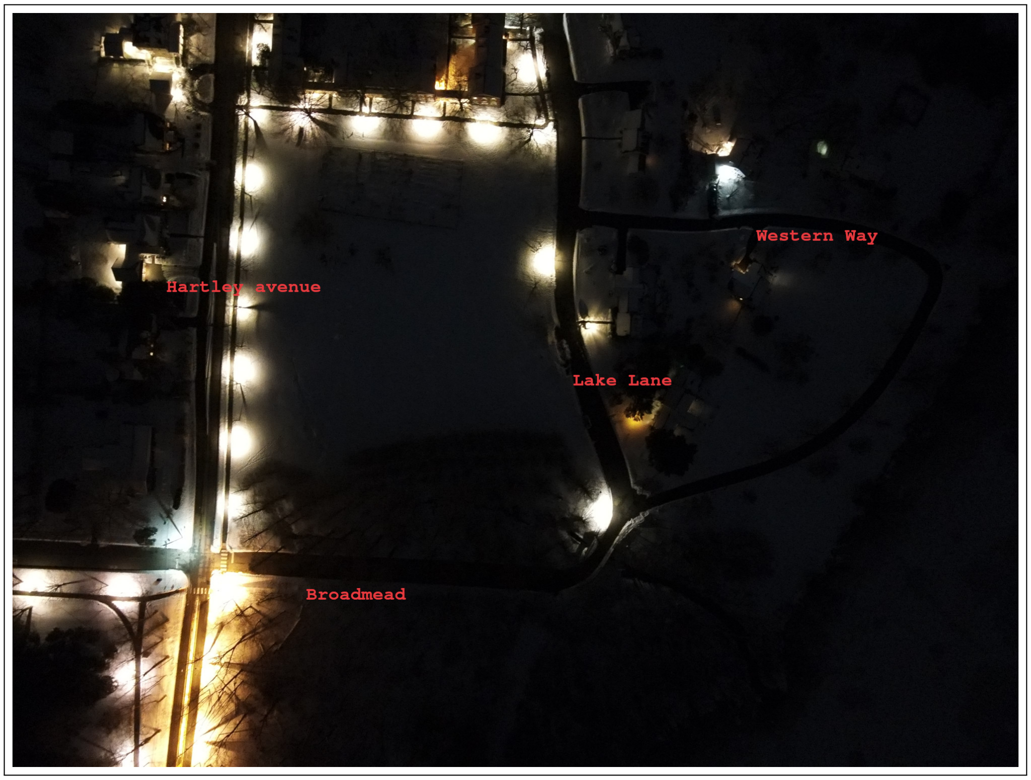


Fig. 13: A positive example: no streetlights on Broadmead, Lake Lane, Western Way, Hartley Avenue. All light seen from above comes from the pedestrian walkway lights. On the negative side, the pedestrian lights are too bright, and their spectra are too white. The fixture at the bottom of Lake Lane is heavily spilling light into the nearby forest.

Fig. 14: The view from the author's first floor bedroom window. The Princeton Standard pedestrian light has been shining in my bedroom window for the past 10 years. Consequently, the shades are down all night, windows are closed, even when a fresh breeze of air would help.

Fig. 15: The location of Princeton's future Lake Campus. The area is currently completely unlit, and provides a natural night-time environment. Introducing new lights will be a major disruption, and the pollution of such lights must be minimized.

Fig. 16: Proper shielding of the light fixtures means no light trespass, no glare, and all light going to the area that is intended to be lit.

C.3.1 Measurements of light trespass from a bollard

Perhaps the worst example for improper shielding of light is the bollards used in Princeton Stadium. I used a drone to measure the infalling light as a function of angle *above the horizon* as seen from the luminaire (Fig. 17 and Fig. 18). Due to the obstruction of the bollard itself, my estimate is that 75% of the light emitted does not reach the ground.

Fig. 17: Light emission as a function of vertical angle for a bollard used in the Princeton Stadium.

C.3.2 Measurements of light trespass from new post-top luminaires on campus

Fitzrandolph Road has three new post-top luminaires installed, perhaps for reasons of testing. These are broadly similar to the Bega 84 121 fixture, but I was not able to establish the concrete models. The Southernmost fixture has an asymmetric internal shielding. The second fixture (middle) has a smaller illuminating surface area (Fig. 19 left), and may have an

Fig. 18: Light emission as a function of vertical angle for a bollard used in the Princeton Stadium. About 75% of the light emitted goes up in the sky.

internal shield (this may be from the Kim Lighting Ouro Post Top series). The third fixture (Northernmost one, Fig. 19 right) has a larger illuminating area (this may be from the Lithonia Radean Post Top series).

Fig. 19: New fixtures on campus at Fitzrandolph; perhaps a Kim Ouro (left) and a Lithonia Radean (right)

I also used a drone to measure the light emission of the third (North) fixture (Lithonia Radean), which resembles the Bega 84 121 luminaire. Overall, the fixture is much better shielded than the campus standard “Princeton type 1” sidewalk lamp. Nevertheless, I found light emission at 0° and 10° above the horizon defined by the plane of LEDs (Fig. 20). If any such fixture stays in the lighting plan, they must be ordered with shielding (such as the “HS” houseside shield in the specs).

C.3.3 Measurements of the light trespass from the standard Princeton fixture

I also measured the emission of the currently widely used Princeton sidewalk fixture (Fig. 21). It is noted that the Bega-like fixture is significantly better shielded than the Princeton Standard lamp. The latter has light emission up to 60° above the horizon (also see Fig. 23).

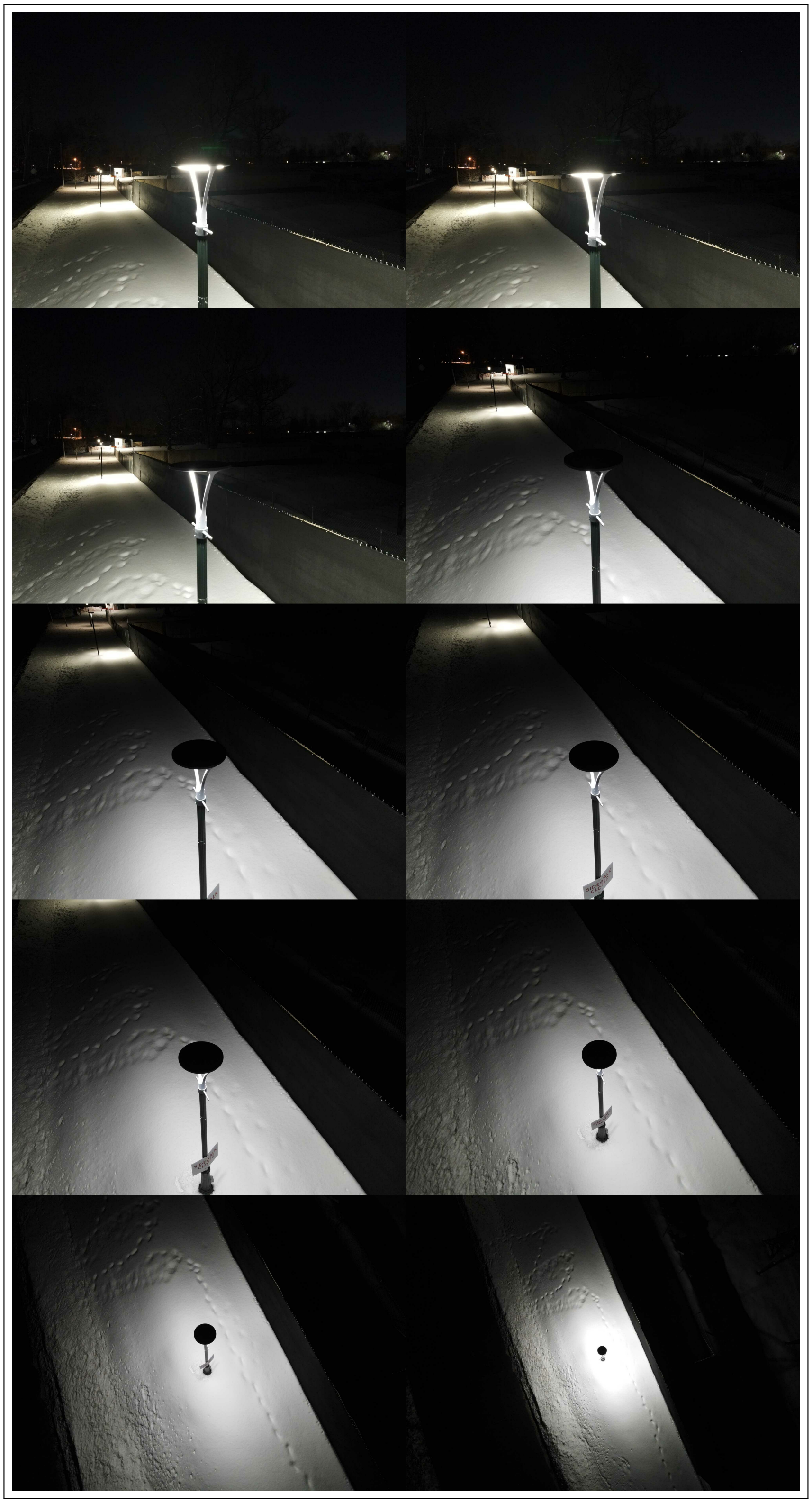


Fig. 20: Measuring the light emission of the Lithonia Radean (or similar) at Fitzrandolph Rd. There is some side-ways emission of light up to 10° above the horizon. Such fixtures must be ordered with the HS houseside shield, and the efficiency of the shield must be investigated.

Fig. 21: Measuring the light emission of the standard Princeton sidewalk luminaire at Broadmead. This light fixture does emit a very significant amount of light sideways and above the horizon. Direct light is emitted up to around 60 degrees above horizon. At the same time, right under the lamp post, a circular shadow remains due to the geometry of the lamp.

Fig. 22: Comparing the light emission of a Lithonia (?) (marked as "Bega") and a Princeton Standard Fixture as seen from directly overhead.

Fig. 23: Light emission of a single Princeton Standard Fixture as seen from about 45° above the horizon. The shielding is poor, the side-ways and upward light emission is significant.

D The Lighting Plan of the Lake Campus as Received

I have reviewed the following documents to understand the current lighting plan:

- `'AX01 Ligman Steamer USE-90002.pdf'`
- `'AX11 84121_BEGA_Photometric.pdf'`
- `'AX11 84121_BEGA_Spec.pdf'`
- `'AX12 84148_BEGA_Photometric.pdf'`
- `'AX12 84148_BEGA_Spec.pdf'`
- `'Lake Campus Lighting Plan - 85 CD 20201217.pdf'`
- `'Lake Campus Site Development 85\% CD Drawings - Appendix A fixture spec and alternates.pdf'`
- `'Lake Campus Site Development 85\% CD Drawings - Site Lighting Drawings.pdf'`
- `'Lake Campus Site Plan & Faculty Research Discussion_May_19_2020.pdf'`
- `'LCSD Site Lighting_LT-100 OVERALL+isoline_210216.pdf'`
- `'LCSD Site Lighting_Luminaire Schedule_A10_210105.pdf'`

My general impression is that the design makes an effort to address light pollution, for example through the use of mostly dark-sky compatible fixtures (albeit with sub-optimal versions). For this, I wish to compliment the architects.

Fig. 24: The lighting plan that I received and used to establish the level of light pollution, and to make specific recommendations

Overlighting

However, we need to do better in order to decrease the light pollution. Altogether 33 AX01, 138 AX11 and 11 AX12 fixtures would be installed.[8]. This is a **huge number of new light fixtures**, which would lead to a very significant light pollution. The area would be substantially overlit. I carried out simulations on the sky background as seen from across Lake Carnegie, from Lake Lane. I took night images, and the single blue emergency light at the Lake Campus field is easily seen through the trees from a distance of 650 meters (0.4 miles). Based on that, using the 3000 K color temperature of the luminaires, and their BUG ratings, the simulated image shows the altered view from across the lake, and the excess sky glow in hazy conditions (Fig. 25)

Spectrum

The spectra of the luminaries is 3000 K, which is at the upper limit of dark-sky friendly designs (updated specs and preferences go for upper limits of 2700 K and 2200 K). Some of the fixtures have no light contours indicated in the design. Certain areas have a redundant overlap of AX01 and AX11 and AX12 fixtures. I found no explicit mention of motion controlled brightening, automatic dimming past midnight, and additional shielding (as offered by the manufacturer).

Shielding

I located a Bega 84 121-like luminaire on campus (Lithonia Radian?), and measured the vertical light profile with a drone to estimate the amount of light spilling horizontally (See Fig. 20). It is much better than the standard Princeton sidewalk lamp, but without shielding, there is light-trespass up to 10° above the horizon.

The IES BUG (Back, Up, Glare) ratings for the Bega fixtures show that there is a "up light rating" of U1 for the 23 W and a "up light rating" of U2 for the larger 47 W model. Due to the BUG ratings, and also the lack of Amber LEDs, and because there are other models that are more sophisticated (e.g. Ligman Macaron) I recommend using other, similar fixtures (see later).

These fixtures would light the forest along the D&R Canal State Park. While the amount of light spill appears small on a linear scale (see lighting profiles in the Bega documentation), it is still very significant on a logarithmic (magnitude) scale, which is what really matters for night vision, nocturnal animals, and in general, nature conservancy. Nocturnal creatures are far more sensitive than the 0.01 fc limit. (Think of an owl's ability to fly through a forest in full darkness at new moon).

I have performed similar measurements for the cylindrical bollards (Fig. 17, Fig. 18). To put it mildly, these are not dark-sky compatible, with upward light emission (waste) of about 75%. If bollards are considered, there are dark-sky friendly versions (Ligman lightsoft 15).

The present lighting plan would certainly not be a breakthrough for decreasing light pollution. It would not be a campus lighting solution that others would admire and aspire to follow. My recommendations are detailed in § E.

[8] Based on counting these on the high resolution printouts

Fig. 25: Top: current view of the Lake Campus from the lakeside. The blue emergency light shines through the forest. Bottom: simulated view with the new Campus Lighting Plan, 3000 K fixtures, some light spill, light reflection from the ground from over 170 light fixtures.

E Recommendations

My recommendations are based on the recent trends and research in limiting light pollution (§ A), the description of the Lake Campus area (§ B), the ways to decrease light pollution (§ C), the current plan (§ D), and all the references and supporting materials (§ H).

- **Any light fixture used in this development must use Amber LEDs, with a dimmable option, and with occupancy sensors.** All lights should be dimmed at a specific time, such as midnight (or similar). This way, the lighting levels can automatically decrease to a small fraction of the maximum output when there is simply no need for light (for example, at 3am on a winter night).
- All walkway fixtures must be set up with **shielding and orientation such that no stray light spills onto the walls and windows of graduate student housing.**
- **No use of any bollards (AX21).** They spill a large fraction of the light into unwanted places (Fig. 17, Fig. 18).
- **Elimination of AX01 street lights within 60 ft of any AX11 sidewalk fixtures**. As argued before, and with numerous well-working examples shown from the Princeton Campus, there is no need to light the streets when the sidewalks are already lit.
- Sidewalk post top luminaires (aka. AX11) should be sparser, with $\sim$60 ft approximate distance. This is to avoid overlighting.
- For any remaining AX01-type street lights (e.g. parking lots), use dimmable Amber LED fixtures. I confirmed with Ligman that their USE-90002 fixture can use amber LEDs. These fixtures are an excellent choice for keeping the light pollution under control. Should any AX01 "Ligman 90002" fixture remain in the plans (parking lots), use IHSS (integrated house shield) or EHSS (external side shield) with Amber LEDs. This corresponds to the code:
  `USE-90002-29W-Type*-W27-FC*-Voltage-DIM (Dimming)-OS-AMB(Amber)`
  Some other dark-sky friendly small street lights are: Lumecon Detroit Series LDS-SAL-30[9], which comes with 2200 K amber LEDs, is dimmable, and has occupancy sensors. Slightly less optimal, because of the use of phosphor converted amber LEDs, but with even 2000 K color temperature, are the CR Astrophile Series[10].
- Instead of the Bega luminaires, which do not support Amber LEDs, and don't appear to have integrated occupancy sensors[11], **use the Lighman Macaron-2 post top fixtures** (Fig. 26). These are state-of-the art, using MicroVos technology[12]. This enables a better control over the exact distribution of light, and also leads to less fixtures used, which can be a cost saving measure. The Ligman Macaron 2 (UMC-20011) fixtures are dark-sky friendly, can have amber LEDs, can do motion control and timed dimming. Furthermore, they can come with two different boards integrated in the luminaire, e.g. one with 2700K, and another with Amber LEDs, enabling the switch between the two at specified times or when motion is detected. Another, slightly less perfect version is the Gardco Pureform

[9] `https://lumecon.com/wp-content/uploads/2015/10/Lumecon-LDS-SAL_10292020.pdf`

[10] `https://crossroadsled.com/lighting-products/phosphor-converted-amber-street-lights/`

[11] I have inquired at Bega about the possibility of these particular fixtures using Amber LEDs, and I received no positive confirmation that they could deliver them with such specifications.

[12] `https://www.youtube.com/watch?v=4vIbMLxV5WU`

post top fixture (Fig. 36). This has the same appearance as the Bega, but also supports Amber-Generation2 LEDs[13].

- No use of Bega 84 148 (aka. AX12) fixtures. These are the larger and brighter versions of the Bega 84 121 luminaires. Using Ligman macaron 2 (UMC-20011) posts the Lake Campus can be adequately lit.
- Even with the best effort of "*damage control*", the light pollution at the Princeton Campus will increase as a result of the Lake Campus development. **The excess amount of light can be offset by converting some of the strikingly overlit campus areas into more nature friendly arrangements**. On top of this list is the lighting of Faculty Road, where all "shoebox" lights (Fig. 33) should be replaced with fully shielded dimmable and motion controlled amber LEDs. This would eliminate the spillage of light into the forest on the North shore of Lake Carnegie, in between Lake Lane and Washington Rd. A broader report on Princeton's light pollution will follow, and will contain more specific ideas for improvements.

[13] https://www.signify.com/en-us/products/outdoor-luminaires/site-area/architectural-posttop/pureform-led-post-top-comfort-ppt

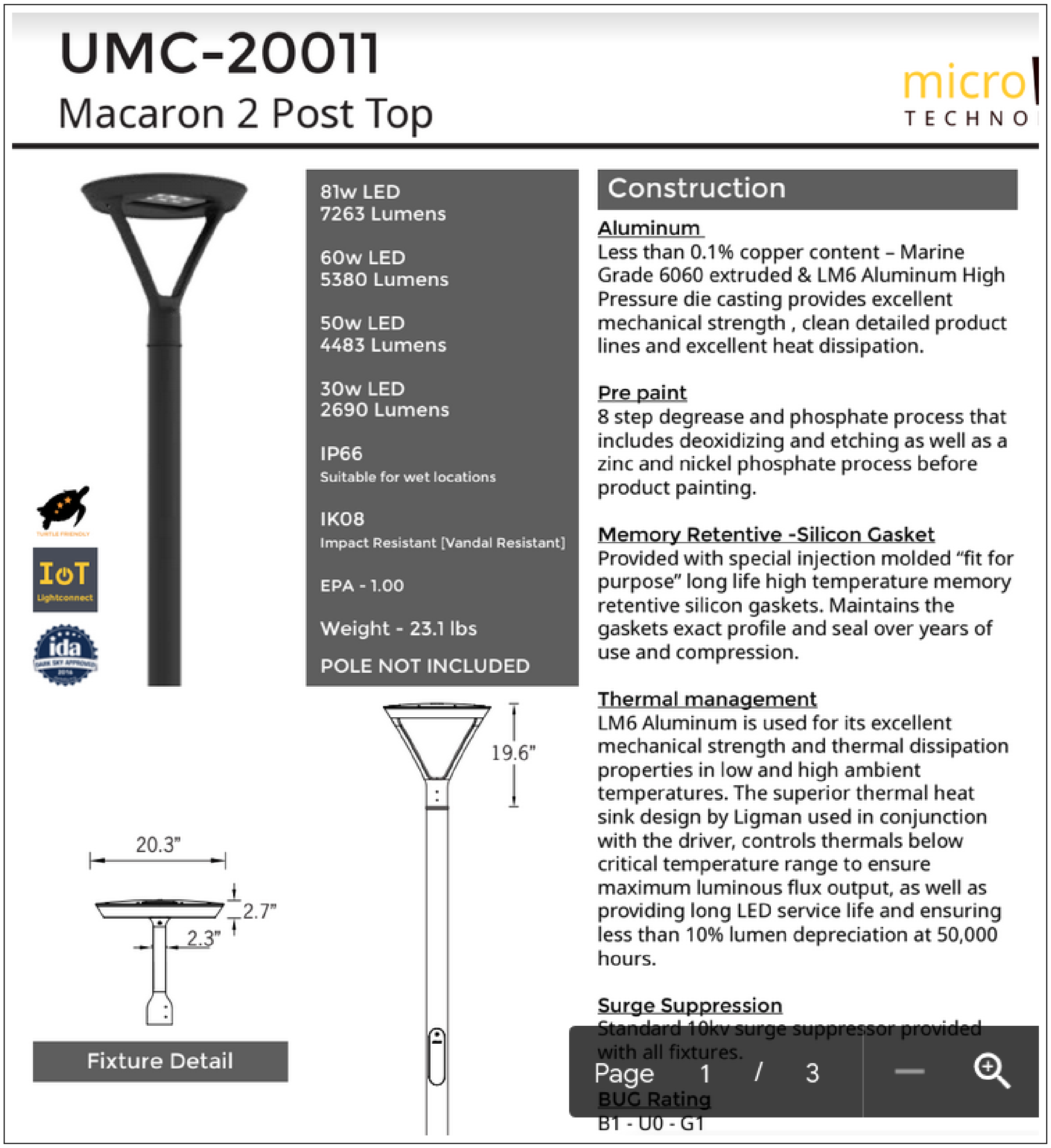


Fig. 26: The Ligman Macaron-2 fixtures are the dark-sky friendliest luminaires I found. They support Amber LEDs. They have built-in occupancy sensor. They can be dimmed. They are perfectly shielded. They can have multiple boards enabling tricks that I have not found elsewhere.

Fig. 27: Various Ligman Macaron products, all dark-sky friendly to the fullest extent.

F Appendix and Supporting Materials

F.1 The "Updated" Princeton University Outdoor Master Plan.

Certain elements from this document[14] are in line with my suggestions. However, I must note that the document requires significant updates, as it does not take into account light pollution, sustainability, and especially the adverse health effects (in light of recent research) with enough weight. For example, lighting levels are based on the ANSI/IESNA RP-8-00 Roadway Lighting Standards (Reaffirmed 2005). This is a 16-year old document, not taking into account many serious side effects of light pollution. Other elements are based on the IES 10th Edition (2010?).

Positive elements from the Outdoor Master Plan that are worth mentioning:

- Pg. 7: "*A few of the newer poles however had lamps peering below the top cover which caused unwanted glare. Other poles were lamped with cooler lamp color temperatures. Both these errors are very noticeable and should be rectified.*"
- Pg. 8: "*Today all roadway lights south of the Elm Drive south gate have been replaced with LED roadway poles spaced approximately 60 ft. o.c. Illuminance levels and uniformity are very good.*"
- Pg. 12: "*If luminaire brightness can be controlled, neighborhoods may find lower-lumen-output luminaires and illuminances at the lower end of IES recommendations to be acceptable and even preferred.*"
- Pg. 12: "*Luminaires delivering warmer-color light, usually lower than 4,000K and often below 3,000K, may be appropriate for older, more traditional-looking neighborhoods, especially if residents have been used to high-pressure sodium or incandescent outdoor lighting.*"

[14] https://facilities.princeton.edu/sites/facilities/files/2.9-15.pdf

Fig. 28: Ligman dual boards enabling various lighting and dimming schemes

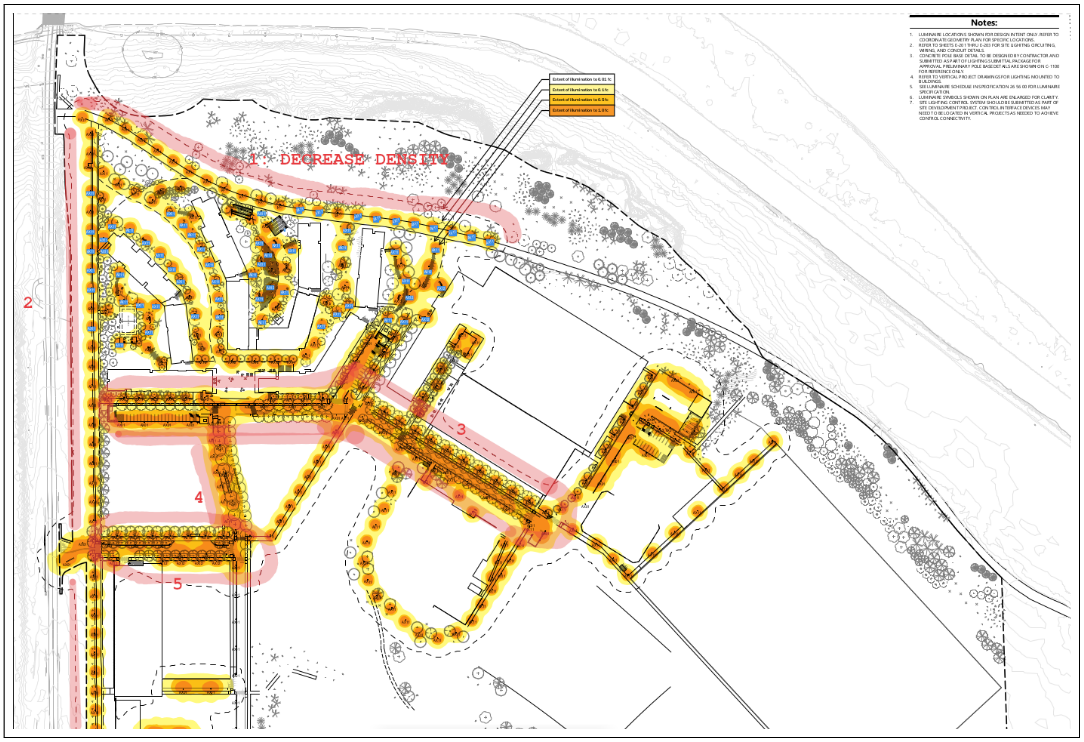


Fig. 29: Suggested changes to the current lighting plan. 1 and 2: Decrease spatial density of luminaires. 3, 4, 5: overlit areas, eliminate AX01 type fixtures.

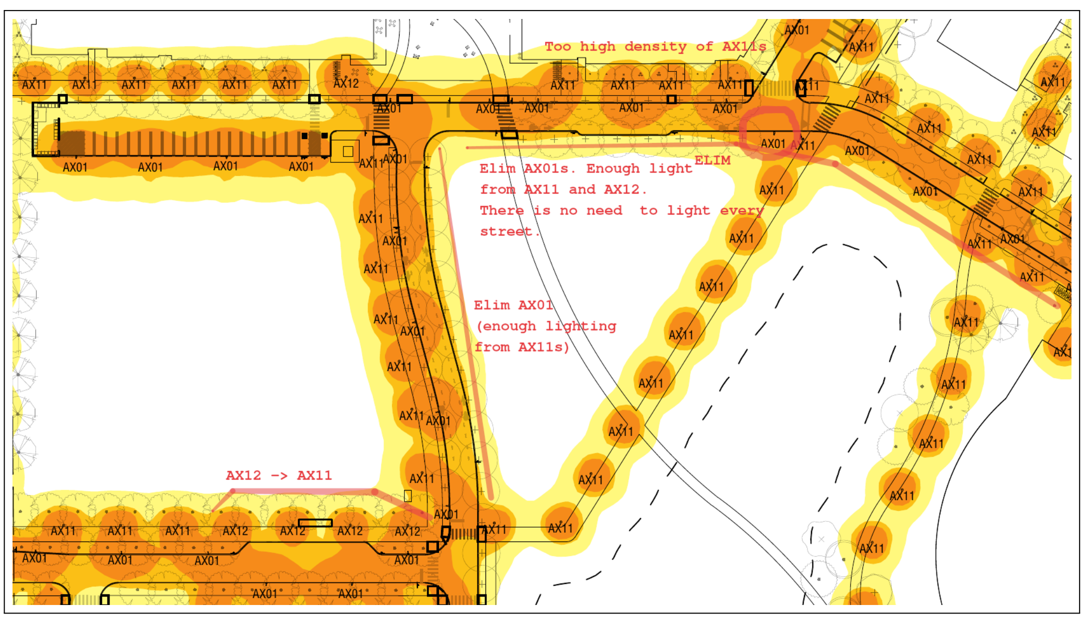


Fig. 30: Suggested changes to the current lighting plan. No need for the larger Bega fixtures, suggest to change all sidewalk luminaires to a single model (see text for suggestions). Other areas of overlighting are marked up.

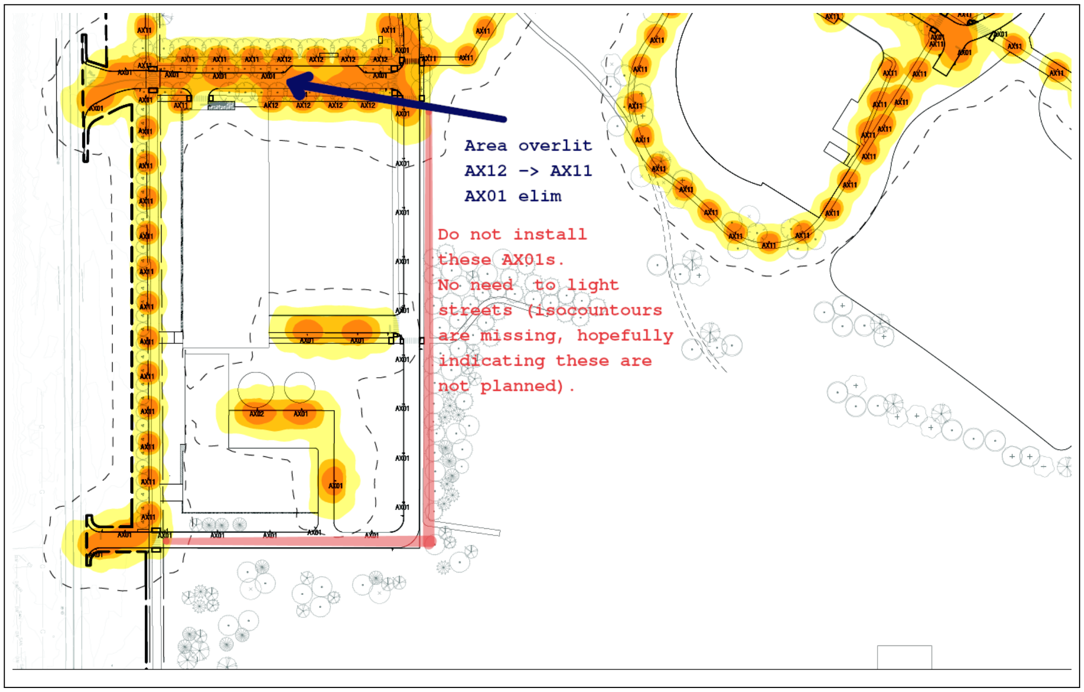


Fig. 31: Suggested changes to the current lighting plan. I assume all AX01 fixtures with no light contour would not be installed. The suggestion is to eliminate all AX01 fixtures except those 5 in the bottom right corner that may be around parking areas.

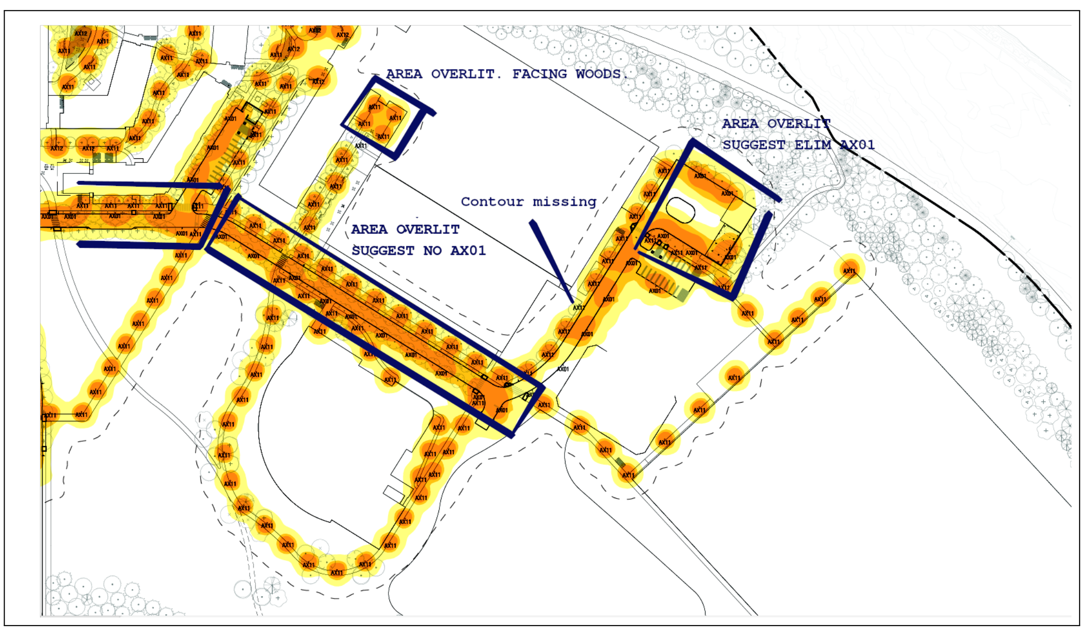


Fig. 32: Suggested changes to the lighting plan.

Fig. 33: Light spilling into the neigboring woods from Faculty road. The lights can be seen from the lakeside, and from across the lake. Changing these fixtures to Ligman USE-90002 ones could offset the increased light pollution from the Lake Campus development.

Lumecon DETROIT SERIES

LDS - SAL
LED Small Area Light

Catalog Number:	
Project:	
Comments:	
Prepared By:	Date:

Description

The LDS-SAL small area light is the first of its kind in Lumecon's LED Detroit Series. Combining a sleek fixture design with energy efficient performance allows this fixture to be used in parking lots, roadways, pathways and general area lighting applications replacing existing fixtures up to 400W HID one-for-one.

Dimensions & Weights

Model	Width	Length	Height
LDS-SAL	13.25"	19.25"	4.35" 6.70" (MAS) 10.72" (SF)

13.25"

4.35"

19.25"

Technical Specifications

Input Voltage: 120-277V or 347-480V.

Housing: Die-cast aluminum housing with 60% gloss polyester powder coat finishes for maximum durability. The base aluminum material is prepared using an environmentally-friendly non-chrome 2-step surface cleaning and passivation process. The process results in a more durable conversion layer than traditional chromate conversion coatings and allows maximum adhesion of the powder coating to the aluminum substrate. Housing features an integrated heat sink and driver compartment built into the fixture design.

Mounting: Mounting arm designed for a square / round pole (standard). Additional mounting options include a pole mounting arm adaptor.

Split Circuit: Optional

Effective Projected Area (EPA): 0.83 ft²

Color Temperature: 2200K, 2700K, 3000K, 4000K (standard), 5000K.

LED Lifetime: All LED's are rated for a minimum of 100,000 hours of continuous operation at ambient temperatures from -40°F/-40°C to 95°F/35°C.

Color Rendering Index (CRI): Minimum of 80 or higher. CRI 90+ available upon request. CRI 90+ not available in 2200K.

Dimming: 0-10V standard dimming capability.

Custom Optics: Lumecon meticulously engineered premium acrylic optical lenses to maximize the distribution and uniformity of light while minimizing cost. Our arrays distribute light at least 21% further and with 29% more uniformity than leading competitors. Lumecon custom lenses create a uniform, well-lit environment that mitigates illuminance "hot spots" and use less wattage than typical LED area lights.

Surge Protection: Thermally protected 20kA/ 40kV varistor type surge suppressor is

Fig. 34: Lumecon luminaires, matching the appearance of the USE-90001, also supporting Amber LEDs. I list these for completeness, but I think the Ligman USE-90001 fixtures are a better choice.

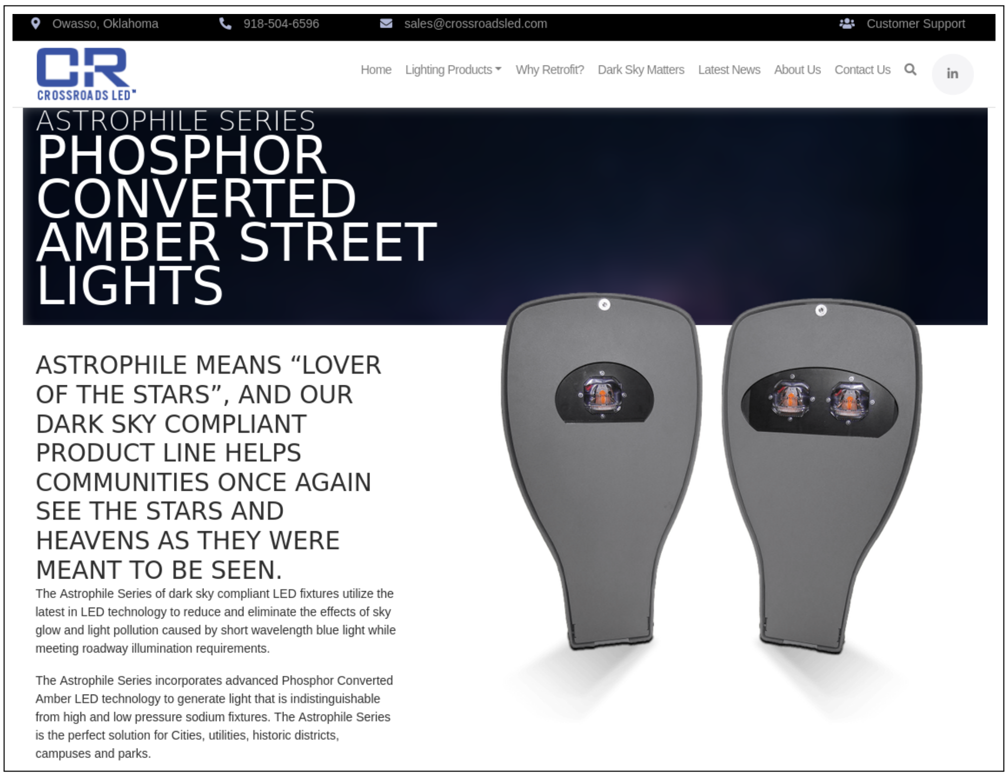
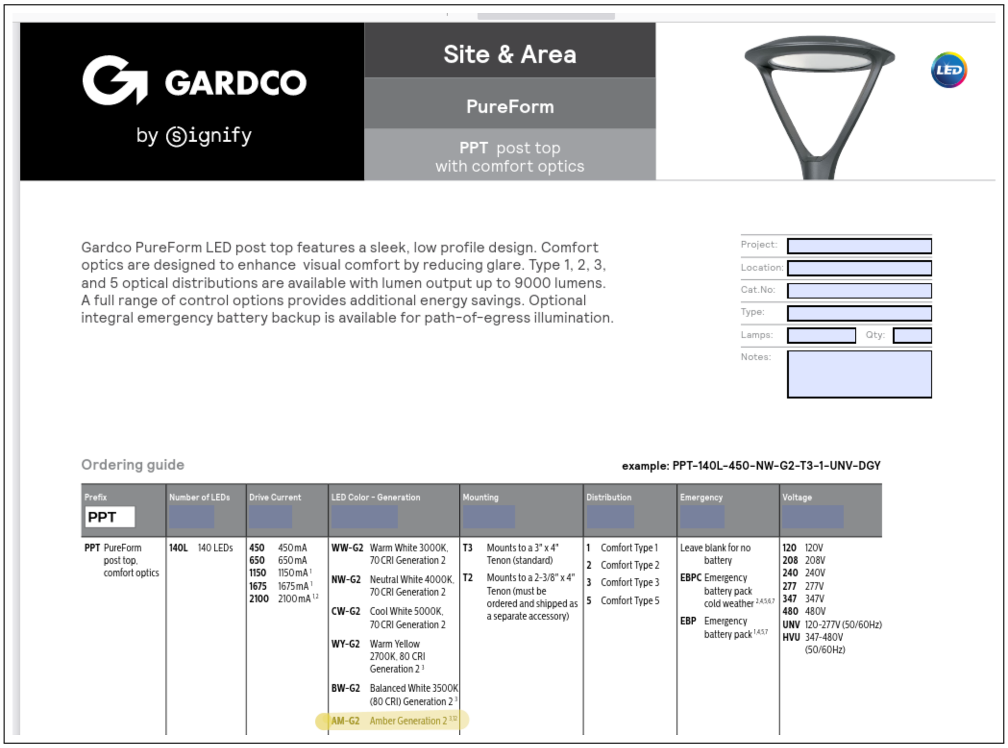


Fig. 35: Astrophile luminaires, matching the appearance of the USE-90001, fully dark sky compatible, zero light trespass, scotopic/photopic ratio of 0.3 (the smaller the better, below 1 is wonderful). See https://crossroadsled.com/lighting-products/phosphor-converted-amber-street-lights/



GARDCO by signify

Site & Area

PureForm

PPT post top
with comfort optics

Gardco PureForm LED post top features a sleek, low profile design. Comfort optics are designed to enhance visual comfort by reducing glare. Type 1, 2, 3, and 5 optical distributions are available with lumen output up to 9000 lumens. A full range of control options provides additional energy savings. Optional integral emergency battery backup is available for path-of-egress illumination.

Project:
Location:
Cat.No:
Type:
Lamps: Qty:
Notes:

Ordering guide

example: PPT-140L-450-NW-G2-T3-1-UNV-DGY

Prefix	Number of LEDs	Drive Current	LED Color – Generation	Mounting	Distribution	Emergency	Voltage
PPT							
PPT PureForm post top, comfort optics	**140L** 140 LEDs	**450** 450mA **650** 650mA **1150** 1150mA [1] **1675** 1675mA [1] **2100** 2100mA [1,2]	**WW-G2** Warm White 3000K, 70 CRI Generation 2 **NW-G2** Neutral White 4000K, 70 CRI Generation 2 **CW-G2** Cool White 5000K, 70 CRI Generation 2 **WY-G2** Warm Yellow 2700K, 80 CRI Generation 2 [3] **BW-G2** Balanced White 3500K (80 CRI) Generation 2 [3] **AM-G2** Amber Generation 2 [3,12]	**T3** Mounts to a 3" x 4" Tenon (standard) **T2** Mounts to a 2-3/8" x 4" Tenon (must be ordered and shipped as a separate accessory)	**1** Comfort Type 1 **2** Comfort Type 2 **3** Comfort Type 3 **5** Comfort Type 5	Leave blank for no battery **EBPC** Emergency battery pack cold weather [2,4,5,6,7] **EBP** Emergency battery pack [1,4,5,7]	**120** 120V **208** 208V **240** 240V **277** 277V **347** 347V **480** 480V **UNV** 120-277V (50/60Hz) **HVU** 347-480V (50/60Hz)

Fig. 36: Pureform Gardco luminaires, matching the appearance of the Bega 121, but supporting Amber LEDs.

- Pg. 12: "*To preserve the park-like nighttime aesthetics of the campus, sparsely locate pole lights along walkways. This applies to walkways that are adjacent to and distant from roadways. Note that very low light levels between poles are to be expected.*"
- Pg. 14: "*Excessive or distracting light trespass into adjacent properties should be avoided with proper shielding.*"
- Pg. 17: "*Avoid or minimize spill light into the night sky.*" Note that overlighting, even with fully shielded fixtures, causes spill in the night sky through reflection from the ground (which depends on the albedo of the terrain under the lamp).
- Pg. 17: "*Consider dimmable luminaires wired to motion sensors to allow for multilevel lighting operation.*"
- Pg. 20: "*Luminaires should have properly controlled light beams by means of shielding to minimize glare and light pollution.*"
- Pg. 20: "*E. Avoid or minimize spill light into the night sky.*".
- Pg. 23: ***"All new pole luminaires should be Dark Sky compliant."*** Note, what dark-sky compliant means has changed over time, and new technology emerged. Perhaps more importantly, effects on health were less known and appreciated than in 2021.

G Motivation

I am not affiliated with any of the lighting companies. I am an astrophysicist who observes the night sky as part of my research, teaching, and passion. I admire nature, and I love our campus. I want to keep the light pollution down, even reverse it, for the reasons spelled out in the Introduction.

Flagstaff, Arizona, is a small town with a population of 75,000, about three times as many people as in Princeton. Flagstaff has been designated a Dark Sky Community by the International Dark Sky Association[15]. This gives me hope; if they could do it, we can surely do it.

Finally, I have done the research for this report "on the side", so please accept any mistakes I have made.

[15] `https://flagstaff.az.gov/3799/Dark-Sky-Community`

H References

- Luginbuhl, C. et al., 2014, "*The impact of light source spectral power distribution on sky glow*", Journal of Quantitative Spectroscopy and Radiative Transfer, 139, 21, https://www.sciencedirect.com/science/article/pii/S0022407313004792
- Aubé, M. et al., 2013, "*Evaluating Potential Spectral Impacts of Various Artificial Lights on Melatonin Suppression, Photosynthesis, and Star Visibility*", PLOS ONE, 2013, https://doi.org/10.1371/journal.pone.0067798.
- Flagstaff Dark Skies: http://www.flagstaffdarkskies.org/critical-dark-sky-issues/lamp-spectrum-light-pollution/
- Spiegel K, Knutson K, Leproult R, Tasali E, Van Cauter E (2005) Sleep loss: A novel risk factor for insulin resistance and Type 2 diabetes. J Appl Physiol 99(5): 2008–2019. http://scholar.google.com/scholar?q=Sleep+loss\%3A+A+novel+risk+factor+for+insulin+resistance+and+Type+2+diabetes+Spiegel+2005
- Bedrosian TA, Fonken LK, Walton JC, Haim A, Nelson RJ (2011) Dim light at night provokes depression-like behaviors and reduces CA1 dendritic spine density in female hamsters. Psychoneuroendocrinology 36: 1062–1069, http://scholar.google.com/scholar?q=Dim+light+at+night+provokes+depression-like+behaviors+and+reduces+CA1+dendritic+spine+density+in+female+hamsters+Bedrosian+2011
- Hansen J (2001) Light at night, shiftwork, and breast cancer risk. J Natl Cancer Inst 93(20): 1513–1515. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0067798#
- Blask DE, Brainard GC, Dauchy RT, Hanifin JP, Davidson LK, et al. (2005) Melatonin-depleted blood from premenopausal women exposed to light at night stimulates growth of human breast cancer xenografts in nude rats. Cancer Res 65(23): 11174–11184. http://scholar.google.com/scholar?q=Melatonin-depleted+blood+from+premenopausal+women+exposed+to+light+at+night+stimulates+growth+of+human+breast+cancer+xenografts+in+nude+rats+Blask+2005
- Stevens RG (2009) Light at night, circadian disruption and breast cancer: Assessment of existing evidence. Int J Epidemiol 38(4): 963–970. http://scholar.google.com/scholar?q=Light+at+night\%2C+circadian+disruption+and+breast+cancer%3A+Assessment+of+existing+evidence+Stevens+2009
- Spiegel K, Tasali E, Penev P, Van Cauter E (2004) Sleep curtailment in healthy young men is associated with decreased leptin levels, elevated ghrelin levels, and increased hunger and appetite. Ann Intern Med 141(11): 846–850. http://scholar.google.com/scholar?q=Sleep+curtailment+in+healthy+young+men+is+associated+with+decreased+leptin+levels%2C+elevated+ghrelin+levels%2C+and+increased+hunger+and+appetite+Spiegel+2004
- Fonken LK, Workman JL, Walton JC, Weil ZM, Morris JS, et al. (2010) Light at night increases body mass by shifting the time of food intake. Proc Natl Acad Sci U S A 107(43): 18664–18669. http://scholar.google.com/scholar?q=Light+at+night+increases+body+mass+by+shifting+the+time+of+food+intake+Fonken+2010
- Steinbach, R. et al., 2015, Journal of Epidemilogy and Community Health, 69, 11, https://jech.bmj.com/content/69/11/1118.

- Falchi et al. 2016, "*The new world atlas of artificial night sky brightness*", Science Advances, 2, e1600377, DOI:10.1126/sciadv.1600377, https://advances.sciencemag.org/content/2/6/e1600377 and https://cires.colorado.edu/Artificial-light.
- Lighting, crime and safety : https://www.darksky.org/light-pollution/lighting-crime-and-safe
- Astrophile luminaires: https://crossroadsled.com/lighting-products/phosphor-converted-ambe
- Lumecon street lights: https://lumecon.com/wp-content/uploads/2015/10/Lumecon-LDS-SAL_10292020.pdf
- Updated Princeton University Outdoor Lighting Master Plan: https://facilities.princeton.edu/sites/facilities/files/2.9-15.pdf This plan is coherent document with a number of positive elements, but needs significant updates, because light pollution, nature conservancy, sustainability and adverse health effects (due to new research) are not taken with enough weight.
- Pureform luminaires: https://www.signify.com/en-us/products/outdoor-luminaires/site-area/architectural-posttop/pureform-led-post-top-comfort-ppt
- Integrating lighting with wildlife: https://www.klikusa.com/case-study/integrating-lighting-wi
- Dark sky friendly lighting: https://www.darksky.org/our-work/lighting/lighting-for-industry/fsa/.
- Saving our stars with Amber LED lighting: https://www.savingourstars.org/amberleds
- A useful twitter feed on Amber LEDs: https://twitter.com/i/events/841713704559378432.
- IES BUG ratings: https://www.ies.org/wp-content/uploads/2017/03/TM-15-11BUGRatingsAddenc
pdf%\itemFlagstaffisaDarkSkyCommunity:\url{https://flagstaff.az.gov/3799/Dark-Sky-Comm