Outdoor Lighting and the Effects of Artificial Light at Night (ALAN)

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List of Abbreviations

ALAN…………………………………………………………………. Artificial Light at Night

AMA…………………………………………………………... American Medical Association

CCT………………………………………………………….. Correlated Color Temperature

fc…………………………………………………………………………………… footcandles

HID………………………………………………………………….. High-intensity Discharge

HPS…………………………………………………………………….. High-pressure Sodium

IES………………………………………………………….. Illuminating Engineering Society

LED………………………………………………………………………. Light-emitting Diode

LPS…………………………………………………………………………Low-pressure Sodium

MH……………………………………………………………………………….. Metal Halide

SPD…………………………………………………………….... Spectral Power Distribution

1. EXECUTIVE SUMMARY

As Light Emitting Diodes (LEDs) are replacing High Pressure Sodium (HPS) street lights, some groups have concerns about the health and environmental effects of blue-rich LED lights. The AMA released a report recommending that all street lighting have a CCT of less than 3000K, but other organizations felt this threshold was arbitrary and unfounded. To shed light on this dispute, I researched the effects of artificial light at night (ALAN), particularly concerning LED lights, to determine what policies design companies should set concerning outdoor lighting.

I have learned that artificial light at night (ALAN) has been linked to many serious health conditions, including diabetes, cancer, heart disease, obesity, and depression. Light sources with high intensities of 450-500 nm light disrupt our bodies' circadian rhythm and make it more difficult for our eyes to adjust to darkness. LEDs, even low-CCT LEDs, have a spike in intensity in that range. Although sources with high blue light content tend to be more energy-efficient and require fewer lumens for the same visibility, these advantages pale as we consider that the effect on circadian rhythm for sources with high concentrations of blue light has been found to be around five times as severe as sources such as High Pressure Sodium (HPS). Studies have also shown that sources with high blue light content impact natural photosynthesis cycles, disrupt animal behavior, and affect skyglow and star visibility much more severely than warmer sources like HPS.

Unfortunately, I also discovered that CCT, often the only metric that manufacturers release about the light source in a luminaire, is a poor descriptor of blue light content. On average, higher-CCT sources will have higher levels of blue light, but two sources with the same CCT can have wildly different levels of blue light, meaning that a designer cannot know the effects of the light source they choose.

This presents a challenge and an opportunity for lighting designers. It is their mission to provide effective and safe outdoor lighting, and it is crucial to be aware of the effects their projects can have on human health and the environment. To provide exceptional design to clients, designers will need to be pioneers in calling for new light sources and metrics to describe spectral distribution, while continuing to serve their clients excellently with limited information.

Consequently, I recommend lighting designers take the following actions:

1. Demand the development of low-impact sources
2. Demand the development and use of indices to describe spectral content
3. In the meantime, use creative design strategies and, when possible, low-CCT sources to mitigate effects.

2. INTRODUCTION

As LED light sources continue to become more effective and less expensive, the pressure to replace traditional street lights with LEDs increases. This pressure is not without reason: LEDs consume less energy, have better color rendering, and last longer than the high-pressure sodium (HPS) lights that were the previous standard for street lighting.

However, organizations including the American Medical Association (AMA), which released a report on the subject in 2016, have raised concerns about the effects of LED lights on human and environmental health. While the AMA's report expressed support for LED street lighting, it also included a recommendation to use only lights with a CCT under 3000K [1]. Several groups gave dissenting responses to the report. The U.S. Department of Energy pointed out that many of these issues predate LED lighting, and that blue light from LEDs is not inherently more dangerous than light with the same wavelength from other sources [2]. The National Electrical Manufacturers Association and the Illuminating Engineering Society (IES) argued that 3000K is an arbitrary, unfounded, and unnecessarily restrictive limit and that more comprehensive research is needed to determine the best policy recommendations [3] [4]. The purpose of this report is to present the results of my research on artificial light at night (ALAN) and how lighting designers can mitigate the effects of ALAN while providing exceptional design to clients.

In this report, I will discuss the effects of ALAN on humans and the environment, how these effects became so widespread, strategies that can mitigate effects, and possible solutions, including promising new light technologies.

I gathered technical data for this report by reviewing research articles and conference proceeding written by experts in the lighting field. Since part of this report deals with public opinion and how LED lighting is perceived, I have also gathered information from a few reputable news articles.

The remainder of this report is organized in five main sections. First, Section 3 deals with the effects and causes of ALAN. Then, Section 4 details mitigation strategies. Section 5 shows how the strategies presented in Section 4 can be used to reduce the effects of ALAN. Next, Section 6 reviews my main findings and describes why they are important to lighting designers. Lastly, Section 7 presents my recommendations for lighting designers.

3. ARTIFICIAL LIGHT AT NIGHT (ALAN)

As ALAN becomes more prevalent, researchers are starting to catch up with the rapid development in lighting technology, particularly LEDs. While LED lights have been revolutionary for lighting, providing significant improvements in almost all categories, their full impact has recently started to become clear. In this section, I will discuss the harmful effects of artificial light at night and how the rise of LED lighting has triggered a dramatic propagation of these effects.

3.1. Effects

This section discusses the effects of ALAN, separated into three main categories: human health and safety, environmental effects, and sky visibility.

3.1.1. Human Health and Safety

Artificial Light at Night (ALAN) has been connected to many serious health conditions, including diabetes, obesity, heart disease, depression, and certain kinds of cancer [5]. The main problem seems to be melatonin suppression. According to [6, p. 11], “evidence indicates that people living in illuminated urban environments suffer increased breast cancer rates while suffering no more than average rates of lung cancer, which is not linked to melatonin levels.” This would suggest that melatonin suppression due to artificial light exposure plays a causative role in breast cancer. Although it is difficult to be sure of causation, the correlation is strong enough for concern. Melatonin suppression can occur even when the exposure time is very short: Zeitzer et al. found that 2- millisecond flashes of light delayed the circadian rhythm by 45 minutes [7].

ALAN is also an important factor affecting road safety. Contrary to common assumptions, more light does not automatically mean safer roads. According to [8], dimming or switching off lights at night did not affect road collisions. In fact, more light, especially low-wavelength light, may be more dangerous on the road. Jin et al. found that as CCT increases, dark adaptation time, or the time it takes for our eyes to adjust to darkness, also increases [9]. Dark adaptation also increases as road illuminance increases [9]. A longer dark adaptation time means that drivers will be less able to react quickly to threats on the road. Research by [10] supports this conclusion, finding that exposure to blue light at night increased reaction times. Because people perceive blue light as more glaring than other wavelengths, low wavelength street lights can cause comfort issues and even be hazardous if they are not properly shielded [6].

The effect of outdoor lighting on crime should also be examined. More light is often assumed to be a cure-all for crime, but the data do not necessarily support this conclusion. [8] conducted an extensive longitudinal study on road lighting in England and Wales, focusing on four street light adaptation strategies: ‘switch off’, where lights are turned off permanently; ‘part-night’ lighting, where lights are turned off for part of the night; ‘dimming,’ or reducing light output; and ‘white light,’ replacing existing HPS bulbs with whiter, more efficient LEDs. The researchers found weak evidence suggesting a decrease in crime with dimming and white light, but switch-off and part-night lighting did not increase crime. Overall, they were unable to draw strong conclusions. Other studies have claimed to show decreased crime by introducing white street lights, but those studies have also been criticized for using flawed methods including a cross-sectional design, deceptively grouped data, and a failure to consider alternative causal explanations [11].

3.1.2. Environmental Effects

Studies on ALAN and animals have found almost exclusively negative effects. An estimated 60% of all animals are nocturnal, and ALAN disrupts many behaviors including foraging, reproduction, communication, and migration [1] [5]. Birds navigate using the moon and stars, and hatchling sea turtles are unable to find their way to the sea when ambient light levels are too high [6]. Even bridge lighting can cause problems; in a study on salmon, [12] found that areas with bright light attracted up to 10 times more salmon than the no-light areas. This puts salmon, an already endangered species, at a greater risk of predation. Another study on jerboas, a nocturnal desert rodent, concluded that white LED lighting had net negative effects [13]. Although the researchers noted that the jerboas had better foraging efficiency, they also foraged less thoroughly and left more food behind under LED lighting than in the dark. The researchers even suggested that ALAN used as a deterrent has some promise as a rodent pest control method [13].

Few researchers have studied the effects of ALAN on plants, but these researchers have found evidence that ALAN may trigger photosynthesis when it would not normally occur, disrupting natural cycles and seasonal adaptation [5]. This may cause plants to flower, bear fruit, or enter dormant and growth cycles at the wrong times [5].

3.1.3. Sky visibility

Throughout history, celestial bodies have been an important part of human life. For centuries, they have been inspirations for art, poetry, music, religion, and philosophy, essential for navigation, and a constant reminder of the vastness of the universe. However, this human experience is no longer universal: Falchi et al. reveal that as of 2016, over 99% of the United States population experiences light-polluted skies, and 80% of the population cannot see the Milky Way [14]. Light pollution generated in large cities can reach hundreds of miles into sparsely populated areas, making light pollution especially difficult to control. Additionally, as areas of heavy light pollution grow, astronomical research becomes more difficult to conduct and observatories decrease in value [6]. Figure 1, on the next page, shows a map of North America’s artificial sky brightness. The blue zones indicate areas that are considered astronomically polluted. In yellow and orange areas, the Milky Way is partially or completely obscured. At the red and white levels, the sky is so polluted that the human eye cannot fully adapt to dark vision [14].

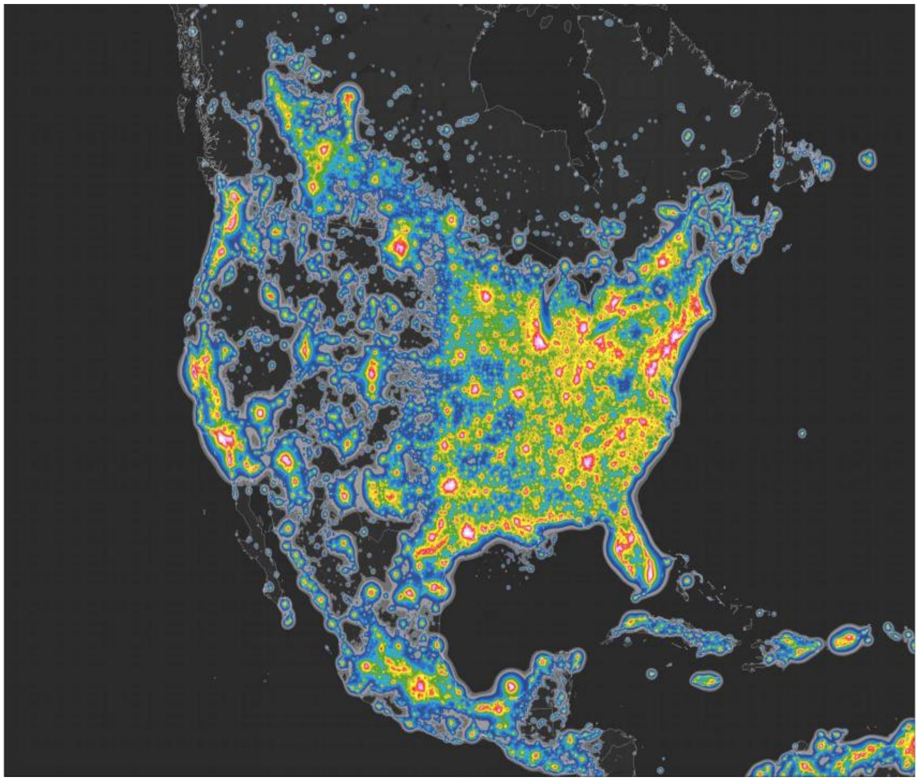

Figure 1: Map of artificial sky brightness levels in North America (Reproduced from [14]).

3.2. Cause: The Advent of LED Light

In its response to the AMA report detailing the effects of ALAN, the US Department of Energy points out that “these issues are neither new nor restricted to LED technology” [2, p. 1]. This is true; but, as I show in this section, the same unique characteristics that make LEDs so attractive have incentivized the spread of these problems far beyond the scale that would be possible with other light sources, and because LEDs have developed so quickly, effective strategies to limit negative effects have not been developed yet. Specifically, in sections 3.2.1 through 3.2.3, I address how the spectral distribution, potential cost savings, and light emission pattern of LED sources have caused the effects presented in the previous section to become nearly inescapable.

3.2.1. Spectral Distribution

The most influential factor in how severe the effects of ALAN are is the wavelength of light. Humans are more sensitive to certain kinds of wavelengths depending on what mode of vision they are in. Figure 2, below, shows normalized sensitivity curves for the human eye under photopic and scotopic conditions.

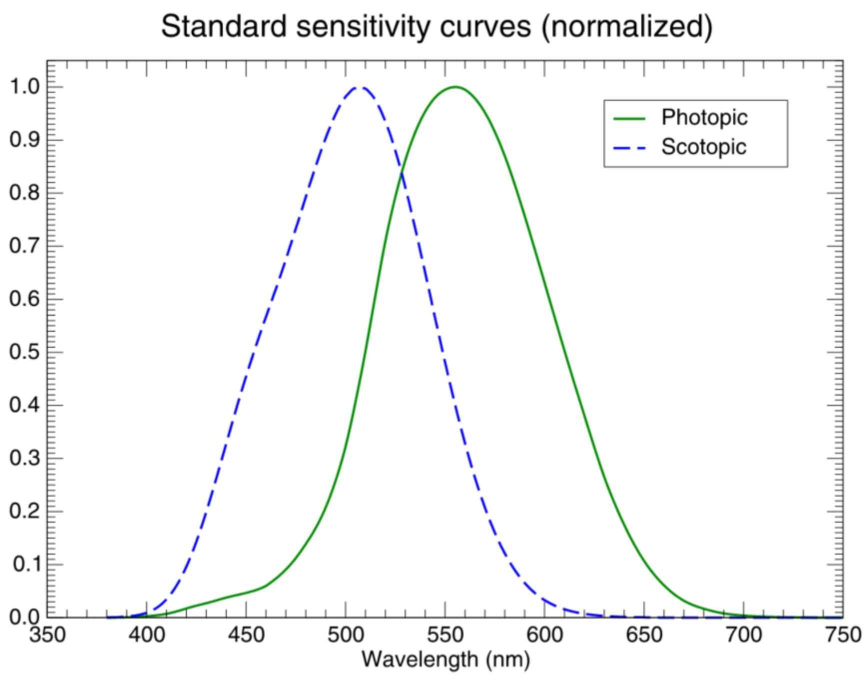

Figure 2: Normalized Sensitivity Curves for Photopic and Scotopic Vision (Reproduced from [15]).

Photopic vision is triggered at higher light levels and is controlled by cone cells in the retina. These cone cells are adept at perceiving fine detail and differences in color. As Figure 1 shows, in photopic vision, the eye is more sensitive to warmer wavelengths, peaking around 570 nm [15]. By contrast, when the eye is in scotopic vision, it is more sensitive to cool wavelengths, peaking at approximately 490 nm. Scotopic vision is controlled by rod cells in the retina; rods lack the ability to discriminate color and fine detail but are very sensitive to low levels of light. Scotopic vision is triggered at low light levels, particularly outside at night. Mesopic vision is a combination of scotopic and photopic vision that occurs when light levels are between scotopic and photopic levels. When people pass by street lights at night, they will likely be in scotopic or mesopic vision and will be very sensitive to outdoor lights with high concentrations of blue-wavelength light.

The effect of blue-wavelength lights on humans and the environment are much more severe than warmer wavelengths. Melatonin suppression in sources with high blue light content can be orders of magnitude higher than in warmer sources. Sources with lots of blue light also contribute more to skyglow for the same lumen because blue light scatters more efficiently in the atmosphere [5]. According to [6, p 14], "In a relatively dark suburban or rural area, where the eyes can become completely or nearly completely dark-adapted (scotopic), the brightness of the sky glow produced by artificial lighting can appear 3–5 times brighter for blue-rich light sources as compared to HPS and up to 15 times as bright as compared to LPS." Blue light also causes the longest dark adaptation times; in fact, for this reason military personnel and astronomers often maintain night vision using red lights [6]. Lastly, the effect on photosynthesis is more acute. Similar to humans, plants have a peak in light sensitivity around 450 nm, so nighttime light in that region is more likely to trigger photosynthesis at unnatural times.

This information is relevant here because LEDs, even low-CCT LEDs, tend to have a spike in power that matches the region of high scotopic sensitivity. As seen on the next page in Figure 3, the intensity in the 450-500 nm region is drastically higher in LEDs than in other HID sources. Aubé et al. found that 5000K LEDs suppressed melatonin 4.6 times more than an HPS source of the same lumen output [5]. Even the 2700K LED resulted in almost 2.5 times more melatonin suppression compared to the HPS [5]. LEDs are most energy-efficient at higher wavelengths, so cities looking for maximum savings are more likely to choose a higher-CCT LED with a higher blue light content.

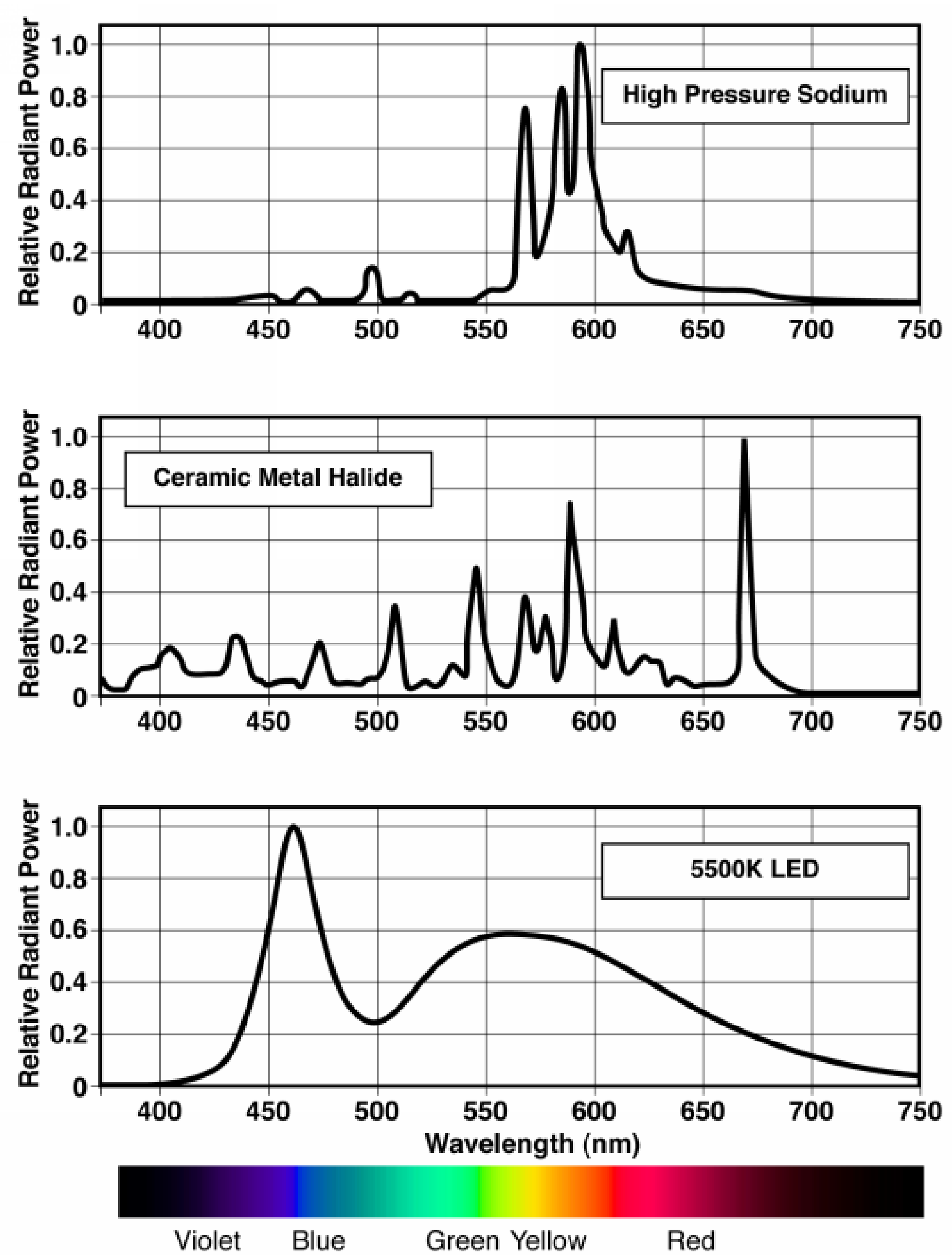

Figure 3: Spectral Power Distributions for HPS, MH, and LED sources (Reproduced from [6]).

3.2.2. Cost Savings

One of the main reasons LED lights are so attractive, especially as a replacement for current HPS or MH streetlights, is because their increased efficacy and lifespan promise significant cost savings. The efficacy of LEDs can be 150 lumens/watt, compared to 75-100 lumens/watt HID sources. The AMA claims this can translate to a 50% reduction in energy consumption [1]. Additionally, LEDs' life expectancy can be twice that of HID sources, promising additional cost savings since lamps need to be changed less often. Figure 4, below, shows the lumen depreciation of common light sources over time. As the figure shows, not only do LED sources last much longer than all other sources, they also maintain more lumens over the course of their life. The metal halide and high-pressure sodium sources start to degrade quickly and lose around 20% of their initial lumen output in the first 5,000 hours. By contrast, the LED source does not drop to 80% output until around 40,000 hours. The cost savings due to switching to LEDs is considerable: Los Angeles replaced 150,000 streetlights with LEDs and expects the switch to save $8 million a year [16]. LED lighting does have a higher up-front cost, but that cost is also decreasing steadily as technology advances.

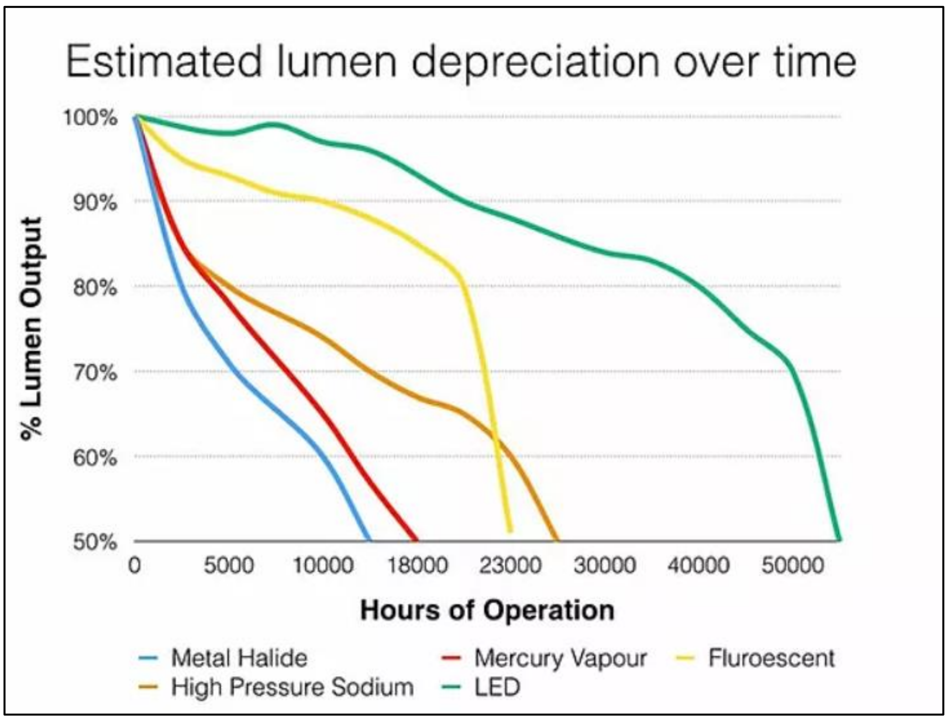

Figure 4: Estimated lumen depreciation for common light sources (Reproduced from [17]).

Of course, decreasing costs are usually considered beneficial. The reason this drop in cost is important here is that as light becomes cheaper, people buy more of it. Streetlights are installed on roads that were previously unlit, increasing ALAN levels. Designers and clients tend to see more light as erring on the side of caution, especially with decreasing costs. But the effects of ALAN are proportional to light intensity; the higher the light level, the more severe the effects [5]. So, as light costs decrease, ALAN levels will increase, intensifying their effects.

3.2.3. Direction of light emission

A unique characteristic of LED lights is the direction of light emission. As shown in Figure 5, below, traditional light sources emit light and heat in all directions. LEDs emit light in one direction, with heat being released in the opposite direction. This means that LED fixtures tend to have a higher fixture efficiency because fewer reflectors are needed, but it also tends to cause more glare than other sources because the light is so focused. Especially since road lighting uses fixtures with a high lumen output, glare from LED lighting can be more severe and more dangerous than from other sources. Proper shielding and placement of luminaires are crucial to avoid hazardous glare on roads.

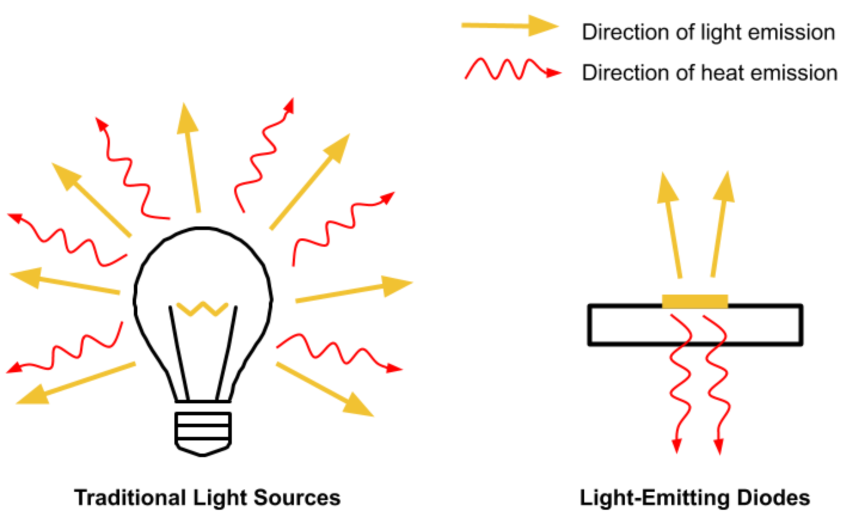

Figure 5: Light and heat emission for traditional light sources vs LEDs

4. STRATEGIES FOR MITIGATING EFFECTS

In this next section, I explain strategies for mitigating the negative effects of ALAN. LED lighting is only going to become more prevalent and implementing these strategies will allow lighting designers to utilize LED lighting in a safe and effective way. Specifically, I discuss ensuring proper design, limiting uplight, and limiting blue light.

4.1. Ensure proper design

Limiting light levels, matching distribution patterns to the lighting area, and ensuring fixtures are properly shielded will minimize glare and unnecessary light. The IES Handbook is much vaguer on its recommendations for outdoor lighting than indoor lighting, but it does recommend illuminance levels between .1 and 3 fc, depending on outdoor activity levels and surrounding light conditions [18]. These levels are almost nothing compared to levels designers usually target for indoor lighting, so if designers are used to indoor spaces, they will need to be careful not to over-light. They should also be sure to choose fixtures that have a distribution pattern that matches the space they are lighting; for example, they should not choose to light a narrow sidewalk with a round distribution pattern. Lastly, designers should use fixture selection and placement to ensure that the light source is shielded from view.

4.2. Limit uplight

Another strategy designers can use to mitigate the effects of ALAN is to limit uplight. Fixtures with lots of uplight waste energy and needlessly contribute to skyglow. With the multitude of fixtures that are available today, designers should be able to find fixtures that match the style of the space for which they are designing and minimize uplight. If designers wish to incorporate uplight techniques for aesthetic purposes, such as grazing from below, they can use strategies to lessen the impact, like dimming or switching off these lights after a certain time.

4.3. Limit blue light

Finally, to lessen the impact of ALAN, designers should limit the use of blue light in outdoor lighting. This strategy is the most difficult for designers to implement because they often do not have access to information on blue light content. Manufacturers usually release the CCTs of the light sources they use, but not the spectral power distributions (SPD). SPDs show the relative quantity of light at all visible wavelengths and are the best resource for determining the makeup of a light source. Figure 6, below, shows SPDs for five different LED lights with the same CCT.

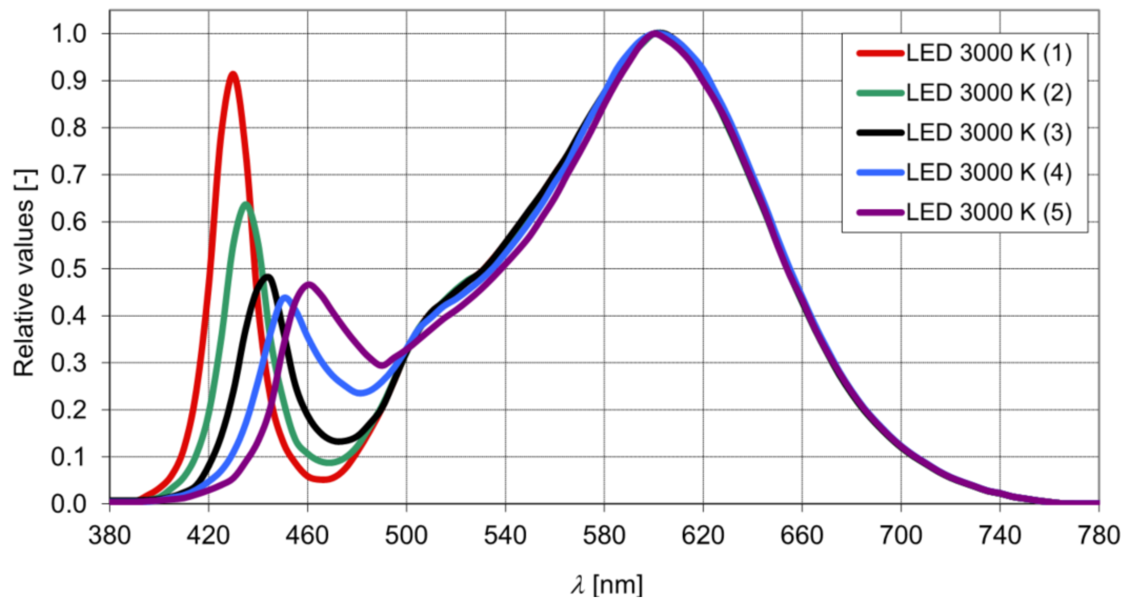

Figure 6: SPDs for five LED sources with the same CCT (Reproduced from [19]).

While CCT is a convenient and universal metric to communicate how a light source looks, Figure 6 reveals that CCT shows an incomplete picture of a light source. All five LEDs shown have a CCT of 3000K but have very different levels of blue light. For example, LED 1 has approximately twice the blue light content of LED 4. There is a general correlation between CCT and blue light content, but [15, p. 406] found CCT to be “a bad descriptor for the evaluation of the content of blue light, especially in the interval of the most frequent CCTs, from 2000 to 4000K.” A designer trying to follow the AMA’s recommendation could choose a light source with a CCT below 3000K but with a blue light content higher than other sources with CCTs well over 3000K. Because manufacturers rarely include spectral power distributions in the information provided to customers, it is difficult for a designer to know if the lights they choose will be harmful to people who will use them.

5. SOLUTIONS

Lighting technology has developed rapidly over the last 100 years; the efficiency of LEDs has seen a thousandfold increase since their invention in the 1960s [20]. I am confident that as technology continues to progress, the lighting industry will introduce light sources, metrics, and strategies that mitigate the negative effects of ALAN without sacrificing the advantages of artificial light. In this section, I discuss how the development of new light sources and indices can solve this problem, and what we can do in the meantime to mitigate its effects.

5.1. Develop and use low-impact light sources

The easiest and most efficient way to make an LED is to have it emit one color of light and then use lenses with phosphor coatings to add other wavelengths. Using the coatings to filter out blue light and add yellow costs energy, which is why the most efficient LEDs have the highest blue light content. Some lighting companies, however, are responding to concerns about blue light and are developing new strategies. Cree has a new type of light that combines blue LEDs with red-emitting LEDs. The resulting color resembles a warm white LED, but with fewer phosphors, and therefore a higher efficacy [16]. Another manufacturer puts 3000K and amber LEDs in the same fixture: "The white LEDs switch off after workers go home, and the amber lights switch on to provide security with minimal impact on astronomers and wildlife"[16, par 38]. LED lighting is easy to make in many colors and has much better control functions than HID sources. Encouraging the development and use of high-efficacy sources and creative control functions will go a long way towards creating a healthier nighttime environment.

5.2. Develop and use new indices to describe the spectral content of light sources

As I stated in section 4.3, it is often impossible for designers to know what the blue light content of an LED source is. The CCT system was developed based on incandescent lights, and in our increasingly LED-centric world, it is less useful. Although releasing a full SPD for every light source may be impractical, several researchers, including [5] and [15], have proposed indices that would more accurately describe the spectral distribution of a source. These indices could provide an "accurate, objective, and quantitative" measure of a source's spectral distribution with a few numbers, estimating a source's potential impact on health and the environment [15, p 399].

Galadí claims that the calculation of theses indices is simple and should use data that manufacturers already have [15]. These metrics will allow designers to be fully informed about light sources and choose fixtures that have the lowest impact on human health, the environment, and sky visibility.

5.3. Use mitigating design strategies

Even as designers push for new and better light sources and metrics, they still must provide clients with the best design possible, even with incomplete information. Strategies described in sections 4.1 and 4.2 will limit the effects of over lighting and glare. CCT is a far from perfect descriptor of a light source, but, as shown in Figure 7 below, there is a general correlation between CCT and blue light content. In the absence of any other information, designers should choose lower CCT sources when possible to limit blue light content, while also considering other issues like color rendering.

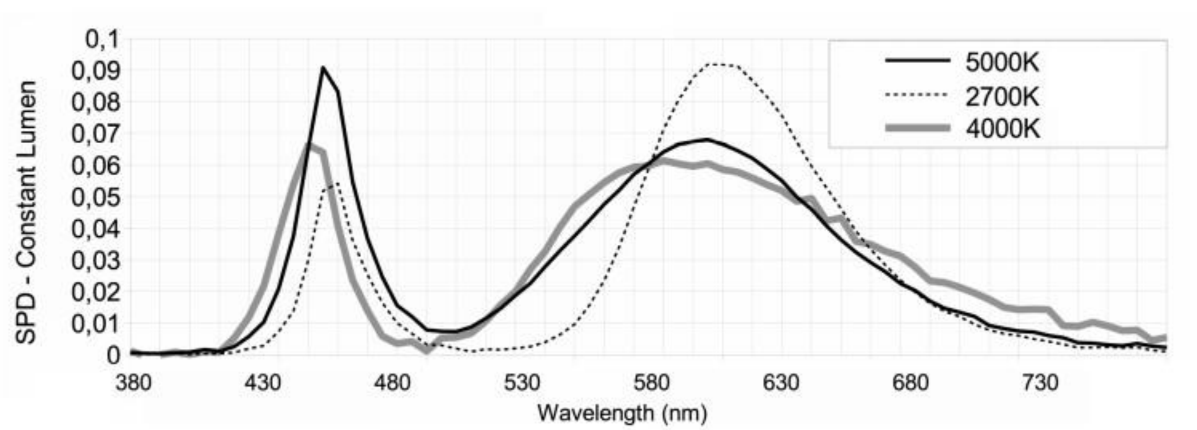

Figure 7: SPDs of three LED sources with different CCTs (Adapted from [5]).

6. CONCLUSION

I found that artificial light at night, particularly in the range of 450-500 nm, does have serious negative effects. ALAN can suppress melatonin, cause road hazards, disrupt natural animal and plant processes and cycles, and obstruct views of the night sky. Lighting designers should be committed to providing the best lighting design possible for their clients and the environment. Considering the effects of ALAN and what designers can reasonably do to minimize these effects while completing the design as the client wants it is crucial. Additionally, designers will be able to use this information to counsel clients on best practices for outdoor lighting.

I have also discovered that these problems surrounding ALAN will be very difficult to solve without restructuring lighting metrics. CCT's value lies in estimating how a light source will look to occupants, but it does a poor job describing a source's spectral content. However, this provides an opportunity for designers to lead the way in calling for manufacturers to release metrics about spectral distribution and develop LED sources with low levels of blue light. By advocating for changes in the lighting industry, designers can be pioneers in lighting design practices and have a lasting impact on the industry.

7. RECOMMENDATIONS

Based on my research, I recommend lighting designers do the following:

1. Demand the development of low-impact sources
2. Demand the development and use of indices to describe spectral content
3. In the meantime, use creative design strategies and, when possible, low-CCT sources to mitigate effects.

As even current low-CCT sources have high levels of blue light, lighting designers should push for the development of new LED sources that are specially formulated to provide safe outdoor illumination and patronize manufacturers who are currently developing these sources. If design firms express a demand for these sources, manufacturers will be more likely to develop and distribute them, leading to higher-quality outdoor light.

Designers should also demand that manufacturers release more information about the spectral content of light sources. Releasing either full SPDs or simpler indices proposed by researchers will allow designers to make informed decisions. In addition, releasing these metrics may incentivize manufacturers to create better LED lights.

Although it would be ideal if these new light sources and metrics were available immediately, we recognize that we live in the real world and these changes will not happen overnight. As designers advocate and waits for lighting metrics to catch up with the rapid development of

LEDs, we still need to serve clients in the best way we can. Designers will need to continue making choices about light sources, even with insufficient information. With that in mind, I recommend that designer use low-CCT sources (3000K or below) for outdoor lighting design whenever possible, as low-CCT sources, on average, will have a lower blue light content. Combined with proper design and control strategies like dimming and timed shutoffs, this will limit the negative effects of ALAN until more information becomes available.

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