DLC
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Whitepaper: Non-white Light Sources for Nighttime Environments

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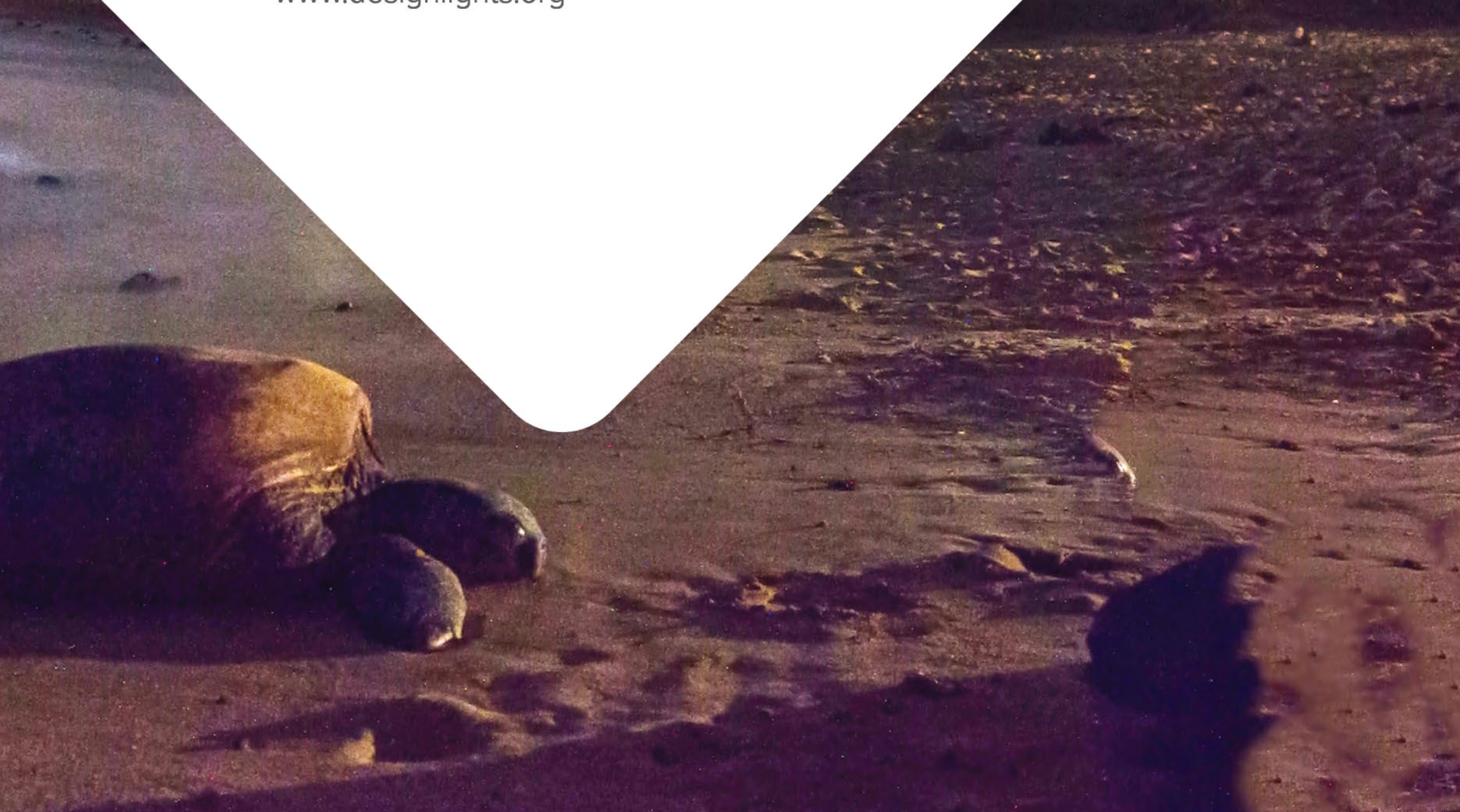

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Executive Summary

Background

The DesignLights Consortium (DLC) recently introduced the first version of its LUNA Technical Requirements. The policy offers a streamlined way to identify and select LED products that meet the efficacy thresholds necessary for inclusion on the DLC's Solid-State Lighting (SSL) Qualified Products List (QPL) while also limiting sky glow and light trespass and helping to mitigate light pollution. LUNA sets performance requirements for specific categories of outdoor LED fixtures so that municipalities, energy efficiency programs, and other outdoor lighting decision-makers can better support their energy reduction goals and abide by dark sky policies and ordinances. LUNA will also help specifiers to fulfill the light pollution and trespass requirements of LEED and WELL building programs, and help projects follow application guidance in the joint International Dark Sky Association-Illuminating Engineering Society Model Lighting Ordinance.

A subset of the DLC's SSL Technical Requirements, the LUNA V1.0 Technical Requirements apply only to white light LED outdoor products with correlated color temperatures (CCT) between 2200K and 3000K, and do not include non-white light (NWL) LED luminaires deemed appropriate for settings such as environmentally sensitive wildlife areas. During development and implementation of the first iteration of LUNA V1.0, stakeholders asked the DLC to consider allowing NWL LED sources, such as phosphor-converted- (pc-) amber and direct emission (de-) amber products, to be eligible for LUNA qualification.

This whitepaper provides an overview of the state of the science and current recommendations for NWL light sources in outdoor lighting applications, as well as why the DLC is not addressing NWL LED luminaires in LUNA at this time. The paper suggests next steps to address gaps in existing research, standards, and guidelines that would make qualification feasible in the future.

Environmental impacts of white light vs. NWL products

Outdoor LED lighting offers a range of benefits over incumbent technologies (such as high-pressure sodium (HPS) and low-pressure sodium (LPS) fixtures), including higher efficacies and improved optical and temporal control. The increased amount of short wavelength (violet-blue) radiation in these LED spectral power distributions (SPD), however, has been linked to several deleterious impacts, particularly if applications use high CCT products and/or areas are excessively lit. The known negative impacts from light at night, at meaningful doses and times, can include:

- Disruption in the circadian systems of animals and plants;
- Disorientation of wildlife such as sea turtles and migrating birds (the latter suffering significant mortality from collisions with illuminated buildings);
- Harm to both diurnal and nocturnal insects; and
- Increases in pathogenic risks.

Against this backdrop, NWL sources that eliminate short wavelength radiation have surfaced as a potential strategy to limit light pollution and other negative effects of anthropogenic/artificial light at night (ALAN). While HPS and LPS lamps have been common for outdoor lighting historically, two types of "amber" outdoor LED fixtures - phosphor-converted amber (pc-Amber) and direct emission amber (de-

Amber) - are becoming readily available, and a third market category of “amber” LED chips with better color rendition (pc-LEDs) is emerging.

Lack of standardization

As researchers and stakeholders seek to describe the capabilities and features of these products, however, lack of standardization in metrics and measures is glaringly apparent. A market review conducted for this whitepaper evaluated the lighting requirements published by various institutions ranging from public advocacy groups to governmental regulators and found little agreement on NWL spectral thresholds and metrics. Likewise, there is wide variation and lack of standardization in lighting and LED chip terminology, and it appears that multiple actors and advocates are working independent of one another to define limits that meet their specific needs.

Findings

With regards to efficacy performance, the DLC found that:

- Very few pc-Amber products could meet DLC’s threshold efficacy requirements.
- No de-Amber products could meet the DLC’s threshold efficacy requirements.

With regards to spectral reductions in relative sky glow, the DLC found that:

- LPS and de-Amber sources, as well as evaluated pc-Amber sources, all produced lower relative sky glow than HPS.
- Pc-LED products had better color rendition than other NWL sources, but increased relative sky glow.
- The scotopic/photopic (S/P) ratio was the strongest predictor of relative sky glow.
- Relative sky glow is not predicted by color fidelity metrics such as CRI R_a or TM-30 R_f.
- There are spectral tradeoffs for each type of NWL product evaluated, and specifiers will have to find a balance between reducing relative sky glow and having good color rendition. No NWL light source outperformed all of the others in every aspect.

In addition to a need for standardization of NWL nomenclature, the whitepaper identifies several research tasks that the DLC must undertake before inclusion of NWL LEDs can be considered. Importantly, these include:

- Evaluation of more data from de-Amber LEDs products, particularly regarding susceptibility of lumen output and lumen and color maintenance to temperature fluctuations.
- Evaluation and development of appropriate luminaire efficacy, color rendition, and color maintenance thresholds for pc-Amber and pc-LEDs.

Calls to action

The lighting industry needs an integrated approach to solving the unintended negative consequences of light pollution on the natural environment. This whitepaper seeks to describe the landscape for a small but promising part of the solution: NWL LED light sources. Since the DLC uses standards to ensure that LED luminaires qualified under DLC technical requirements can be reliably and consistently measured and evaluated worldwide, existing lighting standards must be updated to include NWL sources so that the DLC and other stakeholders can evaluate these products using a consistent framework. To address these types of products in the future, necessary developments include:

- Standardized chromaticity boundaries for NWL products, including “amber,” “red-orange,” “red,” etc.;
- Standardized terminology and naming conventions;
- Standardized nomenclature that encompasses the totality of optical radiation to which non-human taxa are sensitive;
- Guidance on color rendition thresholds for NWL sources;
- Standardized reporting requirements for light source spectral power distribution; and
- Standardized calculation procedures for computing astronomical sky glow and other negative impacts of ALAN.

As efforts get underway to develop uniform standards for NWL LED products aimed at mitigating the negative impacts of ALAN, the DLC looks forward to continued engagement with stakeholders across the industry.

Project Scope and Purpose

The DesignLights Consortium (DLC) recently introduced the first version of its LUNA Technical Requirements. The policy offers a streamlined way to identify and select LED products that meet the efficacy thresholds necessary for inclusion on the DLC's Solid-State Lighting (SSL) Qualified Products List (QPL) while also limiting sky glow and light trespass and helping to mitigate light pollution. LUNA sets performance requirements for specific categories of outdoor LED fixtures so that municipalities, energy efficiency programs, and other outdoor lighting decision-makers can better support their energy reduction goals and abide by dark sky policies and ordinances. LUNA will also help specifiers to fulfill the light pollution and trespass requirements of LEED and WELL building programs, and help projects follow application guidance in the joint International Dark Sky Association-Illuminating Engineering Society Model Lighting Ordinance. A subset of the DLC's SSL Technical Requirements, the LUNA V1.0 Technical Requirements apply only to white light LED outdoor products with correlated color temperatures (CCT) between 2200K and 3000K, and do not include non-white light (NWL) LED luminaires deemed appropriate for settings such as environmentally sensitive wildlife areas.

During development and implementation of the first iteration of LUNA V1.0, stakeholders asked the DLC to consider allowing non-white light (NWL) LED sources, such as phosphor-converted- (pc-) amber and direct-emission- (de-) amber products, to be eligible to qualify under the LUNA V1.0 Technical Requirements. The DLC consulted with Tony Esposito from Lighting Research Solutions to survey the state of the science and the current recommendations for NWL sources in outdoor lighting applications. The DLC was also interested in understanding the performance of NWL LED products relative to white LED products and the organization's own technical requirements.

Terminology

White Light: Light whose CCT falls into the ANSI *Basic* and *Extended* Nominal CCT quadrangles in ANSI C78.377-2017 (see Figure 1).

Non-white Light: Light whose CCT falls outside the ANSI *Basic* and *Extended* Nominal CCT quadrangles in ANSI C78.377-2017 (see Figure 1).

pc-Amber: Short for phosphor-converted amber, a non-white light source that uses a blue LED with a phosphor to produce a broad amber emission, similar to the method used in commercially available pc-White LEDs. Typically produce highly saturated color.

de-Amber: Short for direct emission amber, a non-white light source with a peak emission near 590 nm. Have a significantly narrower spectrum than pc-Amber LEDs and produce a more saturated color.

pc-LEDs: A non-white light source that uses phosphor conversion to yield chromaticities close to the Planckian locus with CCTs less than 2200K. Considered NWL because chromaticities fall outside the ANSI nominal CCT designations. Have more broadband spectral emissions than pc-Amber or de-Amber, and typically, better color rendition.

Chromaticity Diagram: A two-dimensional diagram formed by plotting one of the three chromaticity coordinates against another (e.g., x vs. y, or u vs. v) (see Figure 1).

Planckian Locus: Per the IES: The locus of points on a chromaticity diagram representing the chromaticities of blackbodies having various (color) temperatures (also called the blackbody locus) (see Figure 1).

Spectrum Locus: Per the IES: The locus of points representing the colors of the visible spectrum in a chromaticity diagram (see Figure 1).

This whitepaper outlines the reasons why the DLC is not addressing NWL LED luminaires in LUNA at this time, and suggests next steps to address the gaps and shortcomings in existing research, standards, and guidelines that would make qualification feasible in the future.

Effects of Increasing Anthropogenic Light at Night (ALAN)

Human-produced light at night from electric light sources is often noted by the initialism ALAN.[1] ALAN is increasing year over year [1,2], penetrates marine ecosystems [3], and is exacerbated by increasing market penetration of "blue-rich" LED sources producing consistent short wavelength radiation in the 400-500 nm (violet-blue) range (see for example, [4]). As of 2018, LED outdoor lighting had an estimated penetration rate of 46-50%, and it is estimated that the demand for per-capita light consumption has not been saturated [5,6]. LED lighting offers many benefits over incumbent technologies, including higher efficacies, and better optical and temporal control. However, the increased amount of short-wavelength (violet-blue) radiation in phosphor converted- (pc-) White LED spectral power distributions can be deleterious at night, especially if high CCT LED products are used and/or the application area is overlit.

> *"…more than 80% of the world and more than 99% of the U.S. and European populations live under light-polluted skies. The Milky Way is hidden from more than one-third of humanity, including 60% of Europeans and nearly 80% of North Americans…. 23% of the world's land surfaces between 75°N and 60°S, 88% of Europe, and almost half of the United States experience light polluted nights."*

Sky glow

Sky glow is defined by the Illuminating Engineering Society (IES) as "the brightening of the night sky that results from the scattering and reflection of light from the constituents of the atmosphere in the direction of the observer." In other words, it is the scattering effect of anthropogenic light sources that brightens the night sky and decreases one's ability to see stars. In addition to limiting or eliminating the view of the sky from Earth, sky glow poses potential threats to plants and animals, human health, scientific research, astronomical observations (both professional and amateur), global warming, and wastes a significant amount of energy at great environmental and financial cost.

This wasted light is estimated to cost the United States at least USD $7 Billion yearly, generating nearly 66 million metric tons of CO_2, which is the equivalent of 9.5 million cars [7].[2]

In terms of known potential negative consequences[3], ALAN, at meaningful[4] doses and times, can lead to:

[1] Depending on the reference, ALAN is noted as either artificial light at night or anthropogenic light at night.
[2] This is likely an underestimate since the study was performed in 2010 and light pollution has since worsened [1]. Additionally, this same estimate was approximately USD $1 Billion in 1991 [8].
[3] Christopher Kyba maintains an extensive database of ALAN peer-reviewed journal articles at https://www.zotero.org/groups/2913367/alan_db/library
[4] Meaningful ALAN doses depend on the organism, dose (amount * duration), spectrum, and timing. A meaningful acute dose and spectrum for one organism is not necessarily meaningful for another. Similarly, a meaningful dose impacting one outcome

- An increase in circadian disruption for animals and plants (See for example [9–12])
- Sea turtle disorientation [13,14]
- Negative impacts on nocturnal and diurnal insects [15,16]
- Bird disorientation and collisions with buildings [17,18]
- Increase in pathogenic risks [19,20]

Simply put, light at night can be disruptive, and may cause harm. To minimize its potential negative impact, the DLC recommends that stakeholders consider "Five Principles for Responsible Outdoor Lighting" developed by the IES and IDA (International Dark Sky Association). The Five Principles recommend that responsible outdoor lighting is useful, targeted, controlled, applies low light levels, and uses warmer color lights where possible. The DLC's LUNA V1.0 Technical Requirements align with these Five Principles for Responsible Outdoor Lighting in that light is targeted, controlled, and uses warm-white CCTs between 2200K and 3000K.

With regards to warmer color lights, the Five Principles indicate that outdoor lighting should limit the amount of violet-blue light to the least amount needed. Observers will notice that the LUNA V1.0 Technical Requirements currently do not allow NWL LED spectra, including pc-LED light sources below 2200K, pc-Amber, or de- Amber to be submitted.

Light pollution

Light pollution is an umbrella term that is used to characterize the unintended negative aspects of ALAN. Depending on the context, it can include light trespass[5], glare, astronomical[6] and ecological[7] light pollution, and polarized light pollution[8]. There are several North American and International Standards Development Organizations (SDOs) such as the IES, the International Commission on Illumination (CIE), and the Chartered Institution of Building Services Engineers (CIBSE) that have developed light pollution mitigating standards for white light sources. Importantly, limiting uplight and high CCTs from the luminaire alone, as is specified in the DLC V1.0 LUNA Technical Requirements, is only one tool of the many needed to minimize astronomical light pollution. Some of the easiest and most effective ways to limit astronomical light pollution are to eliminate overlighting, to use controls to task-tune, and to dim and/or switch off lighting when occupancy and traffic levels are reduced [23].

NWL sources that eliminate violet-blue radiation (such as amber and red LED products) have also emerged as a potential strategy to limit ecological light pollution and other negative impacts of ALAN.

measure (e.g., melatonin suppression) may not be impactful on another outcome measure (e.g., circadian phase shifting). Ideally, we will have outcome-measure-specific action spectra for representative organisms that allow better predictions.

[5] Light trespass is the encroachment of light, typically across property boundaries, causing annoyance, loss of privacy, or other nuisance, per the IES.

[6] Light pollution that obscures views of the night sky. [21]

[7] Light pollution that alters natural light and dark cycles in terrestrial and aquatic ecosystems. [21]

[8] Light that polarizes when interacting with human-made objects. [22]

Defining Non-White Light (NWL)

To define NWL, it helps to first define "light", and "white light". To define light, we look to the CIE, who recently updated their definition of light. The CIE Electronic International Lighting Vocabulary (E-ILV) now includes three entries for light [24][9]:

Table 1: CIE e-ILV definitions of light

Term	Definition	Select e-ILV Notes
light, <**psychophysical**> noun	Radiation that is considered from the point of view of its ability to excite the visual system.	Note 1: The term "light" is sometimes used for optical radiation outside the visible range, but this usage is not recommended
light, <**photometric**> noun	Radiation within the spectral range of visible radiation.	Note 1: Sometimes, the term "light" is also used in physics as a synonym for optical radiation, covering the spectral range from 100 nm to 1 mm and sometimes even covering the X-ray spectral range. This misuse of the term "light" should be avoided.
light, <**perceptual**> noun	Perceived light. Characteristic of all sensations and perceptions that is specific to the visual system	Note 1: Light is normally, but not always, perceived as a result of the action of a light stimulus on the visual system.

Notably, all three entries are explicitly linked to human visual sensitivity. Animals and insects may have sensitivity to wavelengths that humans cannot see. For example, salamanders, goldfish, dragonflies, butterflies, and spiders are also visually sensitive to ultraviolet radiation and are more sensitive to red radiation [11]. They may also be more sensitive to optical radiation than humans, and as such, what we perceive as low light may be extremely high irradiance levels for them. This means that the optical radiation emitted from luminaires engineered for human vision, when discussed in the non-human context as a potential source of ecological and/or astronomical light pollution, is not accurately described by the term "light." While we note this potential misuse of the term "light" because it is important for science, we will nonetheless continue to use the term in this paper for lack of a better term and to simplify discussion.

White light

What is "white" light? The most common way to define white light is to use an industry standard. In this case, the ANSI *Basic* and *Extended* Nominal CCT quadrangles in ANSI C78.377-2017 [25] are typically used (**Figure 1**). The ANSI quadrangles range from 2200K to 6500K and are used to qualify white LED luminaires for both interior and exterior Primary Use Designations (PUDs) in the DLC's V5.1 SSL Technical

[9] https://cie.co.at/e-ilv

Requirements.[10] The DLC's V1.0 LUNA Technical Requirements further refines outdoor CCTs to those in the ANSI quadrangles between 2200K and 3000K.

Non-white light

If everything in the ANSI quadrangles is nominally white, then everything that is not in an ANSI quadrangle is "non-white" (**Figure 1**), and this definition of non-white light is used throughout this paper. ANSI C78.377-2017 confirms that the standard does not apply to SSL products that produce colored light.

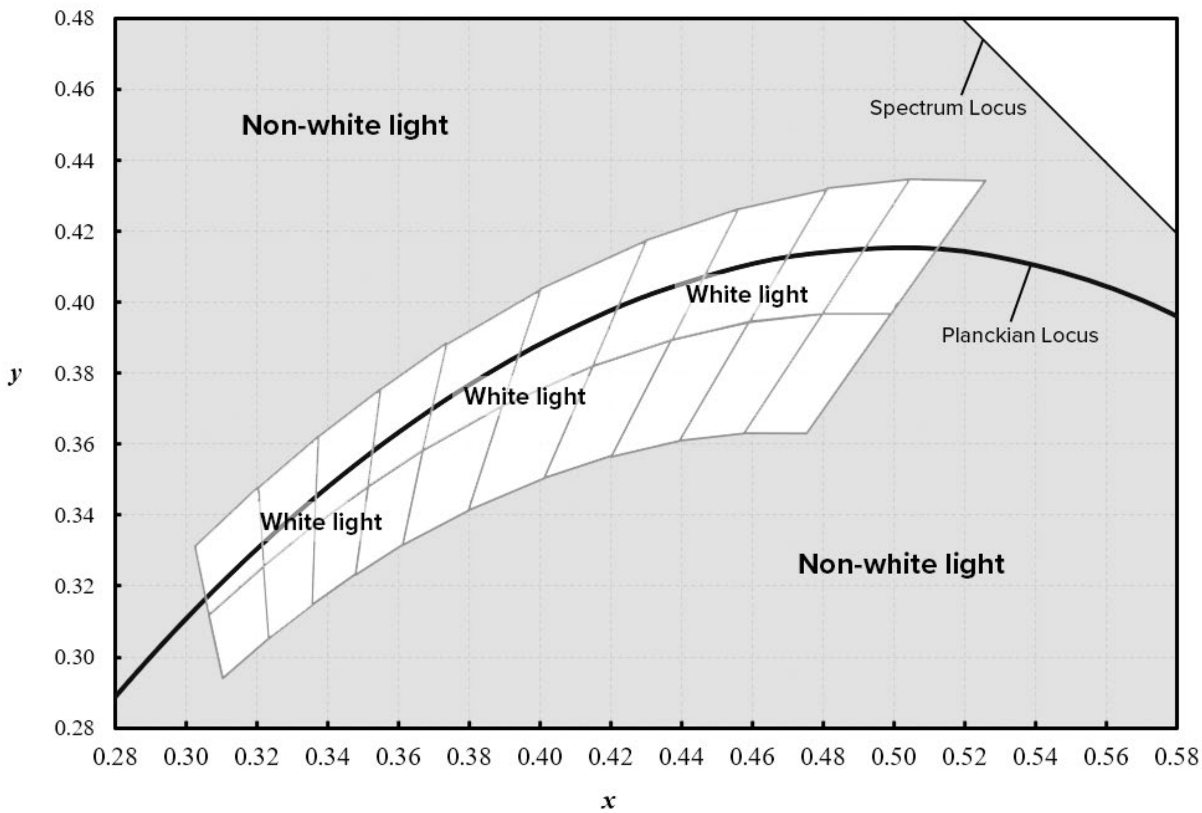

Figure 1: The ANSI C78.377-2017 *Basic* and *Extended* Nominal CCT quadrangles plotted in the CIE 1931 xy chromaticity diagram.

The ANSI SSL chromaticity specification was developed to align with prior fluorescent lamps standards and to reflect the ability of white light SSL sources to produce Flexible and Extended CCTs.

Chromaticity requirements for white and NWL sources for ground vehicle lamps and lighting equipment are given in the Society of Automotive Engineers (SAE) J578 Standard "Chromaticity Requirements for Ground Vehicle Lamps and Lighting Equipment" [26]. This standard defines chromaticity boundaries for white light sources, as well as NWL sources such as red, yellow (amber), selective yellow, green, blue,

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10 ANSI C78.377-2017 (American National Standard for Electric Lamps – Specifications for the Chromaticity of Solid-State Lighting Products) specifies recommended chromaticity ranges for general *indoor* lighting applications illuminated by SSL lamps, luminaires, and light engines. There is no complementary standard for general outdoor applications, and, as a result, the DLC applies the recommended 7-step chromaticity ranges for outdoor SSL white light lamps and luminaires.

signal blue and blue green. The NWL chromaticity boundaries from this standard for yellow (amber) and selective yellow will be used for comparison purposes later in this paper.

Common NWL Sources and Terminology in Outdoor Lighting

Within the astronomical and ecological sky glow literature, NWL sources are characterized almost entirely by lighting technology type (e.g. “Low Pressure Sodium (LPS)”, “High Pressure Sodium (HPS)”, “Amber”, and “Phosphor Converted Amber (PC Amber)”) and irradiance/illuminance level, and rarely with other lighting characteristics, such as the SPD [27]. Other researchers and stakeholders use a number of metrics and lighting technology descriptions to convey the capabilities and features of NWL products. With so many competing descriptors, how can the lighting industry possibly communicate precisely about non-white light?

Types of NWL products on the market

NWL products are common, historically, for outdoor lighting. High-pressure sodium (HPS) and low-pressure sodium (LPS) discharge lamps, historically common in lighting outdoor environments (**Figure 2**), also produce light that falls outside the ANSI quadrangles shown above. These sources are notable for their “yellow-orange” or “amber” appearance and poor color rendition. Despite their poor color rendition, they gained prominence because of their high luminous efficacy.

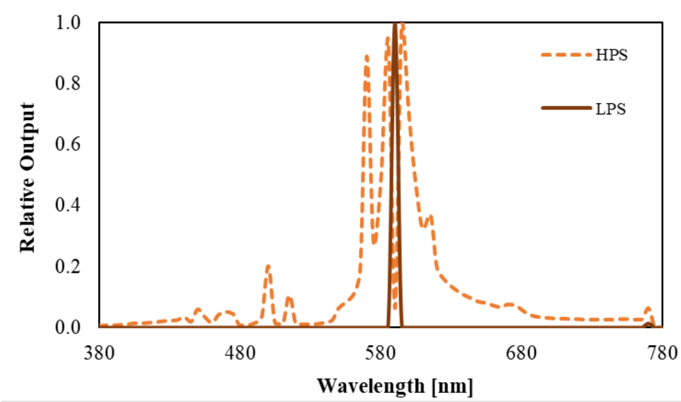

Figure 2: SPDs for high- and low-pressure sodium.

Two types of “amber” LEDs[11] are becoming more readily available in outdoor luminaires. Though the distinction between them is not always clearly communicated on luminaire specification sheets, they have specific benefits and drawbacks that make distinguishing between them important.

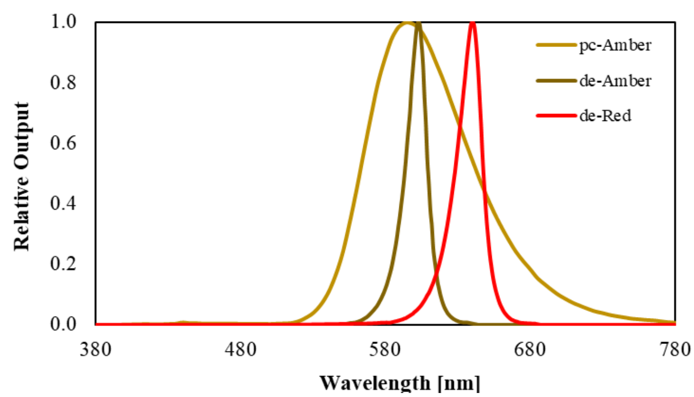

Figure 3: SPDs for a representative pc-Amber, de-Amber, and de-Red LED.

The first type of amber LED is phosphor-converted amber (pc-Amber), which is similar to typical commercially available white LEDs (**Figure 3**). Pc-Amber LEDs are sometimes referred to with nominal CCT designations below 2200K—such as “1600K” or “1700K”—though these sources typically have

[11] “Amber” LEDs marketed for automotive applications often use the terms “yellow” and “selective yellow” depending on their chromaticity coordinates, as defined in SAE J578.

chromaticity coordinates that are located closer to the spectrum locus than to the Planckian locus (**Figure 5**), making them highly saturated.

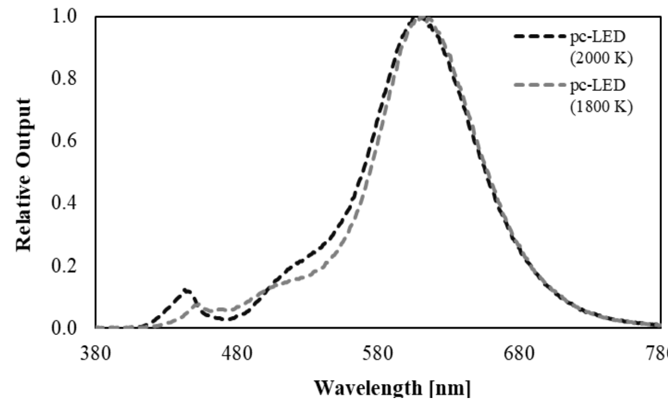

Figure 4: SPDs for two pc-LEDs near the Planckian locus at 2000K and 1800K.

The second type of amber LED generates light via direct emission with a peak emission near 590 nm. Phosphor conversion is not used. These LEDs have a significantly narrower spectrum than pc-amber LEDs (**Figure 3**) and have a more saturated color. These LEDs will be referred to in this paper as "direct emission amber", or "de-Amber" LEDs. The peak wavelength and spectral width of direct emission LEDs vary by manufacturer. The spectral power distribution (SPD) for a "de-Red" LED is shown in **Figure 3**.

A third, and new to the market category of NWL LEDs uses phosphor conversion to yield chromaticity coordinates on or near the Planckian locus but at CCTs less than 2200K. These light sources generate light through the same method as typical pc-White LEDs but are considered NWL because they have chromaticities outside the ANSI quadrangles. These LEDs are neither pc-Amber nor de-Amber. By comparison, they have more broadband spectral emissions (**Figure 4**), which also typically means they have better color rendition. These LEDs will be referred to here as pc-LEDs, and may sometimes include a CCT designation (e.g., "pc-2000K" and "pc-1800K").

Pc-Amber and pc-LED luminaires are marketed as replacements for HPS luminaires. De-Amber and de-Red LED luminaires are marketed for use in coastal communities with sea turtle nesting beaches.

Inconsistent NWL naming/binning by LED chip manufacturer

LED chip manufacturers sort chips into groups or "bins", where chips within each bin have relatively similar performance characteristics, compared to chips in other bins. These binning practices differ by chip manufacturer. As one example, **Figure 5** shows the pc-Amber bins for various manufacturers. In some cases, the pc-Amber bins available from LED chip manufacturers extend beyond the "Yellow (Amber)" chromaticity boundary specified in SAE J578 and shown in **Figure 5** as a dashed yellow line. As a result of inconsistent binning practices, it is not as simple as adopting SAE J578 Yellow (Amber) boundary for pc-Amber products, because existing pc-Amber products falling outside of the boundary would not be included.

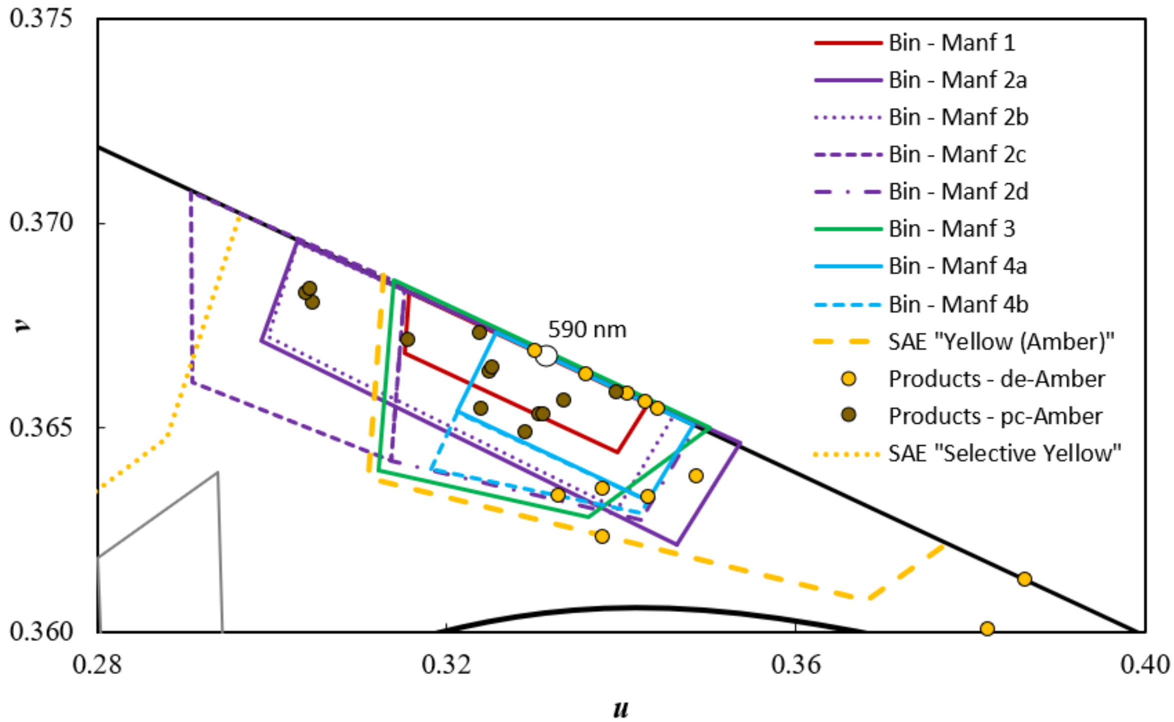

Figure 5: An enlarged portion of the CIE 1960 *uv* chromaticity diagram near 590 nm showing the pc-Amber chromaticity bins for four anonymized LED chip manufacturers as well as the chromaticities of various pc-Amber and de-Amber LED chips and luminaires. For reference, the ANSI C78.377-2017 *Basic* 2200K quadrangle is shown at the lower-left-hand corner, as is the Planckian locus and spectrum locus.

Inconsistent NWL naming by LED luminaire manufacturers

A review of NWL outdoor LED luminaire specification sheets was performed to evaluate the variation in nomenclature used in the market. To increase the likelihood of finding NWL luminaires, the search targeted products listed on the Florida Fish and Wildlife Commission's (FWC) *Wildlife Lighting Certification Program* and/or the International Dark Sky Association's (IDA) *Fixture Seal of Approval (FSA) Program*. The FWC certification is restricted to only de-Amber LEDs; the IDA FSA also allows pc-Amber products and pc-White products up to a maximum CCT of 3000K. More information on the spectral requirements for these programs is in **Table 3**.

Table 2 shows a selection of phrases and nomenclature used on LED luminaire manufacturer specification sheets compliant with the FWC (middle column) and the IDA FSA (right column). In several cases, products appear on both lists. At the time of evaluation (Q3 2021), relatively few amber products were listed on the IDA list. Although the FWC requirements specifically disallow pc-Amber sources, **Table 2** indicates that at least one pc-Amber luminaire is included in their list, and other products with ambiguous nomenclature may also be using pc-Amber chips.

Overall, **Table 2** indicates that there is little consistency applied to naming conventions of de-Amber and pc-Amber LEDs. In many cases, the underlying technology cannot be easily deduced based on the provided description, and no SPD is provided. Consistent nomenclature is a simple solution to help stakeholders understand the underlying amber technology. As an alternative, because pc-Amber and de-Amber are easily distinguishable by their SPDs, providing SPDs on product literature removes all ambiguity. The most comprehensive solution is to use both on specification sheets: consistent nomenclature and SPDs.

Table 2: Nomenclature used to describe amber spectrum choices on luminaire specification sheets

Amber technology	Sample terminology used in FWC-listed luminaires	Sample terminology used in IDA-listed luminaires
pc-Amber	• CCT option of "AMBPC Phosphor converted amber"	• Phosphor Converted Amber Street Lights: CCT listed as "available in 2000K" • CCT option "AMB Phosphor Converted Amber" "Available in Phosphor Converted Amber with Peak intensity at 610nm
de-Amber	• "Amber LED linear modules have a minimum wavelength of 583 nm" • CCT option listed as "AMB" • "Direct Amber LED is narrow spectrum with dominant wavelength at 596 nm (peak wavelength at 601 nm)" • "Turtle-friendly" lighting: "590 nm diode supplied as standard." CCT option of "TS (590 nm)" (SPD shown) • "Fully shielded luminaire that is FWC approved." "Wavelength of 590 nanometers" (SPD shown) • "Wildlife-Friendly Amber (585 - 595 nm)" • "Amber (1541K)" (SPD shown, de-Amber) • "590 nm Amber" option. "LONG: LED color is verified as 585nm minimum and 595nm maximum" (likely de-Amber) • CCT "Amber" option (SPD shown) • "CITY OF FLAGSTAFF & TURTLE FRIENDLY COMPLIANT" "Narrow-Spectrum Amber LEDs" "Peak wavelength between 585 & 595 nanometers and a full width of 50% power no greater than 15 nanometers" (SPD shown) • CCT option of "ANBWL "Limited wavelength amber"	• LED Narrowband Amber: Spec sheet lists "Peak Dominant Wavelength" as "Available in 592 nm, 592 nm, and 595 nm ± 2.5 nm" • Lumen" option of "Amber" and/or Dual "Amber" and 3000 K "Amber LEDs are monochromatic, narrow spectral bandwidth that only emit long wavelengths >560 nm and <625 nm • CCT option of "AMB = Amber, 590 nm". Amber option is listed with this note: "Narrow-band 590nm +/- 5nm for wildlife and observatory use."

Amber technology	Sample terminology used in FWC-listed luminaires	Sample terminology used in IDA-listed luminaires
Technology unclear	• CCT option of "AMKX" (Amber) • CCT option of "A Amber 595 nm" and "R (Red, 620 nm)" • CCT option of "Amber". "FWC Certification, AMBER light Turtle friendly" • CCT Option "AM - amber LED turtle friendly 585-595nm" • "Amber (A)" option • "Amber" option for "Color". "Amber LEDs 585-595 nm Dominant Wave Length" • "Red-Orange (1000K)" options (technology unclear) • CCT Option "Amber (No light below 560 nm)" (SPD shown, "red-orange")	• "Amber and custom available." "Turtle Friendly". CCT option of "2K – 595 nm" • CCT option listed as "2K – 580 nm" • CCT option of "AM – Amber, 595 nm" • CCT option of "AM – Amber, 595 nm" • CCT option of "AMB Amber 595nm Peak" • "Available in 580nm Amber". CCT option of "2K = 580 nm – Amber" • CCT option of "AM – Amber, 590 nm". "turtle friendly Amber LED options" • CCT option of "AM, Amber-595 nm Peak" Listed as "Wild life friendly" • CCT option of "AMB = 590 nm, Amber" • CCT option of "Amber (590 nm available for "Turtle Friendly"/ observatory applications)" • "Amber" option for "Color". "Amber LEDs 585-595 nm Dominant Wave Length" • CCT option of "AMB – Amber, 590nm Peak" • "Turtle friendly Amber LED options" "AM – Amber, 590 nm available" • CCT option of "TSAM=Turtle Safe Amber (585-595nm)" • CCT/CRI option of "TRL Turtle Friendly Amber LEDs, 625nm"

Use of NWL sources by lighting specifiers/designers

Limited availability and lack of standardized descriptions for NWL sources make nuanced references nearly impossible, causing lighting specifiers to often use technology-based designations, such as HPS, LPS, and "amber" LED when describing NWL sources. **Figure 6** shows two scenarios where unintended confusion may occur as a result.

Interviews with select lighting designers suggest that it is uncommon for lighting designers to specify NWL light sources for use in the outdoor nighttime environment. Designers are not frequently included in projects where NWL is considered in sensitive environments.

When they are included, they face a suite of challenges:

1. NWL products are uncommon and often necessitate a special order from manufacturers, usually requiring a minimum order quantity. Often, that minimum order quantity makes these products unavailable for small projects. These factors increase the cost and lead time for acquiring NWL products and decrease the likelihood that they will be included in a lighting installation.
2. There is little published guidance for L0 and L1 lighting zones (dimly lit, sensitive areas where NWL may be appropriate).
3. It is challenging to get end users and government officials to buy and use controls due to concerns with security, litigation, government regulations, use of proprietary solutions, complicated software, cost, etc.

4. NWL products are not currently eligible for DLC qualification, making them less likely to be rebated by utilities.
5. Environmental impact studies, which are sometimes required for project implementation, must specify what local taxa are impacted by installed light sources. Because lighting specifiers (designers/engineers) and ecologists/biologists use different terminology and have different expertise, these studies can be difficult to perform. Importantly, amber is not a one-size-fits-all approach because many species react to amber, and some have specific heightened sensitivities to amber. Nuanced and easy-to-implement recommendations for NWL are needed for non-scientists.

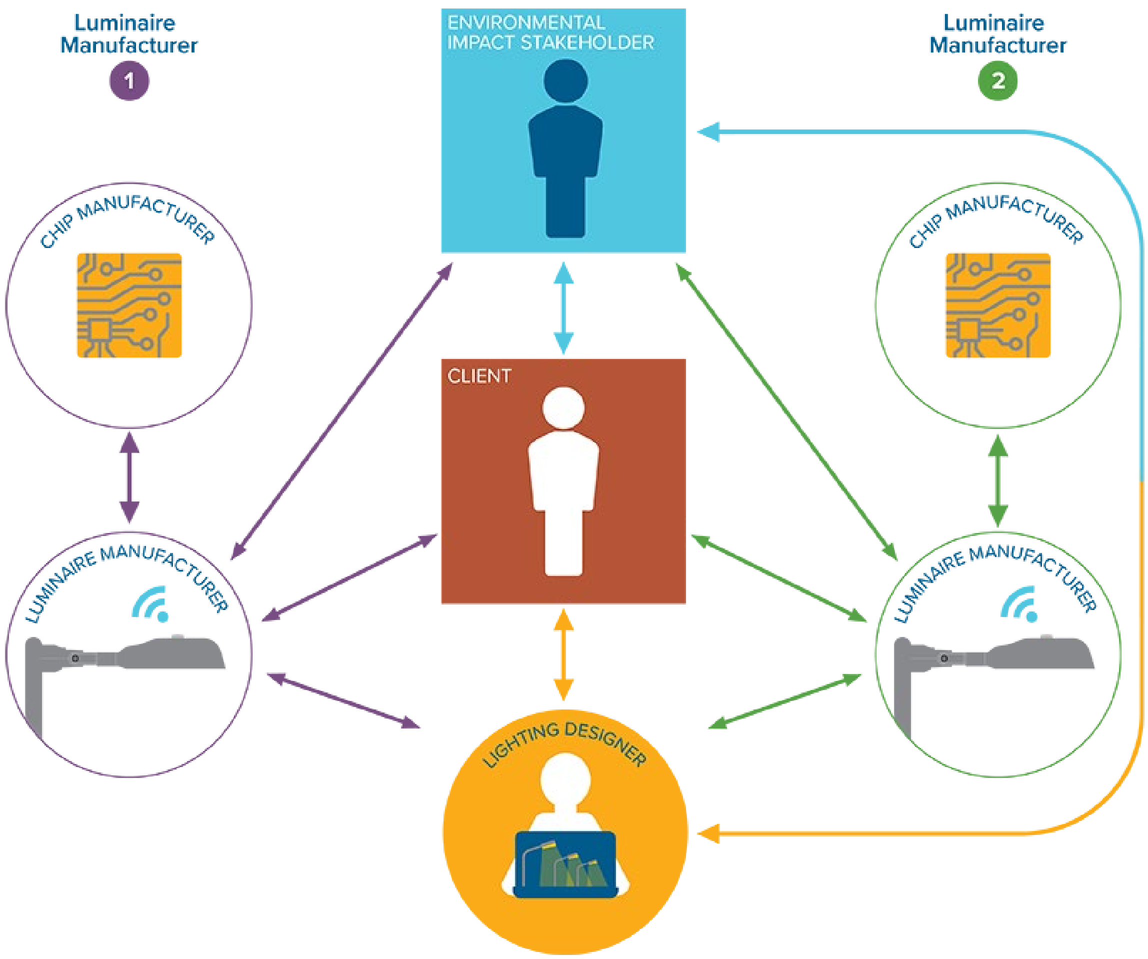

Figure 6: Inconsistent terminology and a lack of SPDs on the specification sheet can lead to unintended confusion in the market. Two potential scenarios that could result are: 1) Luminaire Manufacturer A is using different nomenclature than Luminaire Manufacturer B, even though both Chips A and B have the same SPD (e.g., both are pc-Amber or de-Amber); or 2) Luminaire Manufacturer A is using the same nomenclature as Luminaire Manufacturer B, even though Chips A and B have different SPDs (e.g., Chip A is a pc-Amber, and chip B is a pc-LED).

A Need for Standardization for NWL LED sources

To understand the policy and market landscape for NWL LED sources, the DLC conducted a market review of standards, guidelines and regulations, and associated product listings in Q2 2021.

Lack of Standardization in Guidelines/Regulations for NWL and/or CCT

As part of the market review, the lighting requirements and recommendations for NWL and/or CCT published by various institutions ranging from public advocacy groups to governmental regulators were evaluated. **Table 3** shows the summary of the reviewed spectral recommendations and requirements. Notable technical requirements for NWL amber products are given by the "Wildlife Tuned" category from the International Dark Sky Association (IDA), the Florida Fish and Wildlife Commission (FWC), and the county code of the Big Island of Hawaii (Hawaii County Code, HCC).

Table 3: Spectral astronomical or ecological light pollution recommendations or requirements from various bodies

Organization or Regulating Body	Spectral Recommendation or Requirement
IDA International Dark Sky (IDA) Fixture Seal of Approval (FSA) – For Commercial Luminaires	Light sources shall have a maximum CCT of 3000K
IDA – For Residential Luminaires	Light sources shall have a maximum CCT of 3000K
IDA – "Innovation"	No more than 7% of visible emissions in 380-520nm
IDA – "Wildlife Tuned"	Sea turtle specific spectrum: 0% less than 565nm
FWC - Florida Fish and Wildlife Commission (FWC) Wildlife Lighting Certification Program	0% radiation below 560 nm Short wavelength light sources, PC Ambers, RGBs, dual lighting boards, and color change options are not acceptable.
HCC - Hawaii County Code	Lamps with less than 2% radiation between 400 nm and 500 nm have no operation restrictions, other new lighting technologies are prohibited or must be switched off from 11 PM to sunrise (Class 1 lighting). 1931 CIE xy chromaticity coordinates outside of any of the traffic signal color boxes as defined by ITE ST-052 500/AGS-PM/1105.
Smart Outdoor Lighting Alliance (SOLA) Community Friendly Lighting (CFL) Program	Less than 25% radiation between 430 nm and 530nm. This is typically achieved by light sources with CCTs ≤ 3000K.
Soft Lights Standard	Maximum CCT of 2200K for business and residential areas. CCT between 1000 K and 1800 K for sensitive and rural areas. Maximum CCT of 2700K for headlights.
Low Impact Lighting Standard	CCT ≤ 2200K AND less than 6% radiation below 500 nm. If average illuminance is below 5 lux: CCT ≤ 2700K AND less than 10% radiation below 500 nm.

Organization or Regulating Body	Spectral Recommendation or Requirement
Australian Guidelines for Outdoor Lighting	Percent radiation below 500 nm "as low as possible" Radiation above 680 nm "should also be avoided" LEDs with a nominal CCT ≥ 3000K should not be used in ecologically sensitive areas. Warm white LEDs with a nominal CCT ≤ 3000K or lower usually radiate a very low blue component and can be recommended from a health and ecological point of view.
City of Flagstaff, AZ	Preferred Source – LPS lamps and Narrow-Spectrum Amber LEDs
The UK Parliament's All-Party Parliamentary Group (AAPG) for Dark Skies	CCT ≤ 3000K. CCT ≤ 2400K in certain protected areas such as nature reserves and national parks.
French decree of 27 December 2018 relating to the prevention, reduction and limitation of light pollution	CCT ≤ 3000K. Additional requirements for protected areas such as nature reserves and parks: CCT ≤ 2700K for the "built environment" of towns and villages, ≤ 2400K otherwise.

Overall, the most specified lighting parameter is maximum CCT. Very few recommendations include designations of NWL. Some guidelines use strict cutoffs with technically defined parameters (such as maximum CCT) while others use less precise language such as "as low as possible". Commercially available pc-White LED products cannot meet the spectral criteria of FWC, HCC, or the IDA "Wildlife Tuned" certification programs and are not likely to meet the spectral requirements of the IDA "Innovation" certification program.

Lack of standardization in LED luminaire and chip terminology

In the industry, the term "amber" is a catch-all for LED luminaires that encompasses pc-Amber products, de-Amber products, and in some cases, pc-White products marketed as amber. Some luminaire manufacturers use CCT values (e.g., 1800K)[12] to describe their products' chromaticity. Others use the terms: "Turtle Safe Lighting", "Turtle-Friendly Lighting", "Coastal Wildlife Amber", or similar terminology. Stakeholders need to be able to understand the lighting technology characteristics they are evaluating. In addition, sea turtles are sensitive to both intensity and spectrum, so an "amber" luminaire that produces too much light is not "turtle-safe" nor "turtle-friendly". Application dosage and timing matters, as does spectrum.

In many cases, but not all, LED chip manufacturers use the term "amber" for de-Amber LED chips, and "PC Amber" for pc-Amber LED chips used in general lighting applications. In some cases, "amber" LED chip products have a peak or dominant wavelength up to 625 nm; making it unclear at what point these "amber" products become "red-orange" or "red" products. Note that according to the SAE J578 standard mentioned previously, the yellow (amber) boundary extends to a peak wavelength of about 595 nm, and the red boundary begins at a peak wavelength of about 605 nm.

Florida Fish and Wildlife Commission listed product terminology

Most of the reviewed FWC-listed luminaires used a de-Amber chip with a peak or dominant wavelength near 595 nm. However, this was not always the case. Notably, one product with a pc-Amber option was

[12] In one set of reviewed photometric files, the luminaire manufacturer reported a CCT of 1400K for their "amber" outdoor LED products.

found in the FWC list even though the FWC states that pc-Amber products cannot comply with their Wildlife Lighting Certification Program. Another luminaire had radiant power below 560 nm, even though this is not allowed by the FWC. This luminaire used a red-orange chip, with a peak/dominant wavelength near 630 nm. Several luminaires used nomenclature or descriptions that made the underlying LED technology unclear. Among all the products, there is little consistency in lighting terminology or in the product specification code. Various descriptors are used, various peak wavelengths are listed, and in some cases, nothing is written other than “Amber” or “FWC-compliant” (see **Table 2**). Less than half of the luminaires reviewed included an SPD on their specification sheets or websites.

International Dark Sky Association listed product terminology

The IDA FSA permits light sources with CCT ≤ 3000K, so it is common for manufacturers to list the nominal CCT of their products. Some IDA compliant fixtures are also FWC compliant fixtures, and those are usually indicated with verbiage like “IDA-compliant”, “FWC-compliant”, “Turtle-friendly”, and inclusion of the various seals of approval, and/or with the CCT designation of “Amber”.

Overall, NWL options for fixtures are commonly listed under the CCT option of a specification sheet’s catalog code, but it is not always indicated if the LED is de-Amber or pc-Amber. The CCT of a de-Amber product depends on the peak wavelength, and peak wavelengths for de-Amber vary. For example, the calculated CCT of de-Amber LEDs may vary from approximately 1600K (at a peak wavelength of 595 nm) to approximately 2300K (at a peak wavelength of 585 nm) – see **Figure 7**.

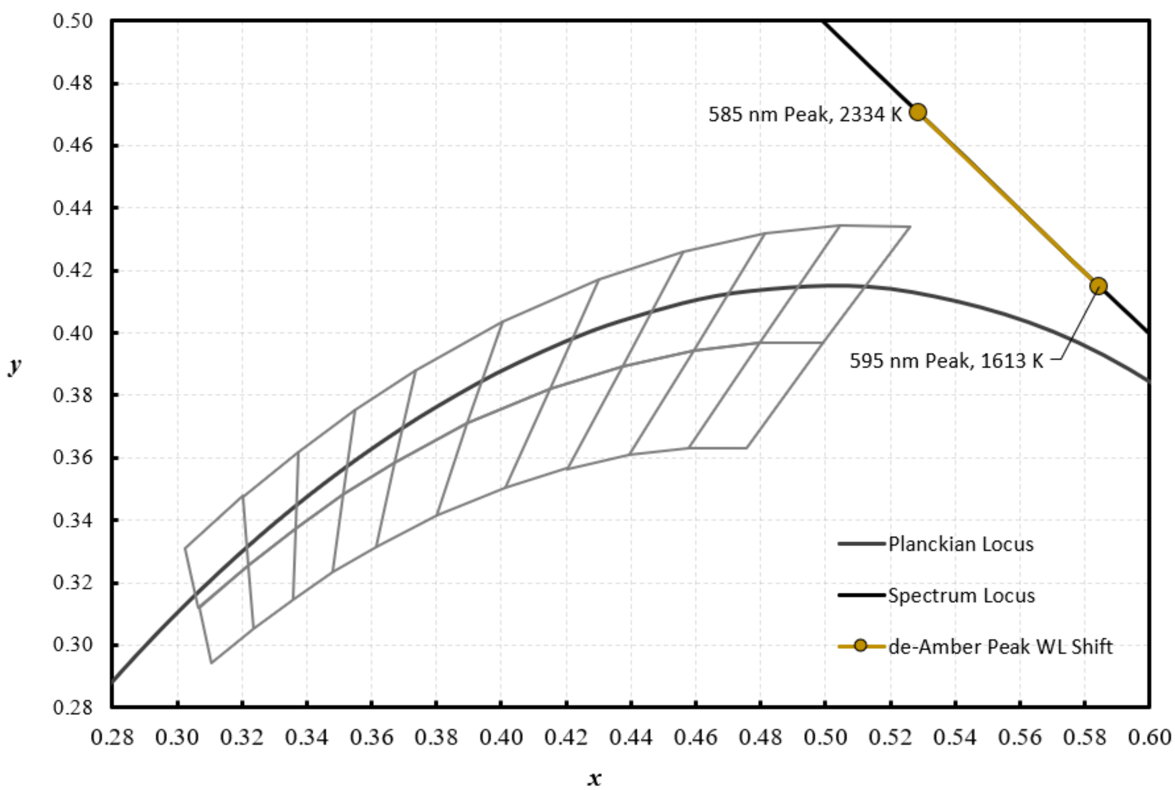

Figure 7: The range of chromaticities and calculated CCTs that can be achieved by a de-Amber LED with a 10 nm peak wavelength shift.

Lack of standardization from standards developing organizations (SDOs)

Table 3 makes it evident that there is little agreement on NWL spectral thresholds and metrics used to limit short-wavelength (violet-blue) optical radiation. It is unclear why there is so much variation, and if the specified waveband ranges and/or threshold metrics should continue to be meaningfully different from an astronomical or ecological light pollution basis. There appear to be multiple actors and advocates working in silos to define limits that meet their specific needs, creating an unnecessary burden on LED chip and luminaire manufacturers trying to create appropriate lighting products for these applications.

While several publications exist from standards developing organizations (SDOs) geared towards minimizing astronomical light pollution, they do not typically address spectral aspects beyond limiting CCTs, and do not specifically address evaluation of or specifications for NWL sources. However, some SDOs are investigating spectral considerations of astronomical and/or ecological light pollution. For example, the IES has created a new committee (the Outdoor Nighttime Environment, or "ONE" committee) to "establish lighting guidelines for the nighttime environmental factors of sky glow and wildlife preservation".[13]

Lack of standardization for chromaticity standards

The most specified attribute of a light source is its chromaticity, specifically, its CCT. As mentioned previously, the DLC relies on the ANSI C78.377-2017 quadrangles to define acceptable CCT boundaries for white LED luminaires for indoor and outdoor PUDs. The current quadrangle with the lowest CCT in this standard is 2200K. What is the best way to describe light sources with chromaticities outside of the ANSI quadrangles? A few considerations are provided below:

- Are SSL light sources with CCTs lower than 2200K but along the Planckian locus perceived as white?
- Should *Basic* and *Extended* CCT quadrangles below 2200K be defined?
- Are the existing 7-step quadrangles (developed for human photopic vision) applicable to outdoor lighting applications (where low light levels often result in human mesopic vision)? Are larger MacAdam ellipses necessary, or is another method needed to define quadrangles for outdoor lighting applications?
- What are the best and most meaningful naming conventions for pc-Amber and de-Amber sources? Is a chromaticity specification sufficient?

Getting to standardization in the industry

Nominal designations must be developed and standardized by consensus, because chip and luminaire manufacturers are currently doing this independently, leading to inconsistent color naming and nominal designations and confusion across the industry (see **Figure 5**). Luminaire manufacturers should also show the LED SPD on their specifications sheet to help both specifiers and regulators understand the underlying chip spectrum.

[13] https://www.ies.org/ies-committees/detail/?committee_id=bd2f321a-0050-c773-d948-925d7caf4445

Lighting SDOs are encouraged to address this problem to help manufacturers communicate and differentiate their products, to help specifiers and other stakeholders understand a product's color characteristics, to help regulators communicate what products are allowed or disallowed in their regulations, and to help researchers publish species-specific data in ways that can be applied practically, to deliver better lighting.

Performance Comparisons for NWL Light Sources

The DLC is interested in understanding the performance of NWL products in order to support efforts to reduce astronomical and ecological impacts of ALAN while also considering energy efficiency and lighting quality characteristics that underpin the LUNA V1.0 and SSL V5.1 Technical Requirements. This section aims to understand the performance of these NWL technologies relative to the DLC's existing performance requirements.

This section also defines a holistic method to characterize a NWL source in terms of luminaire efficacy, color rendition, lumen and chromaticity maintenance, and sky glow potential. Use of this holistic method of light source characterization, in addition to SPD information, would enable stakeholders to compare light sources accurately to make better predictive decisions about outdoor lighting.

Luminaire efficacy

To help ensure energy optimization – a key component of the DLC's mission – a minimum threshold of 105 lm/W is used for outdoor SSL products to meet listing qualifications. An efficacy allowance is available for products with CCTs below 3000K, resulting in a threshold efficacy of 100 lm/W for these lower CCT products. To understand commercially available outdoor luminaire efficacies, photometric data (e.g., .ies files) were downloaded in Q3 2021 from websites of commercial manufacturers who list products on the DLC's SSL QPL. Photometric data for available commercial "amber" products were also downloaded. The DLC used Photometric Power Tools (Lighting Analysts, Inc.) to calculate and categorize luminaire efficacies. Products were also categorized by either 1) the CCT keyword in the .ies files, or 2) the manufacturers' catalog number nomenclature. Where the manufacturer reported CCTs of 1400K-2000K, the products were categorized as pc-Amber.

Figure 8 shows the results for over 45,000 roadway and/or area luminaires. A few trends are evident:

1. No de-Amber products meet the DLC's threshold efficacy requirement. The average luminaire efficacy for de-Amber was 53 lm/W. On average, this is approximately 47% lower than the DLC's threshold luminaire efficacy of 100 lm/W for outdoor luminaires with CCTs of 2200K to 2700K.
2. Very few pc-Amber roadway/area luminaires are available that could meet the DLC's 105 lm/W threshold. The average luminaire efficacy for pc-Amber was 39 lm/W. On average, this is 61% lower than the DLC's threshold luminaire efficacy of 100 lm/W for outdoor luminaires with CCTs of 2200K to 2700K.
3. Both de-Amber and pc-Amber luminaires would likely require luminaire efficacy allowances to be able to be listed on the SSL QPL. However, luminaire efficacy is critically important to electric utilities and energy efficiency programs that must meet stringent savings goals to provide rebates, and/or meet their state's climate or decarbonization goals. Therefore, efficacy

allowances for NWL products might need to be combined with part-night dimming and/or application-based efficacy requirements to meet efficiency goals.

4. The DLC's luminaire efficacy threshold for pc-White LED outdoor luminaires is higher than the average or median calculated luminaire efficacy for these commercially available pc-White roadway or area luminaires. This means that the DLC luminaire efficacy thresholds are not yet the baseline for these outdoor roadway/area products.
5. Few products are available with reduced short wavelength (violet-blue) content (regardless of efficacy). Sixty percent of the photometric files evaluated included 3000K LEDs, 29% included 2700K, 11% included 2200K, and less than 2% of products included "amber" LEDs.

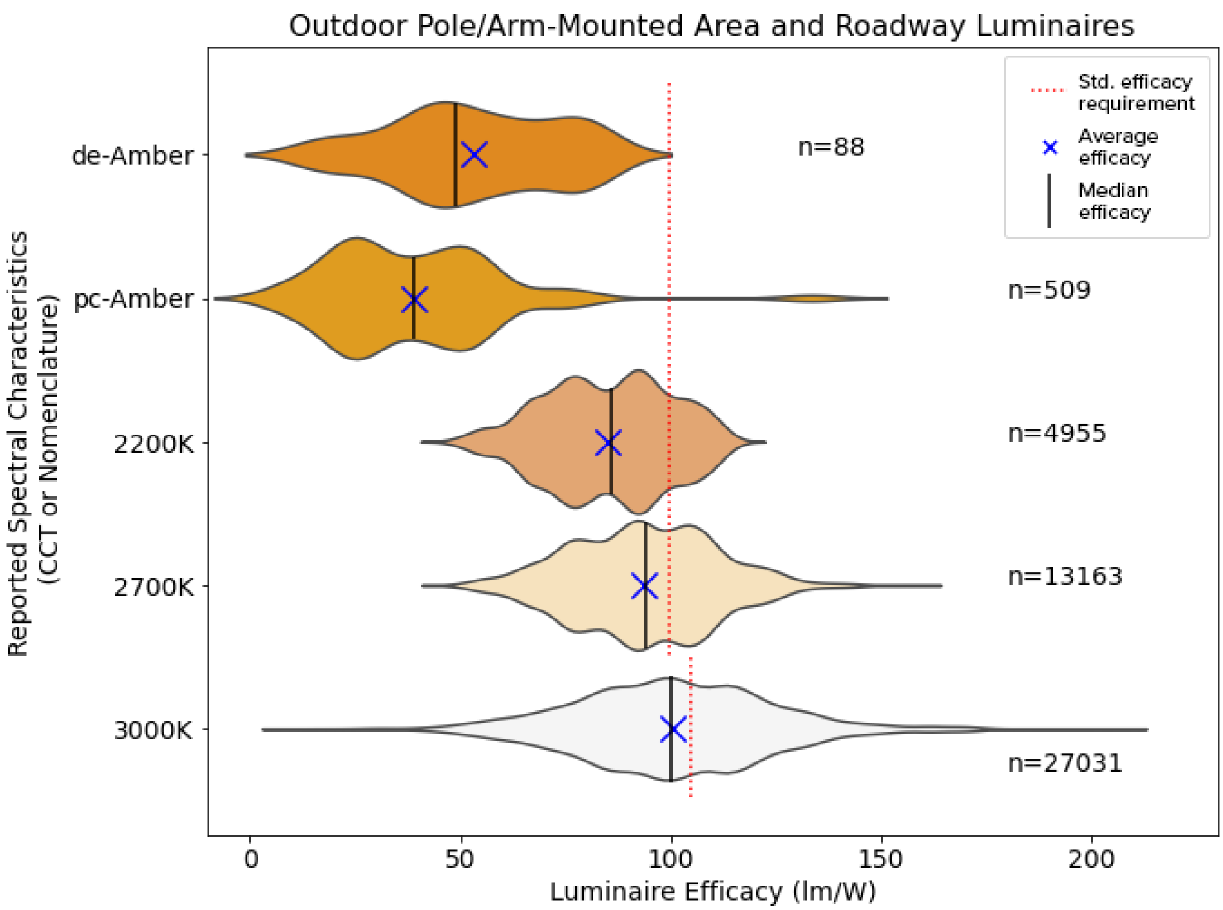

Figure 8: A violin plot for the calculated luminaire efficacy versus the self-reported spectral characteristics for 45,000 outdoor LED roadway and area luminaires. The height (y-dimension) of each "violin" represents the relative number of products at each efficacy. The greatest number of luminaires at each CCT/nominal designation occurs where the violin shape is tallest (largest y-dimension), and few products are available at calculated luminaire efficacies where the violin shape is narrow (smallest y-dimension). Average luminaire efficacy is indicated with a blue "X"; median luminaire efficacy is indicated with a small black vertical line. The DLC's minimum threshold Standard luminaire efficacy is shown with the red dashed line; an efficacy allowance is provided for products with CCTs between 2200K and 2700K. For the most part, neither pc-Amber nor de-Amber luminaires could meet the DLC's Standard efficacy threshold requirement.

Lumen and color maintenance

To understand lumen maintenance and color maintenance predictions relative to the DLC's thresholds, NWL chip level data was acquired. ANSI/IES LM-80 [28] and ANSI/IES TM-21 [29] reports were evaluated for three pc-Amber chips and one de-Amber LED chip.[14,15] In addition, discussions with representatives of LED chip manufacturers were conducted to understand trends and failure modes. Rather than presenting chip-level data, a summary is presented here.

For reference, DLC lumen maintenance and color maintenance thresholds are as follows:

- **V5.1 Standard**
    - Lumen maintenance: $L_{70} \geq$ 50,000 hours
    - Color maintenance ("All Outdoor and high-bay products"): "Chromaticity shift from ≈1,000-hour measurement to ≈6,000-hour measurement shall be within a linear distance of 0.007 ($\Delta u'v' \leq 0.007$) on the CIE 1976 (u', v') chromaticity diagram"
- **V5.1 Premium**
    - Lumen maintenance: $L_{90} \geq$ 36,000 hours
    - Color maintenance thresholds the same as DLC Standard
- **V1.0 LUNA**
    - Lumen maintenance: Maintains L_{70} and L_{90} designations of "Standard" and "Premium"
    - Color maintenance: Same as V5.1 Standard

Pc-Amber LEDs have similar life and performance as typical pc-White LEDs because they employ the same underlying technology. Pc-Amber LEDs behave similarly to pc-White LEDs with regards to optical and electrical characteristics and lumen maintenance. In some cases, pc-Amber may out-perform some nominally pc-White LEDs in terms of lumen maintenance or color maintenance since they may have less red phosphor, which tends to degrade before other phosphors (resulting in a "blue" shift). An analysis of three pc-Amber ANSI/IES LM-80 and ANSI/IES TM-21 data sets showed that the evaluated pc-Amber LED chips could meet DLC V5.1 Standard and Premium threshold for L_{70} and L_{90} hours.

De-Amber LEDs are distinctly different from pc-Amber LEDs in that they emit light directly and do not down-convert radiation using a phosphor.

Two major issues with de-Amber LEDs were identified:

1. They have a substantially lower initial external quantum efficiency than pc-Amber and pc-White. [30]
2. They are highly sensitive to temperature change.

Changes in temperature are accompanied by fluctuations in light output, life, peak wavelength, and chromaticity. ANSI/IES TM-21 reports for one de-Amber chip demonstrated that increased ISTMT

[14] Very little data on de-Amber chips was readily available or shared. More data is needed for this chip type to make predictions about lumen maintenance or chromaticity maintenance performance.
[15] Some of the lumen maintenance data is publicly available, other data was provided confidentially to the DLC's consultant. All color maintenance data was provided confidentially to the DLC's consultant.

temperatures (from 85 °C to 105 °C) resulted in 50% lower L_{70} hours and would not meet the DLC Standard lumen maintenance requirements.

Color maintenance

For color maintenance, the difference in the CIE 1976 *u*'*v*' chromaticity coordinates (Δ*u*'*v*') from 1,000 to 6,000 hours was evaluated using LM-80 report data.

In one conversation, pc-Amber was quoted as having a color maintenance of "2 steps" (i.e., Δ*u*'*v*' ≤ 0.002) and de-Amber was quoted as having color maintenance of "3 steps" (i.e., Δ*u*'*v*' ≤ 0.003). Evaluated report data corroborated these claims and demonstrated that the three evaluated pc-Amber chips and one de-Amber chip were able to meet DLC V5.1 Standard thresholds for Δ*u*'*v*'.

However, de-Amber LEDs were indicated by a few interviewees to be highly sensitive to temperature changes with potential peak wavelength shifts of up to 10 nm (between 25 °C and 85 °C). Mathematically shifting a real SPD by 10 nm (see **Figure 7** for an example) and computing the chromaticity difference results in a Δ*u*'*v*' near 0.060, which is several orders of magnitude larger than the DLC's minimum requirements. As this evaluation data was limited to one de-Amber chip, more data is needed to investigate color maintenance shifts.

Conclusions from the lumen and color maintenance evaluations

All three evaluated pc-Amber LED chips complied with the DLC Standard, Premium, and LUNA lumen maintenance and color maintenance requirements. The single evaluated de-Amber LED chip complied with the DLC's color maintenance requirements, but variably complied with the DLC's lifetime requirements depending on operating temperature.

The consensus is that de-Amber LED chips are highly sensitive to changes in temperature and, as a result, lumen output can vary by more than 50% in typical operating conditions. This leads to potentially large fluctuations in luminous efficacy, which may deviate greatly from published or predicted luminaire efficacy, and compromise energy performance.

More data are needed to have better confidence that pc-Amber LEDs will have similar maintained performance as pc-White LEDs with regards to the DLC's lumen maintenance and color maintenance technical requirements, but preliminary evaluations suggest that they perform similarly. Preliminary data for de-Amber LEDs suggests that high temperature sensitivity results in a suite of complications impacting attributes such as light output, lumen maintenance, and color maintenance not present with typical pc-White LEDs.

Color rendition

Color rendition measures were calculated for commercially available de-Amber, pc-Amber, and pc-LED chips, and an HPS and LPS lamp for reference. Calculated measures included measures from ANSI/IES TM-30-20 (R_f, R_g, $R_{f,h1}$, and $R_{cs,h1}$), CIE 13.3-1995 (R_a and R_9), and The Total Light Source Error Score (R_d).[16]

Specification sheets of more than 50 "amber" luminaires were reviewed, but none provided color rendition values for these products. Therefore, to determine the color rendering performance of

[16] See the Appendix for definitions of R_f, R_g, $R_{f,h1}$, $R_{cs,h1}$, R_a, R_9, and R_d.

common NWL sources, SPDs were procured from various sources that included colleagues, the library of the IES TM-30-18 Calculator, the library of the DOE Sky Glow Comparison Tool, and by digitizing plots from publicly available LED chip data sheets.

Table 4 summarizes some representative data. As expected, narrowband products such as LPS and de-Amber have the worst rated color rendition with nearly zero color fidelity, and very high Light Source Error Scores (poor color discrimination). This is due to their near monochromatic emission spectra. Performing relatively better is HPS, with color fidelity of 19/42 (CIE R_a / TM-30 R_f) and an R_d of 40. Notably, HPS has historically been understood to have poor color rendition with little ability to distinguish between colors.

Pc-Amber LEDs performed better due to their increased short and middle wavelength radiation content and a broad emission spectrum near 590 nm, but still do not meet DLC's V5.1 color rendition thresholds. They have, on average, relatively higher color fidelity than HPS (CIE R_a ranging from 36 to 58 and TM-30 R_f ranging from 42 to 64), depending on manufacturer, and worse color discrimination than HPS (R_d > 40).

Table 4: CCT, color rendition, Relative Sky Glow and S/P Ratio values of some representative NWL LED chips and HID luminaires.

	pc-Amber				de-Amber			pc-LED			
Metric	**Mf. A**	**Mfr. B**	**Mfr. C**	**Mfr. D**	**Mf. A**	**Mfr. B**	**Mfr. D**	**Mfr. C**	**Mfr. C**	**HPS**	**LPS**
CCT	1775	1873	1735	1724	1314	1619	1728	1998	1828	2041	1721
Average color fidelity **(R_f)**	42	48	64	50	2	1	1	76	78	42	0
Average gamut area **(R_g)**	40	48	66	54	0	0	0	95	91	62	0
Local Chroma Shift Hue-Angle Bin 1 **($R_{cs,h1}$)**	-31%	-29%	-22%	-32%	-76%	-82%	-82%	-16%	-17%	-47%	-99%
Local Color Fidelity Hue-Angle Bin 1 **($R_{f,h1}$)**	35	40	54	36	0	0	0	69	67	13	0
CIE General Color Rendering Index **(R_a)**	37	41	58	36	-13	-28	-29	73	72	19	-46
CIE Special Color Rendering Index 9 **(R_9)**	-114	-108	-58	-115	-340	-417	-428	-27	-26	-221	-496
Light Source Error Score **(R_d)**	84	76	60	84	636	592	568	16	16	40	312
Relative sky glow **(RSG)**	0.51	0.58	0.69	0.50	0.18	0.25	0.27	1.25	1.21	1.00	0.23
Scotopic-to-photopic ratio **(S/P Ratio)**	0.40	0.45	0.50	0.39	0.17	0.23	0.25	0.79	0.76	0.63	0.22

*Cells are shaded to indicate performance relative to HPS. Red indicates the product performs more poorly, yellow is about equal performance, and green indicates improved performance. All metrics are defined in the Appendix.

This data suggests that to potentially qualify de-Amber or pc-Amber LED luminaires in the future, the DLC would need to provide new color rendition thresholds for these products to balance the human need for color rendition versus the need to limit astronomical and ecological light pollution.

Finally, pc-LED products near the blackbody at nominal CCTs of 2000K and 1800K were recently announced by a LED chip manufacturer and are marketed as "LED replacements for HPS". These products are included in **Table 4** and have calculated color fidelity values (CIE R_a: 72/73; TM-30 R_f: 78/76) that approach those achievable by common pc-White LED light sources. As shown in **Table 4**, these pc-LED chips would meet the DLC's V5.1 Technical Requirements for color rendition.

All evaluated NWL sources severely desaturate red hues, with pc-2000K and pc-1800K LEDs performing the best ($R_{cs,h1}$ = -16% and -17%, respectively), and de-Amber/LPS performing the worst.

Relative sky glow reduction

Astronomical sky glow is a form of light pollution described by the IES as "the brightening of the night sky that results from the scattering and reflection of light from the constituents of the atmosphere [of Earth] (gaseous molecules and aerosols), in the direction of the observer".[17] Electric light sources that contribute to astronomical sky glow include at least the following: sports field lighting, advertising signage, media screens, façade lighting, street lighting, car headlights, light leakage from residential and commercial buildings, greenhouse lighting, fishing lights, and lighting on drilling rigs and other industrial sites.

Are NWL sources a suitable strategy for reducing sky glow, all else being equal? To answer this question, we computed Relative Sky Glow (RSG) for two datasets: 1) commercially available NWL SPDs (including de-Amber, pc-Amber, pc-LED, HPS, and LPS), and 2) a set of 12,245 simulated SPDs that we generated as linear combinations of real LED spectra.

Computing sky glow

Because there is not yet a standard prescribing sky glow metrics, the DLC used the Relative Sky Glow (RSG) metric, which was computed using an unlocked version of the DOE Sky Glow Comparison Tool Excel Calculator [31] accompanying the work of Kinsey et al. [32]. The Sky Glow Comparison Tool, which is described briefly in ANSI/IES TM-37-21, estimates sky glow relative to the following:

- A specified baseline SPD (the "reference"), which was set to HPS because of its historical significance in street lighting
- The percent uplight of both the comparison source (the "test" source) and the reference source (HPS), which was set to zero for both sources
- The observer's location (near or far), which was set to "near"
- Atmospheric conditions (clear or cloudy) which was set to "clear"
- The relative lumen output of the test and reference source (HPS), which was set to 100% (equal output) to isolate the impact of spectrum
- The weighting of the raw data according to an observer's adaptation state, which was set to scotopic adaptation for direct comparison to the results of Kinzey et al. [32]

The selection of "near" and "clear" is representative of applications with large amounts of sky glow and where spectrum likely has the largest impact. In this paper, sky glow computed with this selection of parameters will be referred to simply as "RSG" or "relative sky glow" for brevity.

RSG results for the large dataset of simulated spectra

RSG was computed for 12,245 simulated SPDs generated using random linear combinations of a base set of real LED spectra. The base SPDs were gathered from manufacturers websites and published data, and

[17] https://www.ies.org/definitions/sky-glow/

have the following designations: royal blue, blue, cyan, green, mint, lime, pc-Amber, amber, red-orange, and red. The SPDs span the visible spectrum and include both pc- and de- LEDs.

Key findings include the following:

- CCT is a poor predictor of sky glow (**Figure 9**). At each CCT a wide range of RSG is achievable, suggesting that any lighting specification using CCT as the only spectrally derived measure may result in largely different spectral contributions to sky glow.
- Color fidelity (i.e., CRI R_a or TM-30 R_f) has nearly zero ability to predict the portion of RSG related to light source spectrum (e.g., there is a wide range of potential relative sky glow values for any given CRI R_a value) (**Figure 10**).
- The results showed that no SPD within any of the ANSI quadrangles, including 2200K, produces a lower sky glow than HPS. Because the base set of LEDs represents significantly higher spectral flexibility than is present in commercially available phosphor-converted LEDs, these results suggest that it is unlikely that any commercially available outdoor luminaire with a chromaticity in an ANSI bin will have lower sky glow than HPS (all else being equal besides light source spectrum).

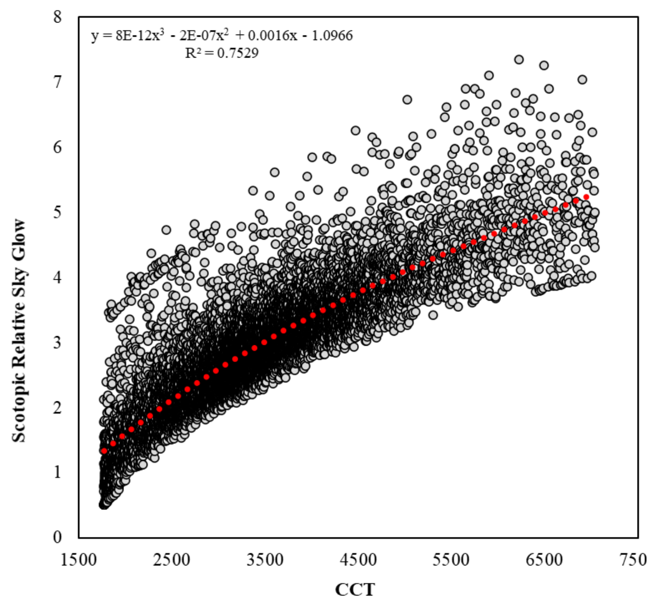

Figure 9: Relative sky glow as a function of CCT for 12,245 composite SPDs. The red dotted line is a polynomial trendline. CCT is not a good predictor of sky glow (Coefficient of Determination (R^2) equals 0.75), as at each CCT, a wide range of RSG values are possible, up to a factor of 3x different.

- The Scotopic-to-Photopic ratio (S/P ratio)—which describes the ratio of a light source's SPD that is coincident with the Scotopic Luminous Efficiency function (V'-λ) to its SPD coincident with the Photopic Luminous Efficiency Function (V-λ)—is a notably strong predictor of RSG and the strongest predictor of all those considered (**Figure 11**). The higher the S/P ratio, the higher the RSG.

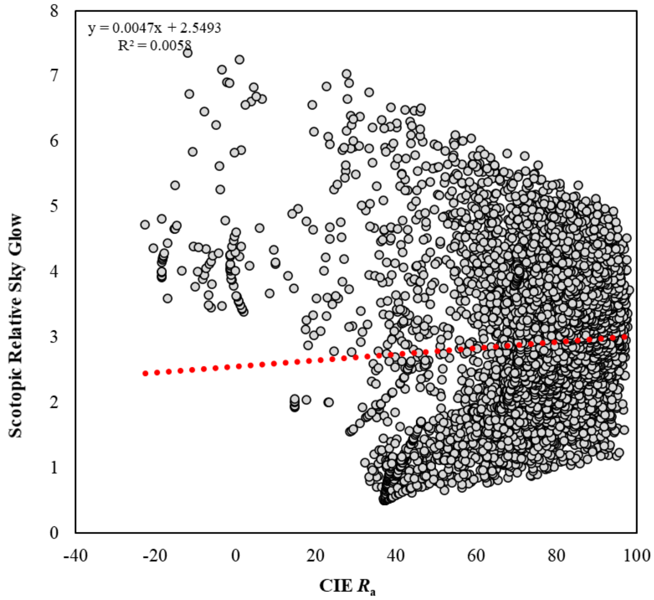

Figure 10: Relative sky glow as a function of the color fidelity metric CRI R_a for 12,245 composite SPDs. The red dotted line is a polynomial trendline. RSG is not predicted by CRI R_a as shown by the Coefficient of Determination (R^2) equaling 0. At each R_a value, a wide range of RSGs is possible, up to a factor of 6x different.

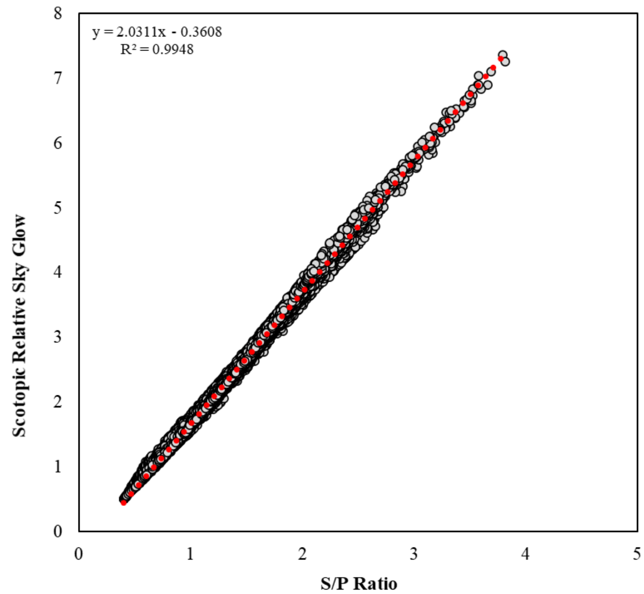

Figure 11: Relative sky glow as a function of S/P ratio for 12,245 optimized SPDs. S/P ratio was a very strong predictor of RSG, as shown by the Coefficient of Determination (R^2) equaling 0.99.

RSG Results for real NWL sources

What is the RSG for commercially available NWL sources? RSG was computed for pc-Amber, de-Amber, pc-1800K, pc-2000K, HPS, and LPS. Results are provided in **Table 4,** on page 25.

LPS and de-Amber have nearly equivalent RSG and the lowest RSG of all light sources considered; they both have significantly lower RSG than the baseline HPS light source. RSG for pc-Amber varies by manufacturer, but all pc-Amber LEDs considered had lower RSG than HPS. Finally, pc-2000K and pc-1800K have higher RSG than de-Amber or pc-Amber sources, slightly higher RSG than HPS and, on average, lower RSG than pc-White LEDs in the ANSI quadrangles.

Like the results for the large dataset (**Figure 11**), the S/P ratio is a strong predictor of relative sky glow.

Overall performance comparison summary of NWL products

With regards to efficacy performance, the DLC found that:

- Very few pc-Amber products could meet DLC's threshold efficacy requirements.
- No de-Amber products could meet the DLC's threshold efficacy requirements.

There are spectral tradeoffs between the three categories of NWL LED chips evaluated, as shown in **Table 4**.

- No NWL source has the best performance in all categories.

- De-Amber has the lowest relative sky glow but has nearly zero ability to render colors.
- Pc-Amber LEDs have comparable or better color rendition (depending on the manufacturer) and lower relative sky glow than HPS, but don't have the best color rendition nor the lowest relative sky glow.
- The pc-1800K and pc-2000K LEDs have the best color rendition of those considered, but also the highest relative sky glow of the evaluated NWL products (slightly worse than HPS).

The collected data indicates that pc-Amber LEDs behave similarly to pc-White LEDs because of their underlying technological similarities. This includes good lumen and chromaticity maintenance and no special failure mechanisms. To consider inclusion of pc-Amber and pc-LEDs on the DLC QPL, appropriate efficacy, color rendition, and color maintenance thresholds must be evaluated.

Data for de-Amber LEDs was difficult to acquire. The data that was acquired suggests that de-Amber LEDs are highly susceptible to temperature fluctuations with output, peak wavelength, and chromaticity varying significantly with temperature. To consider inclusion of de-Amber LEDs on the DLC QPL, more data is needed before appropriate thresholds can be evaluated.

Gaps in Research

This is a dynamic time for light pollution research. The emerging science is showing both positive and negative effects of NWL on astronomical and ecological light pollution (see footnote 3 for a maintained citation database). Gaps in the research are being identified and explored. The lighting industry needs better metrics to understand if, when, and how to apply NWL light sources in sensitive environments. To support these metrics, the industry needs:

- Action spectra (i.e., spectral and temporal (photoperiodic, circa-lunar, circa-annual) sensitivity functions) for representative species, including logistic functions for additive, sub-additive, or super-additive responses to polychromatic spectra.
- Knowledge of how NWL will be accepted by the public. Specifically, perceived safety, acceptance, and brightness research for NWL sources compared to pc-White and optimized LED spectra for outdoor applications is needed.
- To encourage manufacturers and researchers to fully characterize their light sources in the literature with SPDs and relevant metrics, rather than just naming the light sources and/or using peak wavelength values.

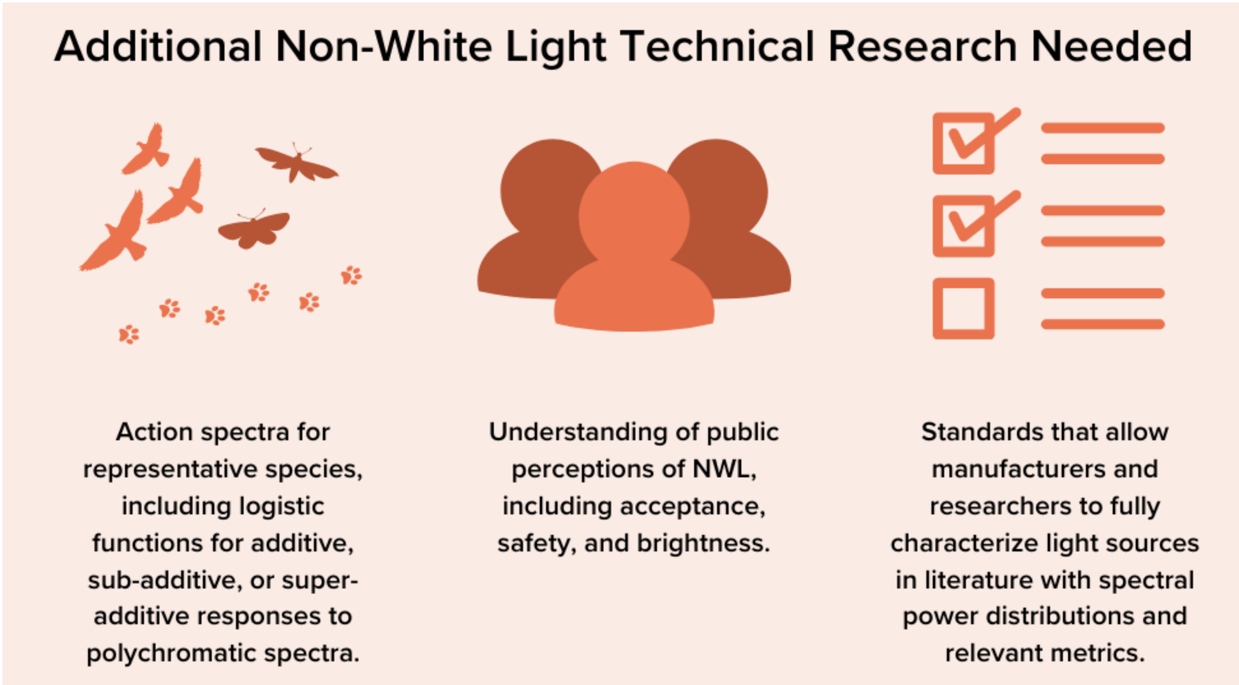

Figure 12: Summary of additional non-white light technical research needed to begin to address the negative consequences of ALAN.

Calls to Action

The lighting industry needs a holistic approach to solving the unintended negative consequences of astronomical and ecological light pollution. The overarching challenge is to create tailored SPDs, light levels, and schedules appropriate for various outdoor lighting applications, while being respectful of the effects of electromagnetic radiation on all affected living things. In this whitepaper, the landscape is described for one small but promising part of the solution: NWL amber LED light sources. Various SDOs, such as the IES and CIE, are currently working on standards that address light pollution, and the DLC encourages them to continue this work and to expand their scopes.

The DLC relies on such standards to ensure that qualified LED luminaires that meet DLC technical requirements can be reliably and consistently measured and evaluated worldwide. Current lighting standards must be updated to include NWL sources so that the DLC and other stakeholders can evaluate these products using a consistent framework. Necessary developments to qualify these types of products include:

- Standardized chromaticity boundaries for fixed NWL products in outdoor applications, including “amber”, “red-orange”, “red”, etc.
- Standardized terminology and naming conventions.
- Standardized nomenclature that encompasses the totality of optical radiation to which non-human taxa are sensitive.
- Guidance on color rendition thresholds for NWL sources.
- Standardized reporting requirements for light source spectral power distribution.

- Standardized calculation procedures for computing astronomical sky glow and other negative impacts of ALAN.

Once these standardization activities are completed, more complete and consistent comparisons between light sources in various applications will be feasible, benefitting many stakeholders seeking to improve the built environment. Regulatory and governmental, and non-governmental stakeholders, as well as lighting designers and the lighting industry, will have better tools to consider the holistic impacts of ALAN, its impacts on non-human taxa, and on our view of the night sky.

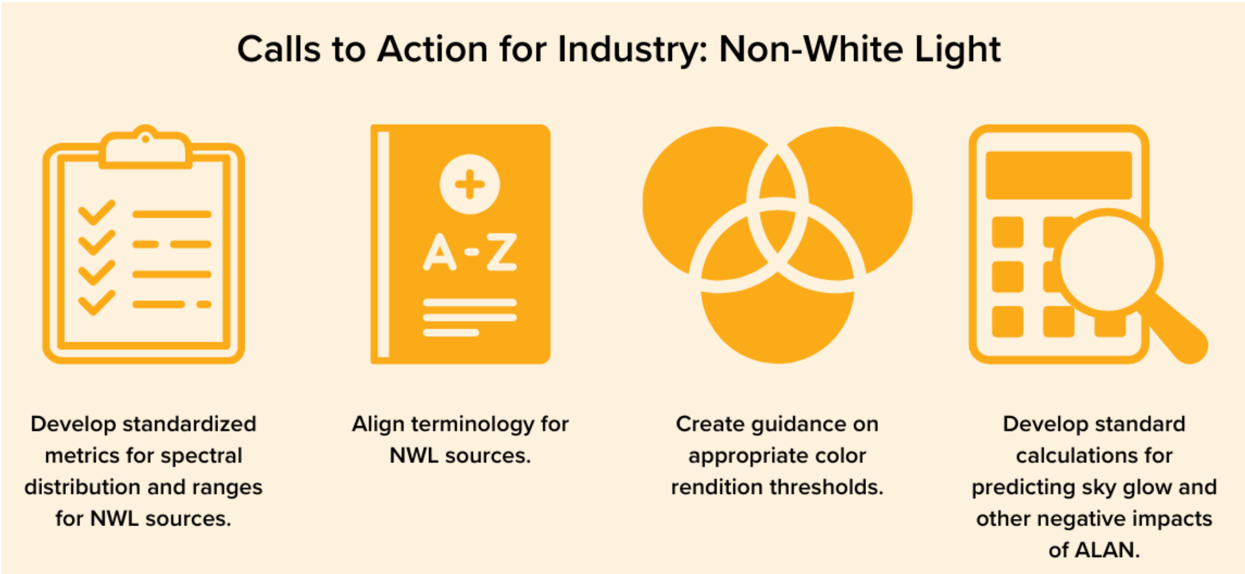

Figure 13: Calls to action to the lighting industry to begin to solve the unintended negative consequences of astronomical and ecological light pollution.

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Appendix

Average Color Fidelity, R_f: The average deviation of 99 Color Evaluation Samples (CES) relative to a broadband reference illuminant at the same CCT. Larger deviations lead to lower R_f values. R_f is conceptually similar to, though mathematically different than, CIE R_a ("CRI").

Average Gamut Area, R_g: The average increase or decrease in chroma (saturation) relative to a broadband reference illuminant at the same CCT. A value greater than 100 indicates an average increase in chroma (saturation); a value less than 100 indicated an average decrease in chroma (saturation). R_g is conceptually similar to, though mathematically different than, the Gamut Area Index (GAI) metric from the Lighting Research Center (LRC).

Local Color Fidelity Hue-Angle Bin 1, $R_{f,h1}$: the average deviation of the nominally "red" CES relative to a broadband reference illuminant at the same CCT. $R_{f,h1}$ describes only the average magnitude of difference from the reference illuminant, not the direction of that difference (i.e., increase or decrease in chroma). The larger the deviation, the lower the value. $R_{f,h1}$ is conceptually similar to, though mathematically different than, CIE R_9 ("R_9").

Local Chroma Shift Hue-Angle Bin 1, $R_{cs,h1}$: the average increase or decrease in chroma (saturation) of the "red" CES relative to a broadband reference illuminant at the same CCT. $R_{cs,h1}$ provide specific information about the increase or decrease in chroma (saturation) relative to the reference illuminant. A value greater than 0% is an increase in chroma (saturation); a value less than 0% is a decrease in chroma (saturation). There is no other similar measure of color that is conceptually similar to $R_{cs,h1}$.

CIE General Color Rendering Index, R_a (e.g., "CRI"): the average deviation of the 8 Test Color Samples (TCS) relative to a broadband reference illuminant at the same CCT.

CIE Special Color Rendering Index 9, R_9 (e.g., "R_9"): the average deviation of the 9^{th} TCS relative to a broadband reference illuminant at the same CCT. This color sample is saturated red. Note that this color sample is not included in the CIE R_a calculation.

The Light Source Error Score, R_d: a measure of color discrimination. R_d is computed by determining the transposition of caps of the Farnsworth Munsell 100 Hue Test (FM-100) hue test relative to their order under CIE Standard Illuminant C. A lower value is better. For reference, a standard HPS lamp has an R_d near 40–48, a standard linear fluorescent may vary between 0 and 24, LEDs vary widely from zero to above 40, and CIE D65 has an R_d of zero… "Light sources relevant to illumination engineering are expected to have R_d values below 48, with values below 12 or 16 expected to promote good color discrimination." See [33–35] for more information.

S/P ratio: the ratio of a light source's SPD that is coincident with the Scotopic Luminous Efficiency function (V'-λ) to its SPD coincident with the Photopic Luminous Efficiency Function (V-λ). The Luminous Efficiency functions are shown in **Figure 14**.

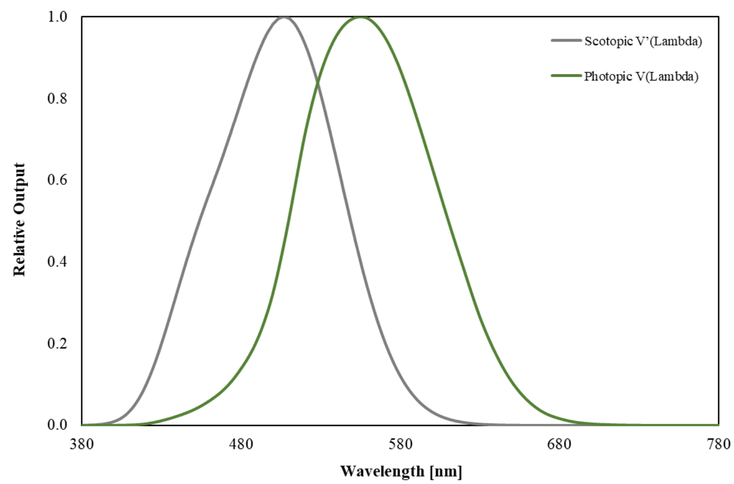

Figure 14: Luminous efficacy functions.