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► **To cite this version:**

Irena Fryc, Maciej Listowski, Christophe Martinsons, Jiajie Fan, Dariusz Czyżewski. A Paradox of LED Road Lighting: Reducing Light Pollution Is Not Always Linked to Energy Savings. *Energies*, 2024, 17 (22), pp.5727. 10.3390/en17225727 . hal-04791448

HAL Id: hal-04791448

<https://hal.science/hal-04791448v1>

Submitted on 19 Nov 2024

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Article

A Paradox of LED Road Lighting: Reducing Light Pollution Is Not Always Linked to Energy Savings

Irena Fryc ¹, Maciej Listowski ¹, Christophe Martinsons ², Jiajie Fan ³ and Dariusz Czyżewski ^{4,*}

¹ Faculty of Electrical Engineering, Białystok University of Technology, Wiejska 45d, 15-351 Białystok, Poland; i.fryc@pb.edu.pl (I.F.); maciej.listowski@pb.edu.pl (M.L.)

² CSTB, Centre Scientifique et Technique du Bâtiment, Division Acoustique, Vibrations, Eclairage et Electromagnétisme, Saint Martin d’Heres, 75016 Paris, France; christophe.martinsons@cstb.fr

³ Institute of Future Lighting, Academy for Engineering & Technology, Fudan University, and Shanghai Research Center for Silicon Carbide Power Devices Engineering & Technology, Shanghai 200433, China; jjajie_fan@fudan.edu.cn

⁴ Faculty of Electrical Engineering, Warsaw University of Technology, Pl. Politechniki 1, 00-661 Warsaw, Poland

* Correspondence: dariusz.czyzewski@pw.edu.pl

Abstract: A variety of LED types can be employed for street and road lighting purposes. White phosphor-converted LEDs represent the most widely used option. However, amber LEDs are increasingly being used to reduce some negative effects associated with light pollution. These LEDs can be manufactured using both phosphor-converted and monochromatic direct chip technologies. This paper addresses the link between the reduction in short-wavelength light emissions which contribute to sky glow and the energy efficiency of LED-based road lighting. This paper focuses on an example illustrating the common misconception that reducing light pollution also means saving energy. Through the consideration of how spectral power distribution influences both mesopic vision and the amount of emitted blue light, it has been concluded that while monochromatic direct amber LEDs consume more energy than their white or amber phosphor-converted counterparts, their use in outdoor lighting is justifiable due to their potential effects of reducing sky brightness.

Keywords: street lighting; LEDs; energy consumption; light pollution



Citation: Fryc, I.; Listowski, M.; Martinsons, C.; Fan, J.; Czyżewski, D. A Paradox of LED Road Lighting: Reducing Light Pollution Is Not Always Linked to Energy Savings. *Energies* **2024**, *17*, 5727. <https://doi.org/10.3390/en17225727>

Academic Editor: Paulo Santos

Received: 25 October 2024

Revised: 8 November 2024

Accepted: 13 November 2024

Published: 15 November 2024



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1. Introduction

The installation of street lighting serves two primary purposes: to enhance both the safety of pedestrians and road traffic and the visual appeal of the area. Researchers have conducted extensive studies on the optimal design of street lighting to ensure user comfort [1] and desired lighting conditions [2,3]. This involves maintaining the appropriate contrast between the object and the background [4], while limiting glare [5] to ensure comfortable viewing [6]. Additionally, studies have focused on minimizing the operating costs [7] and limiting ambient light pollution [8–10]. Contemporary photometric requirements for road lighting are presented in the CIE Technical Reports: CIE 88-1990 Guide for the Lighting of Road Tunnels and Underpasses [11], CIE 115-2010 “Lighting of roads for motor and pedestrian traffic” [12], and the European Standard EN 13201-2 “Road lighting—Part 2” [13]. So, the number and geometric arrangement of luminaires needed for specific types of roadways are calculated on the basis of the requirements given by these documents. The Figure 1 showing spectral power distributions of high h-pressure sodium (HPS) and low-pressure sodium (LPS) which presents the prevailing technologies for outdoor lighting for a considerable period of time. This was due to a number of factors, including their luminous efficacy (around 100 lm/W), long lifespan, and relatively low maintenance costs in comparison to older technologies such as incandescent or mercury vapor lamps.

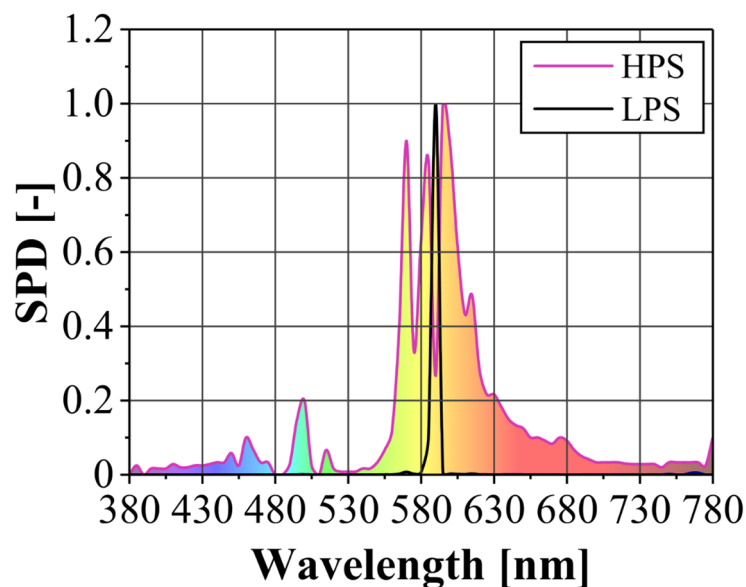


Figure 1. The spectral power distribution (SPDs) of high-pressure sodium lamps (HPS) and low-pressure sodium lamps (LPS).

Nowadays, white phosphor-converted light-emitting diodes (White pc-LEDs) [14,15] are gradually replacing C-MH, HPS, and LPS lamps for road lighting [16]. The introduction of White pc-LEDs into road lighting was driven by a number of factors, including their high luminous efficacy reaching 170 lm/W, but in popular practical road lighting implementations, this level is 120 lm/W [17–19] (if technology other than White pc-LED lighting technology is considered, for example white perovskite light-emitting diodes (pe-LEDs), the luminous efficacy can reach 200 lm/W [20,21], but this technology is not popular due to problems with stability and manufacturing consistency [20,22]). Also, their compact dimensions that facilitate the precise shaping of the luminous intensity distribution (LID) of the luminaire [23], their robust durability in outdoor illumination applications [24], the potential for a high number of LEDs to be utilized in a single luminaire, which, although limited by the size of the luminaire head, still enables the attainment of almost any desired luminous flux from the luminaire [25], the simplicity of luminous flux control and the capacity to modify the power and luminous flux in accordance with the intended application [26,27], their ability to withstand shocks [28], which is particularly crucial in the illumination of overpasses or bridges, and their lifespan now being longer than that of sodium lamps [29] makes them advantageous.

In contemporary lighting installations, White pc-LEDs [30,31] with a nominal correlated color temperature (CCT) of 4000 K and chromaticity within the 7-step 4000 K ANSI quadrangle [32,33] are preferred in many countries. However, some countries such as France now impose the mandatory use of CCT values less than 3000 K [34,35]. In order to identify the suitable LEDs that meet the specified generic requirements of a CCT of 4000 K and the chromaticity of 7 steps, the publicly available databases “Real Light Source SPDs and Color Data for Use in Research” [30] and “EMPIR 15SIB07 Photo LED—Database of LED product spectra” [31] were considered in this work. These databases contain 298 entries on LED sources that align with the desired criteria. Figure 2a illustrates their spectral distributions and Figure 2b presents their chromaticities. White pc-LEDs emit a broad spectrum of light with a significant blue content and an emission peak located around 450–470 nm. The wavelengths in that spectral range scatter more effectively in the atmosphere than longer wavelengths, and this fact increases the chance that a photon emitted upward returns to Earth as sky glow [36,37]. Moreover, this blue-rich spectrum has been demonstrated to increase glare [38] but also disrupt wildlife behavior [39,40], with a negative impact [41,42] on flora [43], fauna [44,45], and ecosystems [46–48]. The majority of animals, including many insects, are adapted to living in a nocturnal world [49]. In

the absence of light, they can hide from predators, feed, hunt, and reproduce. Additionally, the numerous species are more sensitive to short-wavelength light [50,51], whereas amber-colored light induces less effects on them. Furthermore, exposure to artificial light, especially at night, represents a potential threat to human health [52]. This is due to the fact that it causes perturbations of the human biological clock, affecting the circadian rhythm, sleep, and other issues [53,54].

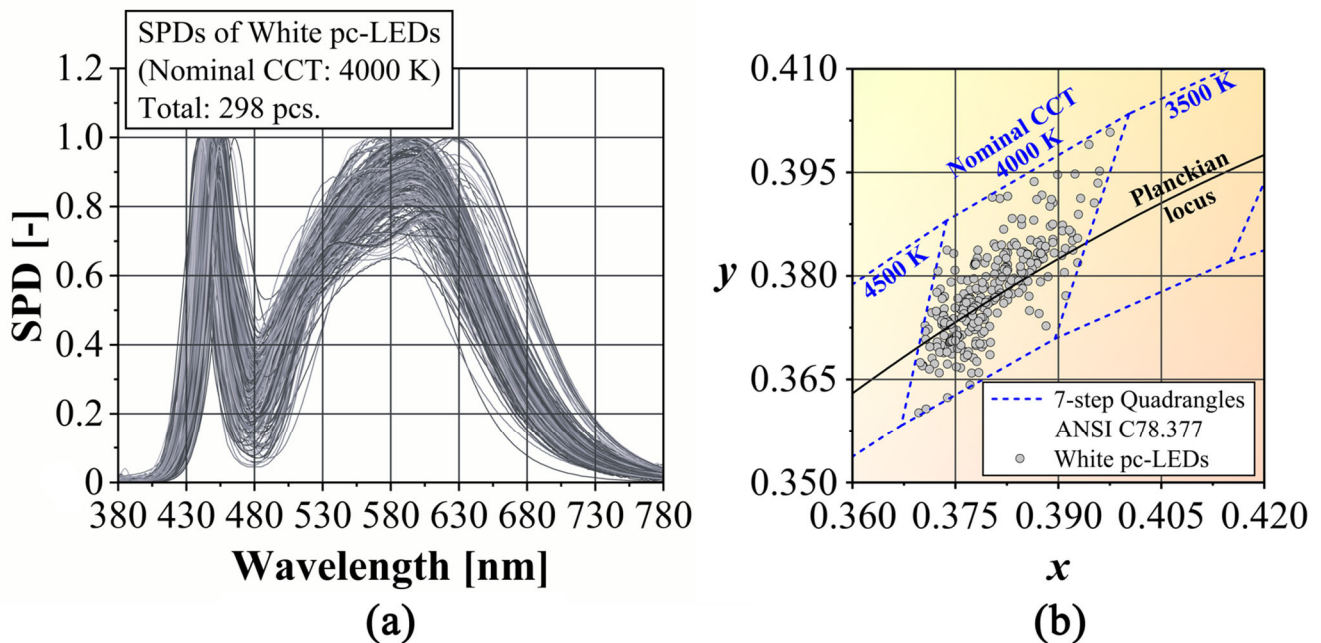


Figure 2. (a) Spectral power distribution (SPD) of luminaires equipped with typical White pc-LEDs having nominal CCT of 4000 K; (b) chromaticity points corresponding to SPD plotted in (a).

To mitigate these undesirable occurrences, some recent recommendations were made to promote the use of low-CCT orange-colored LEDs in outdoor lighting [55] with spectral power distribution (SPD) somewhat comparable to that of sodium lamps [56]. Such LEDs are called amber LEDs. Their narrow spectral distribution and the absence of short-wavelength light offer significant advantages over traditional White pc-LEDs for protecting wildlife-sensitive areas that need to be illuminated [42]. Amber LEDs emit light predominantly in the orange spectral range, typically between 590 nm and 620 nm, through two possible distinct mechanisms. Direct emission amber LEDs (amber de-LEDs) emit orange light directly from their chip with a luminous efficacy around 40 lm/W [57]. Phosphor-converted amber LEDs (Amber pc-LEDs) utilize the phosphor coating that converts blue light emitted by the LED chip into longer-wavelength amber light with luminous efficacy values around 100 lm/W. It is important to note that the luminous efficacy values of these LEDs are lower than those of both White pc-LEDs and legacy HPS and LPS lamps. Nevertheless, amber LEDs offer the possibility of being precisely controlled by “smart city” control systems, which is not feasible with sodium lamps. In addition, the reduced maintenance costs associated with them make them a preferred choice over legacy lamps [58]. It is crucial to recognize that in order to maintain the same illuminance levels, the consumption of electricity will be significantly higher when utilizing amber LED technology in comparison to White pc-LED [57,59].

The SPDs of currently available amber LEDs are illustrated in Figure 3a. The chromaticities are represented as the yellow dots for amber pc-LEDs and as the orange dots for amber de-LEDs (Figure 3b) in the CIE color space diagram. This type of diagram is also used by manufacturers to categorize amber LEDs based on zones of chromaticity tolerance. It is also important to note that different manufacturers have markedly disparate tolerance ranges for this purpose. The AE J578 APR2020 [58] standard incorporates the tolerances

of amber chromaticities utilized by multiple manufacturers for the characterization of their products. Figure 3b provides a visual representation of the amber zone boundaries as defined by the standard SAE J578 APR2020 [58,60]. It is important to note that the normative chromaticity range for amber illumination is considerably broader than that of conventionally manufactured amber light-emitting diodes (LEDs) (Figure 3b). This issue is not the consequence of technological limitations as the technology used in LED manufacturing does not impose the restrictions on the ability to produce amber LEDs with chromaticities covering the full range permitted by the standards [58,61]. It is therefore possible that in the future, amber LEDs with chromaticities different from the current state of the art may become widely used.

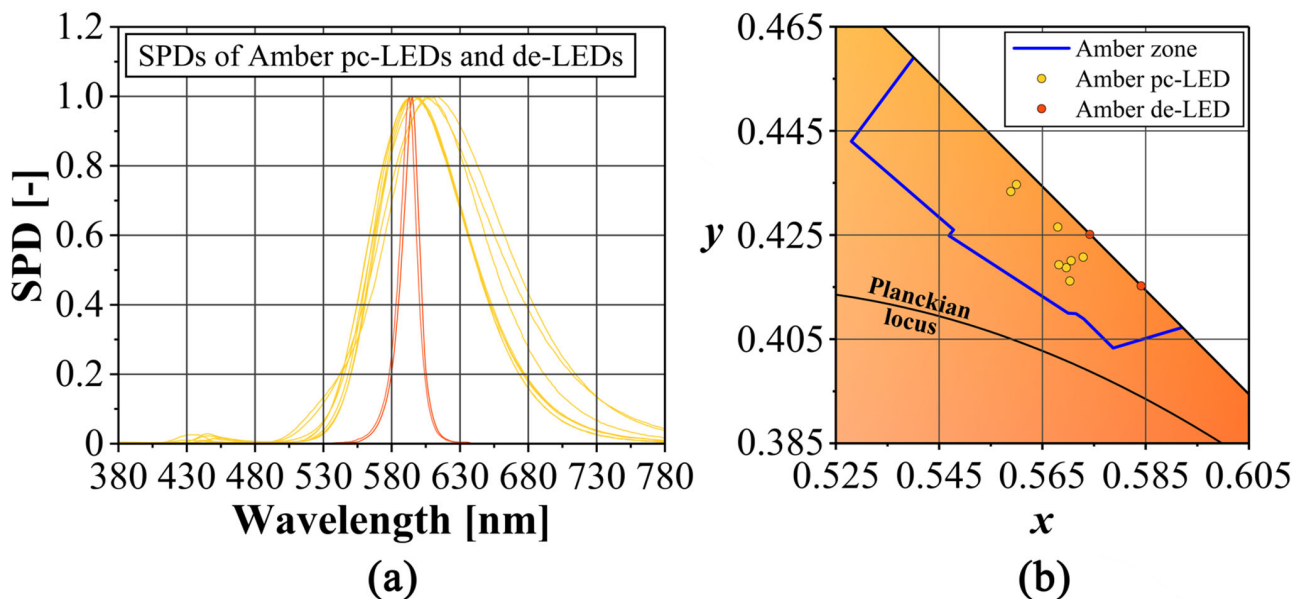


Figure 3. (a) SPDs of amber LEDs made by different technologies [30,31,62], (b) chromaticity coordinates of amber LEDs (yellow and orange dots), and boundary of amber zone (blue line) given in standard SAE J578 APR2020 [60].

From the perspective of outdoor lighting design, it is of paramount importance to assess whether an amber LED manufactured using any technology (characterized by the chromaticity point's location being inside the amber zone) presents a comparable impact on light pollution, as quantified by state-of-the-art methods employed by researchers [58,63,64]. For this purpose, different existing numerical metrics are used below.

The Azul (Azul is the Spanish word for blue)-to-photopic ratio (A/P ratio) describes the ratio of a light source's SPD $S_T(\lambda)$ between 380 nm and 500 nm to its luminous output assessed using the standard photopic luminous efficiency function $V(\lambda)$. The A/P ratio (Equation (1)) is used, for instance, by The Technical Office for the Protection of Sky Quality (TOPC) of the Institute of Astrophysics of the Canary Islands (IAC). This authority defined two different upper limits for the allowed night lights: 0.25 and a more restrictive 0.15 [65].

$$A/P = \frac{\int_{380}^{500} S_T(\lambda) d\lambda}{\int_{380}^{780} S_T(\lambda) \cdot V(\lambda) d\lambda} \quad (1)$$

In addition to SPDs, certain consideration should be given to the impact of perceived brightness levels. At the level of road luminance recommended by the standard EN 13201 [13,66], the vision of the observer (a driver, a pedestrian, etc.) falls in the mesopic regime, corresponding to an intermediate range between photopic vision (typical of daytime vision) and scotopic vision (dark-adapted vision) [67,68]. As presented in CIE 191:2010 [69], in the mesopic range, the spectral sensitivity of the human eye $V_{meso, lamp}(\lambda)$ depends on

the averaged luminance level $L_{av}(\lambda)$ and the SPD of the given light. This CIE document also details the method for determining the eye spectral sensitivity function in this luminance range. The mesopic sensitivity is calculated (Equation (2)) as a linear combination of the photopic $V(\lambda)$ [70] and the scotopic $V'(\lambda)$ spectral sensitivity functions. In Equation (2), the parameter m is the adaptation coefficient and $M(m)$ is a normalization factor ensuring that the maximum value of $V_{meso, lamp}(\lambda)$ is unity. The parameter m reflects the transition between photopic and scotopic vision. It is calculated iteratively based on the photopic luminance and scotopic luminance in the visual field. The detailed algorithm used to calculate its value is provided by the CIE 191:2010 document. As m approaches 1, the vision becomes fully photopic ($V(\lambda)$), and as m decreases toward 0, the vision shifts toward scotopic sensitivity ($V'(\lambda)$).

$$V_{meso, lamp}(\lambda) = \frac{1}{M(m)} \cdot [m \cdot V(\lambda) + (1 - m) \cdot V'(\lambda)] \quad (2)$$

When the human eye is adapted to the mesopic conditions created by a given lighting installation, the perceived luminance $L_{meso, lamp}$ has a different value to the averaged photopic luminance L_{av} [71]. The mesopic luminance (cd/m^2) of a visual adaptation field can be calculated as follows:

$$L_{meso, lamp} = K_{m, lamp} \int_0^{\infty} V_{meso, lamp}(\lambda) \cdot L_{av}(\lambda) d\lambda \quad (3)$$

$L_{av}(\lambda)$ is the luminance of the photopic condition, and $K_{m, lamp}$ corresponds to the human eye's maximum luminous efficacy [68]. The $K_{m, lamp}$ factor is the photometric radiation equivalent which allows for the calculation of photometric values for the visible range (380–780) nm based on the power emitted by the light source. For mesopic vision, the $K_{m, lamp}$ factor will be variable and will depend on the spectral distribution of the light source in question and the luminance level achieved, e.g., on the road. The value of $K_{m, lamp}$ depends on both the $L_{av}(\lambda)$ luminance level and SPD of light. The value of $K_{m, lamp}$ is determined (Equation (4)) from the definition of the candela (SI system), taking into account that for monochromatic radiation of 555 nm, the value of $K_{m, lamp}$ is 683 lm/W .

$$K_{m, lamp} = \frac{683 \text{ lm} \cdot \text{W}^{-1}}{V_{meso, lamp}(\text{for } \lambda = 555.55 \text{ nm})} \quad (4)$$

The Mesopic Flux Ratio (MFR) metric (Equation (5)) [72] can be used to evaluate the light level perceived by the human eye under mesopic visual conditions. The Mesopic Flux Ratio (MFR) is a metric used to evaluate the luminous flux required by a given light source with an SPD $S_T(\lambda)$ to achieve the same mesopic brightness as a high-pressure sodium (HPS) lamp, which serves as a reference. The MFR reflects how the human eye perceives light under mesopic conditions where both photopic and scotopic vision are engaged. Combining this metric with the A/P enables a more comprehensive assessment, making it easier to determine the relationship between perceived brightness and light pollution for various types of light sources.

$$MFR = \frac{K_{m, lamp} \cdot \int_{380}^{780} S_T(\lambda) \cdot V_{meso, lamp}(\lambda) d\lambda}{K_{m, HPS} \cdot \int_{380}^{780} S_{HPS}(\lambda) \cdot V_{meso, HPS}(\lambda) d\lambda} \quad (5)$$

The introduction of the Mesopic Flux Ratio metric simplifies the complex relationship between the potential for sky glow and the luminous flux required to achieve the same mesopic luminance as HPS lighting.

2. Materials and Methods

Road lighting should be designed to ensure good visibility for drivers and pedestrians [73–75]. In this study, we examine a typical 7 m wide road (Figure 4, Table 1) with moderate photometric requirements. This type of road has been lit in accordance with the European Standard [66] M4 lighting class requirements (Table 2). This kind of lighting is seen to offer an optimal balance between safety, visibility, and energy efficiency for medium levels of traffic [76,77].

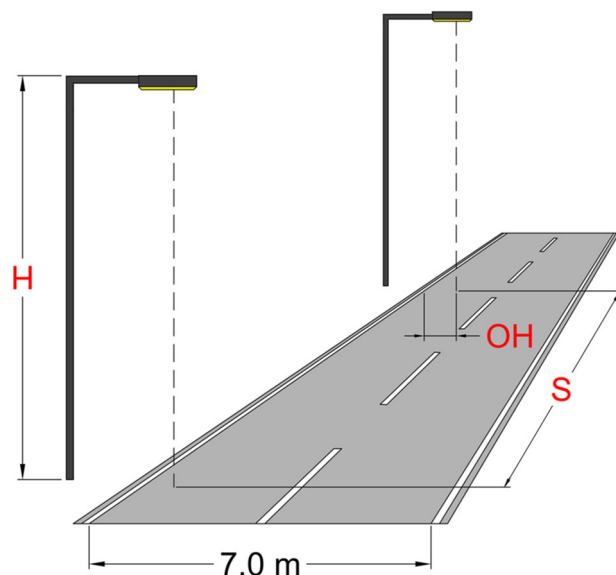


Figure 4. The geometry of a typical road lighting installation of class M4 [41]. S is interdistance, H is luminaire mounting height, OH is overhang.

Table 1. Geometric parameters of luminaire settings of M4-class road.

Parameter	Value
Interdistance (S) [m]	43.5
Luminaire mounting height (H) [m]	8.50
Overhang (OH) [m]	1.50

Table 2. The M4 lighting class photometric parameter requirement according to EN 13201.

Lighting Class	Average Luminance L_{av} [cd/m ²] (Minimum Maintained)	Overall Uniformity U_0 [-] (Minimum)	Longitudinal Uniformity U_l [-] (Minimum)	Threshold Increment f_{TI} [%] (Maximum)	Edge Illuminance R_{EI} [-] (Minimum)
M4	0.75	0.40	0.60	15	0.30

In order to obtain the M4-class road lighting parameters, the typical luminaires based on White pc-LEDs [57,76], amber pc-LEDs, and amber de-LEDs [57] were employed (Table 3). Three luminaires with an identical luminous flux of 9002 lm and an identical luminous intensity distribution curve were considered. Due to the different luminous efficacy values of the different types of LEDs, the number of individual LEDs depends on the chosen type of LED. In the luminaires under consideration, 78 White pc-LEDs were used, 95 amber pc-LEDs were needed, and 316 amber de-LEDs luminaire were required. The luminaires utilizing White pc-LEDs operate at 90 W, which means significantly lower electricity consumption in comparison to amber LEDs which consumed 110 W for the amber pc LED technology and 273 W for the amber de LED technology [57].

Table 3. Luminaire parameters.

Technical Parameters	White pc-LED Luminaire	Amber pc-LED Luminaire	Amber de-LED Luminaire
Number of LEDs [pcs.]	78	95	316
Luminaire luminous flux [lm]	9002	9002	9002
Luminaire power [W]	90	110	274

To evaluate the relationship between energy consumption and light pollution potential, the 298 real SPDs of White pc-LEDs covering the 4000 K ANSI chromaticity range were considered. Given that only a limited number of amber LEDs are currently commercially available (see Figure 3), their technologically feasible SPDs were modeled [78] using spectral modeling techniques, specifically Gaussian functions [79–81]. This approach enabled the creation of the equivalent number of SPDs for both amber pc-LEDs (Figure 5a) and amber de-LEDs (Figure 5b) to match the number of White pc-LEDs.

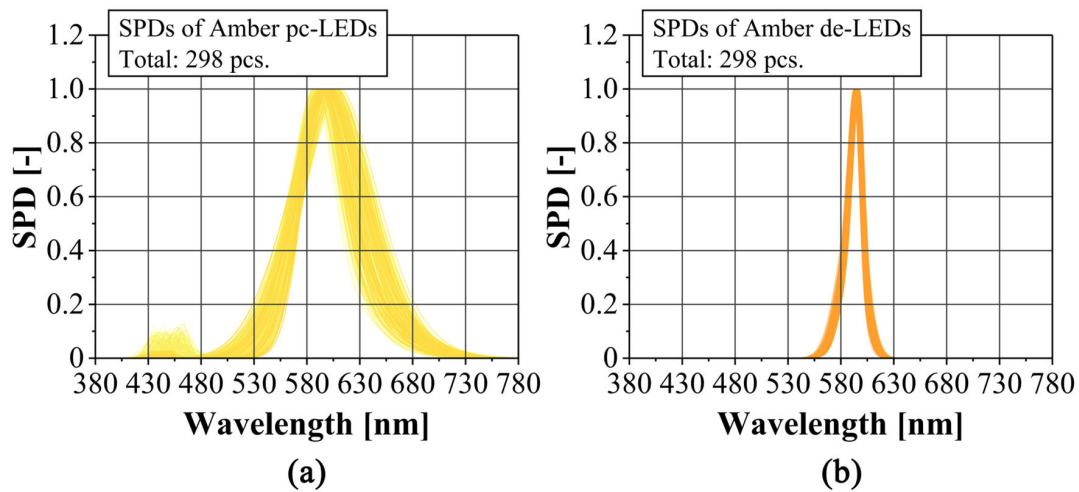


Figure 5. SPDs of modeled amber LEDs (a) based on pc-LED technology and (b) based on DE (direct emission) LED technologies.

Figure 6 provides a visual representation of the chromaticities of amber pc-LEDs and amber de-LEDs evenly distributed across the amber zone in the CIE 1931 chromaticity diagram.

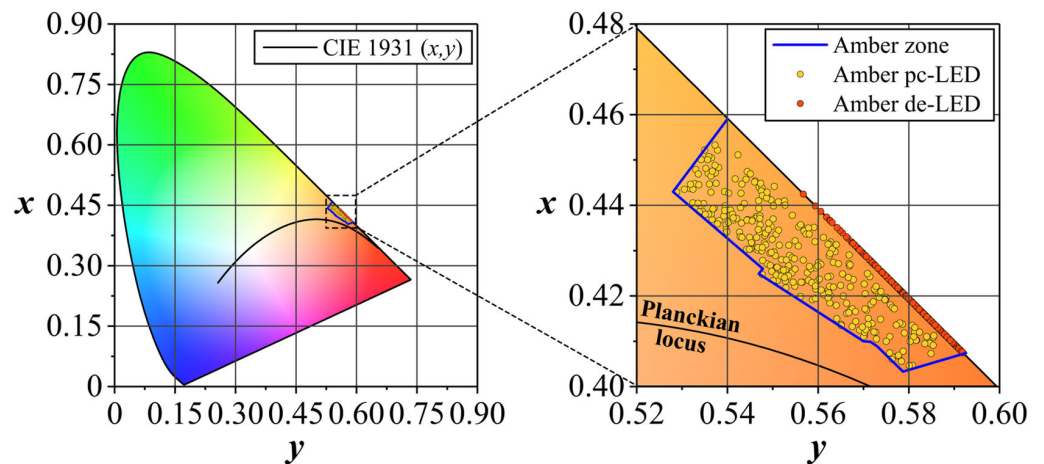


Figure 6. Chromaticity points of amber LEDs under consideration.

3. Results and Discussion

The parameters of interest were calculated. Descriptive statistics were computed and are displayed in the box plot graphs. The symbol “x” on these boxes represents the mean of the given data set, while the middle line denotes the median of the set. The interquartile range (IQR) is represented by the height of the box plot. The limits of the box indicate the first (25%) and third quartile (75%). The outliers have been identified based on the data set and are indicated with a diamond symbol. The term “outlier” is defined as a value that exceeds 1.5 times the interquartile range (IQR). In the event that outliers are present, the whiskers extending from the box indicate the highest and lowest non-outlier values. In the absence of outliers, the whiskers represent the highest and lowest values within the set.

The A/P values presented in Figure 7a indicate that typical White pc-LEDs with the nominal correlated color temperature of 4000 K have a high potential to contribute to sky glow, exceeding the threshold of 0.25 defined by some light pollution regulations [65]. In contrast, significantly lower values are observed for amber pc-LEDs (Figure 7b) and amber de-LEDs (Figure 7c). The further box plot analysis shows that 50% of the A/P values for White pc-LEDs fall between 0.825 and 0.875, while the range is from 0.05 to 0.15 for amber pc-LEDs, and the range is from 0 to 0.0015 for amber de-LEDs.

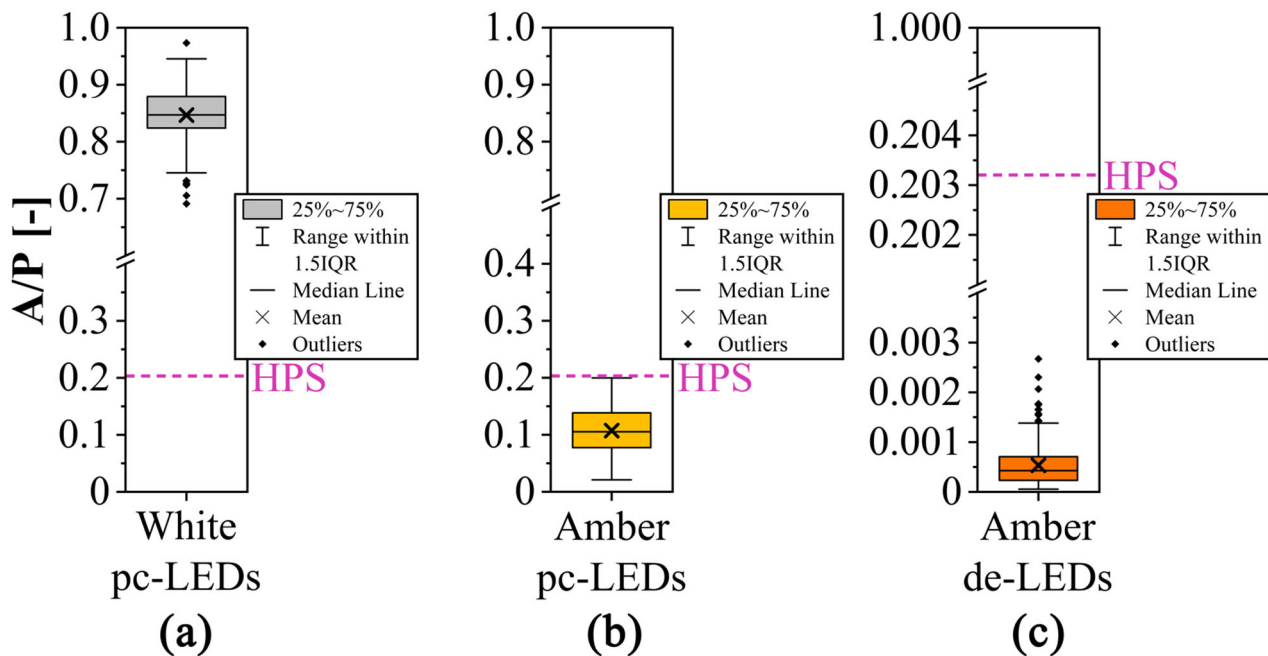


Figure 7. The A/P ratio of LEDs under consideration. (a) White pc-LEDs, (b) amber pc-LEDs, and (c) amber de-LEDs.

However, for the required luminance level (L_{av}) of 0.75 cd/m^2 for the M4 road class, the mesopic luminance favors the SPD of White pc-LEDs, which leads to a brighter perception of the road in comparison with high-pressure sodium (HPS) lamps (Figure 8a). The perceived mesopic luminance for amber pc-LEDs (with 50% of values between 0.68 and 0.70) is close to that of HPS lamps ($L_{meso, lamp} = 0.710$), while the maximum mesopic luminance reaches 0.675 for amber de-LEDs, making them appear less bright. White pc-LEDs give the highest perceived mesopic luminance, with values ranging from 0.80 to 0.83. This necessitates the additional luminous flux for amber pc-LEDs and amber de-LEDs to match the mesopic brightness of the widely used White pc-LEDs.

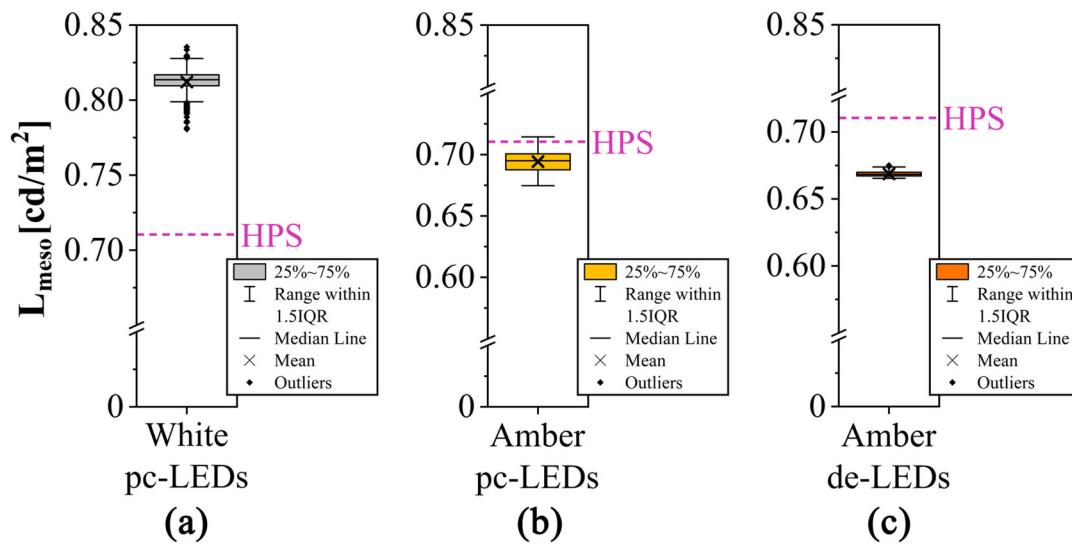


Figure 8. The mesopic luminance values L_{meso} for the same average photopic luminance of 0.75 cd/m^2 created by LEDs under consideration (a) for White pc-LEDs, (b) for amber pc-LEDs, and (c) for amber de-LEDs.

As shown in Figure 7, while “low-impact” amber LED lighting (amber pc-LEDs and amber de-LEDs) significantly reduces sky glow compared to HPS lamps, it would require a higher luminous flux to achieve the same mesopic luminance. However, as shown in Figure 8, HPS lamps would require an even higher luminous flux to achieve the same mesopic luminance. For amber pc-LEDs, the MFR (Figure 9) ranges from 0.948 to 1.01, indicating that up to 5.2% more luminous flux is needed in some cases, while in others the difference is negligible (it is less than 1%). Amber de-LEDs are less efficient, with MFR values between 0.935 and 0.95, meaning that 5% to 6.5% more luminous flux is required to match the mesopic luminance of HPS lamps. In contrast, White pc-LEDs require 12% to 17% less luminous flux to achieve the same mesopic luminance.

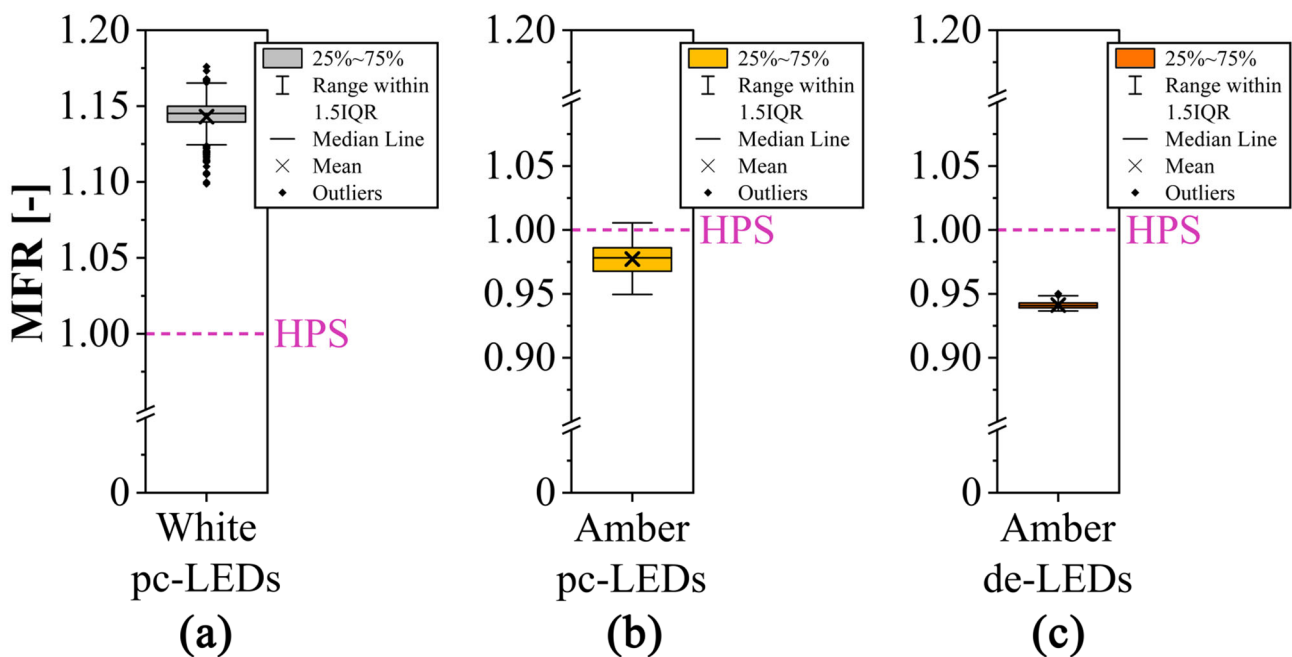


Figure 9. Calculated MFR for different LED technologies: (a) White pc-LEDs, (b) amber pc-LEDs, and (c) amber de-LEDs.

4. Conclusions

This study reveals that implementing amber LED lighting with a low potential for sky glow and low impact on fauna and flora may lead to increasing energy consumption. This conclusion challenges the common belief that saving energy and protecting the environment can be simultaneously achieved.

While amber de-LEDs consume significantly more energy than White pc-LEDs, they are highly effective in reducing sky glow. This fact makes them a suitable choice for environmentally sensitive areas where protecting the nocturnal ecosystems and limiting light pollution are priorities. Despite their higher energy demands, their use can be justified when environmental considerations outweigh economic factors.

In contrast, amber pc-LEDs offer a practical compromise between energy efficiency and light pollution mitigation. Although they currently are less energy-efficient than White pc-LEDs, their reduced contribution to sky glow makes them a viable alternative for road lighting, particularly where both cost efficiency and environmental impact must be balanced.

The introduction of the Mesopic Flux Ratio (MFR) provides a quantitative framework for understanding the trade-offs between energy consumption and the potential for light pollution. The findings demonstrate that reducing sky glow through amber de-LED technology and amber pc-LED technology may require increased energy consumption to achieve the same mesopic luminance ($L_{meso, lamp}$) in comparison with White pc-LEDs. However, advancements in LED technologies, particularly amber de-LEDs, will undoubtedly improve their luminous efficacy, enhancing their potential in future lighting applications. The U.S. Department of Energy predicts that the luminous efficacy of amber de-LEDs will improve by ~200% within the next decade [82], potentially expanding their use in outdoor lighting applications.

In conclusion, the selection of LED technology for outdoor lighting must be weighed with the balance between energy savings and environmental impacts. It requires the careful consideration of how different spectral power distributions impact the potential for light pollution and energy efficiency. With the current state of technology, amber pc-LEDs seem to offer a balanced solution where both energy efficiency and night sky preservation are the key concerns.

Author Contributions: Conceptualization, I.F.; methodology, I.F.; software, I.F.; formal analysis, I.F., M.L., C.M., J.F. and D.C.; data curation, I.F., M.L., C.M., J.F. and D.C.; writing—original draft preparation, I.F.; writing—review and editing, I.F., M.L., C.M., J.F. and D.C.; visualization, M.L. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by Warsaw University of Technology: Open Science V program.

Data Availability Statement: The data sets presented in this article are not readily available because the data are part of an ongoing study.

Acknowledgments: The author would like to express his gratitude to the Warsaw University of Technology for funding the possibility of publishing the results of the conducted research.

Conflicts of Interest: The authors declare no conflicts of interest.

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