Conversion Filters and Methodological Framework for Sustainable LED Urban Lighting

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Abstract—This paper presents comprehensive practical solutions for reducing light pollution in urban LED lighting systems through two complementary approaches: (1) spectral conversion filters for retrofitting existing 4000 K nominal CCT LED luminaires, and (2) a systematic methodology for designing environmentally-conscious lighting installations. The conversion filter method achieves nominal CCT reduction from 4000 K to CCT ≤ 2700 K, providing a cost-effective alternative to complete infrastructure replacement.

The transformation of outdoor lighting from high-pressure sodium (HPS) lamps to LED technology has been driven primarily by energy efficiency considerations. In European installations, this transition has predominantly favored neutral white LEDs with nominal CCT of 4000 K, whose spectral power distribution (SPD) contains a substantial proportion of short-wavelength radiation in the 450–500 nm range (Fig. 1a). While LED systems offer superior energy performance, this spectral characteristic has inadvertently created significant environmental challenges that require comprehensive solutions [1].

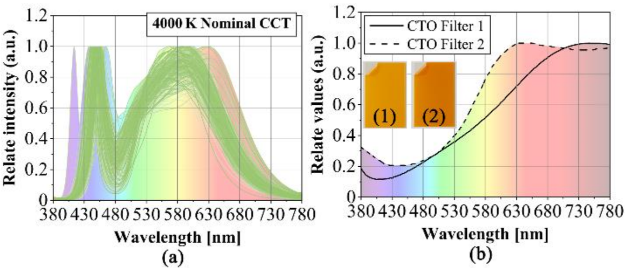

Fig. 1. The relative values of a) spectral power distributions of nominal CCT 4000 K LEDs and b) transmission response of CTO filters.

Recent research has demonstrated that short-wavelength light has a severe impact on nocturnal ecosystems [2, 3], causing disruption of the circadian rhythm through melatonin suppression in both humans and wildlife [4]. Studies show that light sources with nominal CCT above 3500 K cause significantly stronger ecological disturbances than those with nominal CCT below 3000 K at equivalent illuminance levels [5]. In areas with high-CCT lighting [6], nocturnal insect populations are declining by 40–60%. The biological impact extends beyond insects to include birds, bats, and aquatic organisms, with documented effects on migration patterns, foraging behavior, and reproductive success [7]. These ecological concerns have driven increased regulatory attention to outdoor lighting practices, particularly in Europe.

This growing awareness has prompted comprehensive regulatory responses across Europe. The Czech Republic became the first country to legally define light pollution in 2002, requiring zero upward light ratio (ULR) for all new outdoor lighting installations. France subsequently implemented the most comprehensive framework in 2018 [8], establishing nominal CCT limits of 3000 K for urban and suburban areas, 2700 K for natural areas, and 2400 K for protected zones. The French regulations also mandate a ULR of 0% in protected areas and below 1% for public roads, alongside operational restrictions, including the switching off of facade lighting between 1:00 and 7:00 AM and the mandatory dimming of road lighting after 11:00 PM. The implementation of these measures resulted in a 14% nationwide reduction in light emissions between 2018 and 2021 [9], demonstrating the effectiveness of comprehensive regulatory approaches. Italy and Spain implement region-specific regulations. Lombardy's 2000 law pioneered regional approaches. Spain's autonomous communities, including Catalonia (Decree 190/2015 [10]) and the Canary Islands (Law 31/1988 [11]), have established comprehensive frameworks. At the EU level, Joint Research Centre guidelines [12] and CIE standards [13, 14] provide technical guidance for limiting obtrusive light and urban lighting master planning. The International Dark-Sky Association recommends CCT ≤ 3000 K for outdoor lighting [15]. Figure 2 compares the spectral power distributions of various warm white LEDs (2200–3000 K), illustrating the significant reduction in short-wavelength emission compared to 4000 K sources. However, Poland lacks comprehensive legal frameworks addressing light pollution [16], creating a regulatory gap that hinders systematic environmental protection efforts. Given Poland's regulatory gap and the widespread

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deployment of 4000 K LED systems across Europe, this paper addresses this challenge through two complementary approaches: (1) an immediate retrofit solution using color temperature conversion (CTO) filters for existing 4000 K LED luminaires, and (2) a systematic methodology for designing environmentally-conscious urban lighting systems based on European best practices.

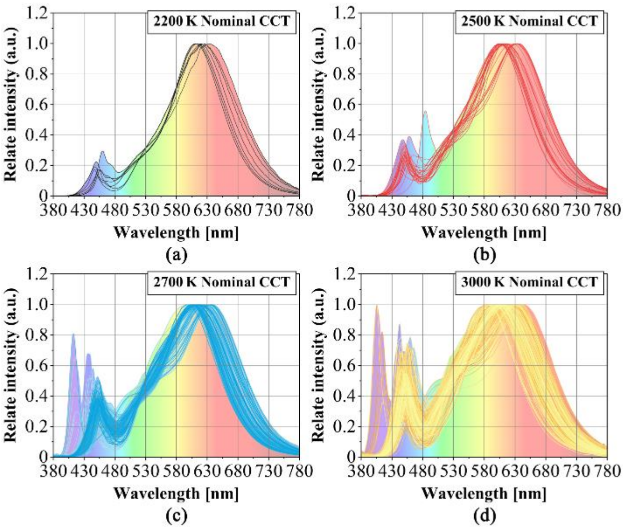

Fig. 2. The relative values of SPDs of LEDs with nominal CCT a) 2200 K, b) 2500 K, c) 2700 K, and d) 3000 K [17].

In existing LED-based park luminaires (Fig. 3a), the feasibility of using a CTO filter in the form of an adhesive film (Fig. 3b–c) to reduce LED nominal CCT from 4000 K to ≤ 3000 K was investigated. Two commercially available CTO filters with different spectral transmission (Fig. 1b) were evaluated. The CTO Filter 1 has transmission of approximately 70–75% in the 600–700 nm range while attenuating 450–500 nm radiation by 50–60%. The CTO Filter 2 provides stronger attenuation with 40–45% transmission in the blue region.

(a) (b) (c) (d)

Fig. 3. Park LED luminaire: (a) without filter, (b) with CTO filter 1 applied, (c) with CTO filter 2 applied, and (d) integrating sphere typically used for luminous flux measurements.

Five LEDs (Table 1) were selected, representing real-world variability of commercial LED products with a nominal CCT of 4000 K and a CRI of≥ 80.

Table 1. The parameters of the considered LEDs

	CCT [K]	Duv [-]	CRI [-]
LED 1	3760	-0.0040	86
LED 2	4215	-0.0035	92
LED 3	3988	0.0009	80
LED 4	3808	0.0062	83
LED 5	4230	0.0053	91

The chromaticity coordinates of the selected LEDs spanned the entire seven-step ANSI tolerance range [18], with samples positioned at the central point and the four corners of the nominal 4000 K ANSI bin. An integrating sphere, as shown in Figure 3d, is a standard apparatus typically used for luminous flux evaluation. The maintained luminous flux (MLF) was calculated from luminous flux values before and after CTO filter application, and was determined as:

$$MLF = (1 - \Phi_2/\Phi_1)\cdot 100\%, \quad (1)$$

where Φ_1 represents luminous flux before and Φ_2 after filter application.

Filter application successfully shifted all LED sources into the warm white range. Both filters achieved target CCT values: CTO Filter 1 resulted in a 2415–2642 K range with about 73% MLF, while CTO Filter 2 achieved 2223–2399 K range with about 64% MLF.

Table 2. The parameters of the LED with the applied CTO Filter 1

	CCT [K]	Duv [-]	CRI [-]
LED 1	2415	0.0005	84
LED 2	2486	-0.0025	94
LED 3	2602	0.0039	80
LED 4	2528	0.0058	84
LED 5	2642	0.0036	90

Table 3. The parameters of the LED with the applied CTO Filter 2

	CCT [K]	Duv [-]	CRI [-]
LED 1	2223	-0.0014	78
LED 2	2258	-0.0039	86
LED 3	2377	0.0013	70
LED 4	2313	0.0028	79
LED 5	2399	0.0010	82

Table 4. The light loss factor (MLF)

	CTO Filter 1 applied	CTO Filter 2 applied
	MLF [%]	MLF [%]
LED 1	73.38	63.20
LED 2	73.80	64.85
LED 3	73.67	64.32
LED 4	73.63	64.44
LED 5	73.97	65.13

The 450–500 nm emission reduction achieved by both filters significantly decreases Rayleigh scattering [19], thereby directly addressing concerns about sky glow. Spectral analysis revealed a 35–45% reduction in blue light emission for CTO Filter 1 and a 50–60% reduction for CTO Filter 2. Color rendering remained acceptable for

outdoor applications, with CRI values ranging from 80 to 94 for CTO Filter 1 and from 70 to 86 for CTO Filter 2. The evaluations confirmed satisfactory visual quality for parks, residential streets, and pedestrian areas, where safety and visual comfort take precedence over high color fidelity.

These results demonstrate that CTO filters provide a viable immediate solution for reducing light pollution from existing 4000 K nominal CCT LED installations. The method enables cost-effective modification of existing luminaires to warm white (2223–2642 K), with light loss factors of 73% for CTO Filter 1 and 64% for CTO Filter 2, offering an alternative to complete fixture replacement. This approach is particularly suitable for parks, natural habitats, and residential zones where immediate intervention is required but budget constraints preclude complete replacement.

For new installations and scheduled replacements, advanced LED technologies should be specified. Phosphor-converted LEDs (pc-LEDs) and multi-chip configurations achieve a warm white output (1900–2700 K) with inherently reduced short-wavelength content [20, 21], while maintaining luminous efficacy comparable to conventional LEDs (>150 lm/W), thereby eliminating traditional efficiency-environment trade-offs.

The systematic implementation of environmentally conscious urban lighting should follow European best practices. Road lighting installations (EN 13201 compliant [22]) should specify full cut-off luminaires at appropriate mounting heights, nominal CCT ≤ 3000 K, and dimming to 50–70% after 23:00. Parks require low-mounted luminaires (h ≤ 4 m) with precise optical targeting, nominal CCT ≤ 2700 K, motion sensor activation, and operation limited to usage hours.

Poland's development of national regulations should incorporate lessons from European frameworks while considering local conditions and existing infrastructure.

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