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Safe and Truly Ecofriendly LED Lighting

Mario Pagliaro

Istituto per lo Studio dei Materiali Nanostrutturati, CNR, Palermo, Italy

Correspondence: Mario Pagliaro (mario.pagliaro@cnr.it)

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ABSTRACT

Truly ecofriendly and safe light-emitting diode (LED) lighting in the built and urban environments requires the use of LED lights emitting significantly lower amount of blue light than conventional, first-generation white LED lights. Thanks to substantial technology progress in the design and manufacturing of LEDs, this is now possible at the same providing vastly enhanced illumination, faithfully reproducing hues with no glare or flickering effects. Driven by awareness of the global relevance of the blue-light problem caused by LED lighting technology and by the precautionary principle, this study provides practical guidelines for the uptake of safe and sustainable LED lighting aimed at policy makers, energy managers and users of LED-based lighting systems. Its outcomes may be useful to inform expanded education in energy management, in which energy, technology, and health aspects are merged with social and economic aspects.

1 | Introduction

In slightly more than a decade since 2012 when efficiency and cost made them competitive with the mainstream lighting solutions, light-emitting diodes (LEDs) have quickly replaced both incandescent, discharge (mercury vapor, sodium, or metal halide) and fluorescent lamps as main sources of white light across the world [1].

Resulting from high luminous efficacy (in lumen/electrical watt, lm/W) and long duration of the new solid-state lamp, energy savings enabled by LED lights are very large. For example, the replacement of 141,089 streetlights in Los Angeles, a city in California, reduced streetlight energy use by 63.1% compared with the high-pressure sodium lamps they replaced [2]. Besides twice higher luminous efficacy (81 vs. 42 lm/W), the new streetlights had an estimated lifetime of 150,000 h, nearly double that of 80,000 h of the sodium lamps [2].

Unfortunately, white light emitted by LED lights contains plentiful blue light. Acute exposure to blue light causes serious health-damaging effects. In detail, exposure to blue light suppresses the secretion of sleep-inducing hormone melatonin, causing insomnia and thus disrupting the circadian rhythm (repeating every 24 h, from Latin circa diem, accusative singular of *dies* for “day”). Lack of sleep causes the stress hormone cortisol to be released, which in turn drives tissue inflammation and plentiful illnesses [3].

Indeed, when negative health effects of the LED streetlight “relamping” in Los Angeles are taken into account, the investment produced a large *negative* return on investment of −146.2% after 10 years [4].

Finally, LED lights can induce glare and flicker. LEDs respond almost instantly to changes in current due to changes in voltage, whereas glare is due to the fact that LEDs are highly concentrated point sources of large luminance. Flickering lights cause annoyance, headaches, migraines, and eyestrain (direct flicker effects at modulation frequencies < 80 Hz and the stroboscopic effect at frequencies > 80 Hz) [5].

In 2010, France's Agency ANSES published an expert appraisal classifying LED lights sold in France in accordance with the international standard EN 62471 on photobiological safety [6]. As a result, for domestic lighting, only LED lamps in risk groups

0 ("no risk") or 1 ("low risk") are currently accessible to consumers in France. The Agency also recommended mandatory indication of the photobiological safety Risk Group on the packaging of LED lights.

Taking into account all the scientific data acquired since 2010 including demonstration of new effects associated with the blue light of LEDs, in 2019 the same Agency reiterated the importance of favoring "warm white" domestic lighting (color temperature below 3000 K), and recommended to limit the exposure of children in particular to the blue-rich light of LED screens of smartphones, tablets, and computers, before sleep and at night [7]. In addition, noting that the screens of computers, smartphones, and tablets are major sources of blue-rich light, and children and adolescents, whose eyes do not fully filter blue light, the expert appraisal showed that even very low levels of exposure to blue light in the evening or at night disrupt circadian rhythm and sleep [7]. Melatonin suppression in sleepiness is higher for children, leading once again scholars to recommend the use of LED light with a low color temperature [8].

Accompanying rapid progress in lighting technology following the introduction of LED lighting, new ways of measuring the effects of light on the human body were developed and standardized. These include metrics like melanopic equivalent daylight illuminance described in the CIE S 026/E:2018 standard including the melanopsin action spectrum, which helps assess how light influences our circadian rhythm [9]; and the latest guidance on glare and flicker from standards such as IEEE 1789-2015 (IEEE Recommended practices for modulating current in high-Brightness LEDs for Mitigating Health Risks to Viewers) and EN 12464-1:2021 (Light and lighting—Lighting of work places—Part 1: Indoor work places) published in 2021 by CEN.

In brief, truly ecofriendly and safe LED lighting in the built and urban environments requires the use of LED lights emitting significantly lower blue light than conventional LED lights, reducing circadian disruption, glare, and flicker while maintaining good color rendering and energy efficiency. Thanks to substantial technology progress in the design and manufacturing of LEDs, this is now possible at the same providing vastly enhanced illumination, faithfully reproducing hues with no glare or flickering effects. Adopting a wider perspective in which management of energy deliberately integrates societal and economic aspects [10], this study provides practical guidelines for guiding the uptake of safe and sustainable LED lighting. Its outcomes may be useful to inform expanded education in energy management, in which energy and technology aspects are merged with economic aspects [11].

2 | Safe, Ecofriendly LED Lighting

The three main parameters used to describe the optical performance of LED lights are the correlated color temperature (CCT), the color rendering (fidelity) index (CRI), and the luminous efficacy of radiation (LER).

The CRI describes the color appearance of objects under a test lamp relative to a defined standard source [12]. Generally calculated as the average value of *R*1–*R*8, and often referred to as *Ra*, where *a* is an abbreviation for "average," CRI is typically comprised between 50 for fluorescent lamps and 100 (highest possible value), for light sources whose spectrum is identical to the spectrum of daylight, very close to that of a black body, typical white-color LEDs have a CRI of 80 or more, with the best multiphosphor white LEDs achieving CRI exceeding 98 (and a TM30 Fidelity Index of 96) indicating high accuracy in reproducing original colors from 99 representative color indexes.

Commercial LED lights indeed typically use blue (or, even better, purple) LEDs and yellow-emitting inorganic phosphors, placed inside the bulb or as a cap above the LED comprised of multiple phosphors. Part of the blue photons generated in the LED is converted into yellow photons, which travel through the phosphor layer. The remaining blue photons and the yellow ones combine to generate a broad-spectrum white light. CCT in Kelvin (K) is used to describe the color (chromaticity) of light of both natural and artificial light sources. For instance, the CCT of sunset is about 2000 K; candle light, 2700 K; moonlight, 4000 K; and daylight, 5000–5500 K. The higher the CCT, the more blue-rich it is and the harsher and brighter it appears.

Comparing five commercial phosphor-coated LED streetlights having CCT of 1870, 2490, 3007, 4075, and 5020 K [13], plots in Figure 1 show evidence that the higher the color temperature of an LED light, the higher the amount of blue light present in its spectrum.

Examining the lighting performance of said LED streetlights as early as 2015, Chinese scholars found that lights with low CCT had the best performance in terms of short dark adaptation, reduced skyglow (higher rain, fog, or haze penetration abilities). The only aspect in which the low CCT lights showed inferior performance was related to color discrimination abilities, which were the lowest when the street was illuminated by an LED having a CCT of 1870 K.

Hence, the reason for which LED streetlights of high CCT (4000 K and higher) have been widely installed across the world in the first decade of their massive uptake (2008–2018) has been due to the fact that LED lights with lower CCTs usually have lower LER (Table 1), and thus result in enhanced electricity consumption.

Nowadays that the health and environmental risks associated with exposure to blue light are well-known and documented, policy makers, companies, or families seeking the uptake of safe and sustainable LED lights should just pursue the installation of lights free of photobiological risk (group 0 in standard EN 624719.

This shift in market demand will drive manufacturers to produce and commercialize high-quality LED lights (poor in blue light), showing no flickering (temporal modulation of the light emitted), no glare, and minimizing light pollution. Besides high-quality optical lenses capable to shield the LEDs from being looked at directly to avoid glare and to direct light where needed, this required manufacturers to develop LED lights emitting little or no blue light and still capable to render rich colors with realistic color tones and a high contrast ratio.

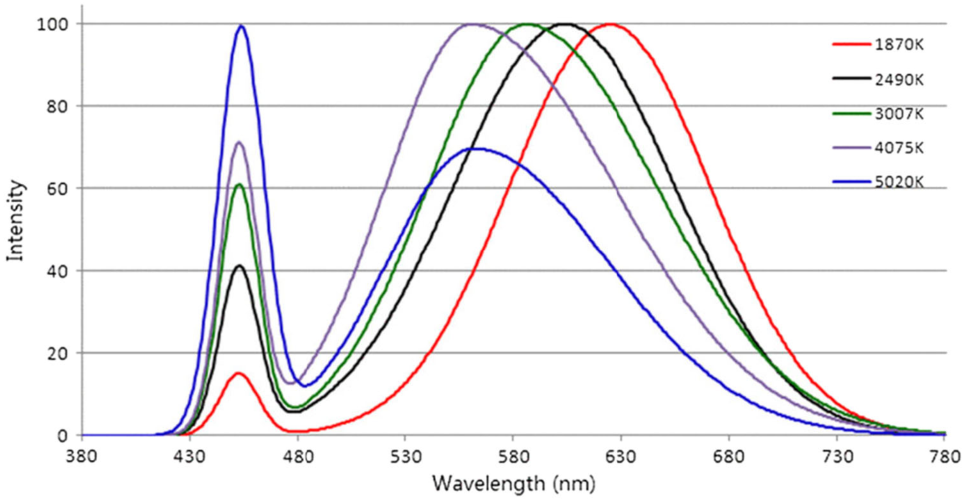

FIGURE 1 | Spectra of five commercial light-emitting diode streetlights tested in China in 2015. Reproduced from Reference [13], CC BY-NC-ND 4.0 Creative Commons License.

TABLE 1 | The main optical parameters of five phosphor-coated LED streetlights tested in China in 2015. Reproduced from Reference [13], CC BY-NC-ND 4.0 Creative Commons License.

CCT (K)	CRI	LER (lm/W)
1870	65.1	286.8
2490	69.7	333.8
3007	71.9	348.7
4075	67.2	379.7
5020	69.4	345.6

Abbreviations: CCT, correlated color temperature; CRI, color rendering index; LED, light-emitting diode; LER, luminous efficacy of radiation.

One approach, which is less costly, is based on control and, thus, on developing new phosphor coating layers (or new lenses). Another, more expensive but affording exceptional results, is based on prevention, namely, eliminating blue light by replacing the LED light source, either replacing the blue with purple LEDs or by replacing inorganic LEDs with organic light-emitting diode (OLED).

2.1 | New Phosphors and Amber Lenses

The less costly yet effective approach to substantially reduce the amount of blue light emitted by white LED lights relies on new phosphor coating layers [14]. Tradenamed «Sunvue» one such layer is a fluorescent dye that acts as phosphor blue-light converting material in place of inorganic phosphors conventionally used in white LEDs.

Manufactured by a large chemical company, the phosphor reduces the amount of blue light by 50%–75%, depending on the color temperature [15]. Coated on the lamp housing instead of directly on the LED chip, the coating improves not only blue screening performance, but also color stability and uniformity of light.

Another low-blue-light LED lamp targeting outdoor lighting applications was recently commercialized by a large LED light manufacturer based in the USA [16]. The new LED emits a warm, amber-white light with less than 2% blue content between 400 and 500 nm with a CCT of 1900 K and CRI of 50.

A solution particularly well suited to retrofit existing LED streetlights employing first-generation LED lights with CCT exceeding 3000 K, with 4000 K often being the most efficient, is the use of amber lenses to attenuate or even remove blue light from the white light emitted.

Amber-colored lenses absorb blue light in LED relatively well, but do not absorb long-wavelength light. When light passes through an amber lens, the blue light is partially absorbed by the lens material, while a smaller amount of blue light and most other colors pass through the lens. Said amber LEDs, chiefly emit light in the orange spectral range (between 590 and 620 nm) [17].

One such amber-colored commercial lens almost completely eliminates blue light while maintaining a good level of optical performance and providing safe night-time illumination [18]. The amount of blue light in a source is essentially depending on the CCT [19]. For example, entries in Table 2 show the amount of blue light (380–500 nm) emitted by a commercial LED lamp following application of two different such amber lenses in methacrylate (PPMA).

Typically, the CCT of an LED having a nominal CCT of 3000 K once coated with one such commercial lens is reduced to 2246 K, whereas another having nominal CCT of 4000 K is reduced to 2551 K.

Using for example said amber lens filters placed on LED lights of 4000 K used to lit the track of an area is located in a national park in Finland, the color temperature of the light emitted is reduced to around 2500 K light, blocking ~99% of the blue light [20].

The lens filter used blocks nearly all (99%) of the blue light emitted by the 4000 K white LED reducing the color temperature to around 2500 K, thereby illuminating the path (a fitness

TABLE 2 | Amount of blue light in commercial LED (Osram Duris S8) coated by two different commercial LED lenses. Reproduced from Reference [18], with kind permission.

LED CCT (K)	C18604_AMBER-2 × 2-ME (%)	C18513_AMBER-2 × 2-T1 (%)
2200	0.19	0.33
2700	0.21	0.41
3000	0.32	0.76
4000	0.38	1.09
5000	0.40	1.25
5700	0.44	1.35
6500	0.45	1.44

Abbreviations: CCT, correlated color temperature; LED, light-emitting diode.

track) ensuring that nocturnal wildlife remains not affected by LED lighting [20].

2.2 | New LEDs

A complementary approach to reduce the amount of blue light and, at the same time, to render rich colors and shades of white as accurately as light found in nature lies in the replacement of ordinary LEDs emitting blue light with LEDs emitting violet (purple) light. In said alternative LED lights, innovative phosphors are used to reduce the low wavelength of violet light and increase the high-wavelength blue light close to the sun's light spectrum.

White light produced from violet LEDs invented by Nakamura, the corecipient of the 2014 Nobel Prize in physics for the invention of the indium gallium nitride (InGaN) LED, these InGaN-based LEDs emit violet (410 nm) light having a higher CRI, luminous efficacy and stability than traditional blue LEDs [21]. Their use to generate white light requires a combination of blue-, green-, and red-emitting phosphors, producing an excellent rendering of colors (*Ra* and deep-red rendering metric *R*9 of 95) due to full-visible-spectrum illumination [22].

Research continues to develop violet excited, blue-emitting phosphors having a high photoluminescent quantum yield under 405 nm able to resist loss in emission intensity and shift in chromaticity with rising temperature [23].

One example is the LED lamps produced by the company jointly established by Nakamura in the USA. On the basis of the gallium-nitride-on-gallium-nitride (GaN-on-GaN) LED architecture, rather than on foreign substrates like sapphire or silicon carbide, these LEDs have very low defect densities (100–1000 times lower than GaN on sapphire) thanks to the deposition of the wide gap semiconductor GaN on native substrate [22]. The architecture originates very high external quantum efficiencies (> 70% in the blue, and nearly 80% in the violet) enabling the use of high-current density operation (GaN-on-GaN chips operate at ~160 A/cm^2, about five times higher than standard LEDs) so that, for the same light output, these LEDs require five times less semiconductor material, eventually allowing significantly LED lighting products (smaller optics and smaller luminaires).

Before being sold in 2020 to another lighting company, the aforementioned firm in 2019 commercialized several high color rendering lamps reducing melanopic lux (a quantity to quantify how blue light affects human biology) by ~40% compared with conventional LEDs that, in the words of Nakamura, «emit-quality light without negatively impacting human health and sleep» [24].

For example, comparing a fluorescent lamp emitting white light with 4100 K CCT with an LED lamp emitting 40% less melanopic lux (18.6 for the LED lamp and 31.2 for the fluorescent lamp), a 2017 medical study found that using the LED lamp of reduced blue content substantially reduced melatonin suppression, whilst maintaining the same visual photopic lux [25].

The said results have general value. A comparative study involving 15 healthy young volunteers (normal good sleepers, who had very good cognitive skills) under tightly controlled laboratory conditions required to spend 49 h starting 6 h before habitual bedtime in two consecutive (baseline and treatment) nights exposed before sleep to light of the same CCT of 4000 K (corresponding to a sunny day shortly after sunrise) and intensity levels (100 lx) produced by a conventional blue LED and a violet LED-based lamp [26]. Exposure to the latter resulted in substantially better visual comfort, increased alertness, and more positive moods in volunteers compared with those exposed to conventional LEDs. In detail, all volunteers those exposed to the uniform spectrum of white light tuned to be closer to natural morning daylight generated by the violet LEDs reported improved sleep patterns, better visual comfort, heightened daytime alertness, and better visual comfort. Furthermore, quantitative data on sleep patterns revealed deeper sleep following exposure to the innovative LED lamp.

These commercial LED lights based on violet LEDs incorporate broadband phosphors (and phosphor layer deposition technology) developed by a Japanese advanced materials company, able to drive appropriate emission peak wavelength and emission half width to solve the typical deficient color regions in the spectrum of conventional LEDs (no violet light, a cyan gap, and a lack of red) [22].

Besides affording reduced scattered reflection, glare, and substantially lower blue-light emission, illumination with these LEDs having a CRI of 98, allows, as noted above for LED lights having to more accurately represent the color of objects as they would appear under natural sunlight, which is near the CRI of 100 of sunlight and significantly higher than the value (80) of conventional white LEDs [27].

Finally, another solid-state lighting technology emitting substantially lower blue light than conventional LED lights employs OLEDs. Widely used in displays and monitors, OLEDs are emissive and do not rely on a white light source [28].

Indeed, in 2021, academic researchers in Japan reported the outcomes of exposing 10 male volunteers to either the 1000 lx

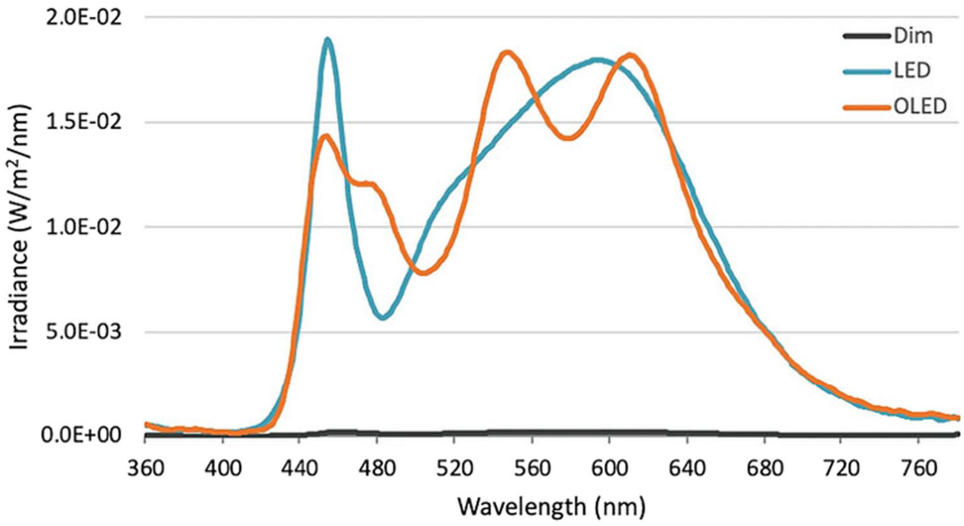

FIGURE 2 | Spectral power distribution of LED, OLED, and dim lights expressed in irradiance used in Tsukawa et al.'s work in 2021. Reproduced from Reference [29], Creative Commons CC-BY 4.0 License. LED, light-emitting diode; OLED, organic light-emitting diode.

LED, 1000 lx OLED, or dim LED (< 10 lx) at eye level for 4 h continuously while maintaining a sitting posture until their habitual sleep time [29]. Light panels were set against the wall directly in front of the participants and adjusted to match the illuminance of around 1000 lx. The spectral power distribution (Figure 2) of polychromatic white light emitted by commercial LED and OLED of the same color temperature 4000 K shows a lower amount of blue light emitted by OLED, especially the peak at 455 nm.

Energy expenditure and core body temperature during sleep were significantly decreased after OLED exposure. Furthermore, fat oxidation during sleep was significantly lower after exposure to LED compared with OLED. In addition, fat oxidation during sleep was positively correlated with 6-sulfatoxymelatonin levels following exposure to OLED, suggesting that the effect of melatonin activity on energy metabolism varies depending on the type of light exposure.

Indeed, a number of OLED panels for televisions (TVs) and monitors manufacturers in the last 2 years have earned third-party certification for eye safety and lack of hazard for circadian rhythm due to low-blue-light emissions (liquid crystal displays, e.g., emit about twice as much blue light as OLEDs) [30].

Chiefly due to short lifetime when compared with inorganic LEDs (in 2013 LED lamps lasted in excess of 50,000 h while OLED lighting panels had 5000–15,000 h lifetime) [31], OLED lighting has remained a niche of the lighting market for nearly two decades. However, technological progress has resulted in significant enhancement of commercial OLED light stability and lifetimes, with related market expansion. Valued at $3.2 billion in 2024, the OLED lighting market was forecasted to grow at a 15.2% annual growth rate from 2026 to 2033, when the market is expected to reach $9.1 billion [32].

3 | Conclusions

Due to their exceptional energy efficiency and durability, LED lights based on inorganic semiconductors since 2012 have quickly replaced all other light sources installed worldwide to lit outdoor and indoor environments.

Unfortunately, first-generation (conventional) LEDs relying on GaN wide bandgap semiconductor deposited on foreign substrates such as sapphire or SiC, emit polychromatic white light containing plentiful blue light. Besides damaging the eye, said excessive blue light causes melatonin suppression that in its turn drives insomnia and tissue inflammation. Lighting is ubiquitous, both in the form of street and domestic lighting. As a result, the world's population exposure to blue light has increased sharply. The situation is worsened by exposure (often also in the evening) to TV displays or computer screens using LED or liquid crystals emitting plentiful blue light.

The need to replace conventional LED lighting with safe and sustainable LED lighting led to the development of protection-based or prevention-based approaches. As briefly summarized in this study, the former approach includes new phosphors and amber lenses able to mitigate the emission of blue light from LED lamps, whereas the latter approach led to the development of new LED technology based either on violet LEDs coupled to new phosphors, or to the use of OLEDs.

Driven by awareness of the global relevance of the blue-light problem caused by LED lighting technology and by the precautionary principle, three simple yet relevant guidelines aimed at local policy makers, energy managers and users of lighting systems emerge from this study.

First, wherever LED streetlights emitting light of higher color temperature, typically 4000 K, are already installed, amber lenses should be urgently installed to lower the CCT of emitted light at little capital expenditure. We agree with the American Medical Association, recommending using streetlights with CCT of 3000 K, and preferably lower, as well as dimming for off-peak time periods to minimize blue-light emission [33].

Second, policy makers and energy managers should adopt LED lighting systems for the built environment (including schools, museums, hospitals, universities, offices, etc.), selecting warm lights (2700–3000 K) of high CRI (95 and higher), free of glare and flicker. These lights already exist on the marketplace, and it is encouraging that lighting and display manufacturing companies commercializing LED lights, displays and monitors emitting limited amounts of blue light, increasingly seek third-party certification that their products do not harm human health and nocturnal wildlife.

Third, domestic users of lighting systems should rely on similar high-quality LED sources. This, in practice, requires to replace conventional polychromatic white LED lamps having poor CRI of 80 and CCT exceeding 3000 K already installed either with LEDs using violet light converted by aptly developed phosphors, or with OLED panels poor in blue light, free of glare and flickering effects.

This shift in the global lighting market demand will induce the lighting industry to switch LED production from conventional to new-generation white LED lights emitting modest amounts of blue light. This, in turn, will cause production expansion and lower the cost of manufacturing safe LED lighting technologies such as the GaN-on-GaN LED architecture, so as to make it affordable to all.

For example, a single light bulb (A19 bulb shape size) emitting 600 lm of white light at 2700 K containing less than 2% blue light commercialized by the company created by Nakamura was commercialized at $39.99 [34] before become out of stock. Currently (late 2025), a 28-cm-long module (a strip) equipped with LEDs built in South Korea with a similar GaN-on-GaN architecture emitting 640 lm of white light at 3000 K with CRI 98 is commercialized in Germany at €12.90 [35].

This trend, I forecast, will continue similarly to what happened with monocrystalline silicon (mc-Si) solar cells. When demand for more efficient photovoltaic modules boomed worldwide, mc-Si quickly replaced less efficient and less expensive polycrystalline silicon (pc-Si) solar cells in just 3 years between 2017 and 2019 [36]. In the latter case, a single company in China completely changed the photovoltaic industry, making mc-Si wafer production cost-competitive with pc-Si wafer production [36].

Like any other study, the present study has limitations. For example, even in the case of violet LEDs incorporating broad-band phosphors creating a spectrum close to that of natural morning daylight [22], we do not know the health effects of prolonged exposure to white light generated by said LEDs.

In conclusion, I agree with Pauley, who first invoked in 2004 the use of the precautionary principle referring to the blue-light problem posed by high intensity lamps, like metal halide, mercury vapor, and fluorescent lamps [37]. At that time, Pauley explicitly asked lighting companies to redesign their products to enhance rather than disrupt this very sensitive and visually separate retinal-circadian system.

This is particularly relevant in the present case of LED lighting because we do not know the medium- and long-term effects of population exposure to excess blue light, nor do we know the same long-term effects on animals and plant ecosystems. The unique versatility of solid-state lighting technology based on the use of inorganic or organic semiconductors has made it possible to achieve substantial progress in slightly more than a decade since LED lighting became ubiquitous in 2012.

This progress will likely continue, and the outcomes of this study will hopefully inform expanded education in energy management, in which energy and technology topics are merged with economic aspects [11].

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Conflicts of Interest

The author declares no conflicts of interest.

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