7. Light pollution criteria

As mentioned in the Preliminary report summary, light pollution is one of the environmental impacts associated with road lighting that is not captured by LCA analysis. Broadly speaking, light pollution can have diverse adverse impacts of artificial light on the environment due to any part of the light from a lighting installation that:

1. is misdirected or that is directed on surfaces where no lighting is required
2. is excessive with respect to the actual needs
3. causes adverse effects on human beings and the environment"

Some strong opinions were expressed by certain stakeholders about this topic, with the most extreme arguments stating that the most environmentally friendly road lighting system is the one that was never built in the first place.

Although the aforementioned argument is technically correct and valid, it must be emphasised that the EU GPP criteria does not intend in any way to influence the decision to light a road or not. The way EU GPP criteria should fit into procurer decisions is illustrated in Figure 13.

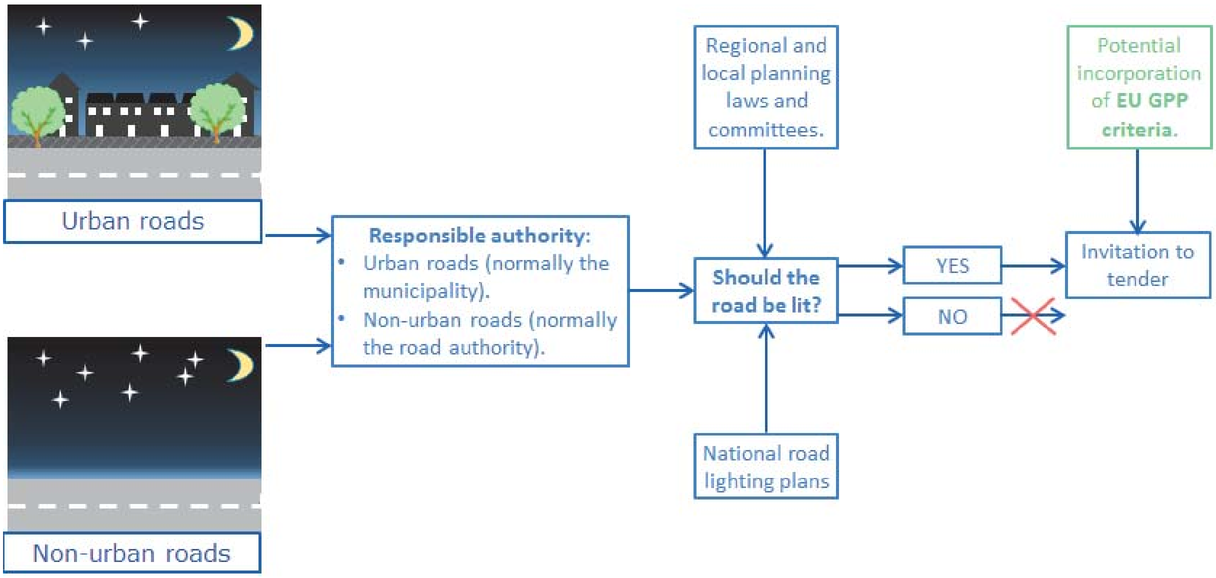


Figure 13. Role of EU GPP criteria in planning process for road lighting installations

From Figure 13, it is clear that the decision making process of whether or not to light a road is the responsibility of the relevant public authority and that the decision will ultimately be determined by provisions made in national, regional and local planning procedures. Only once the decision to light a road has been taken and an Invitation to Tender (ITT) is drafted, would EU GPP criteria potentially apply.

One example of national planning guidelines for limits on upward light pollution is that of the UK, which is based on technical guide CIE 126:1997. In a similar manner, Catalonia (DECRETO 190/2015) (Spain) has developed its own planning law for public lighting. The levels recommended in these two regions are split into "lighting zones" and are compared to CIE 126:1997 in the table below

Table 12. Upward light limits as a function of environmental zone in UK, Catalonia and CIE 126

Environmental lighting zone	Maximum R_{ULO} (%)		
	CIE 126 / 150	UK (ILE, 2002)	Catalonia non-curfew/curfew
E0, Intrinsically dark: UNESCO Starlight Reserves, IDA Dark Sky Parks, major optical observatories.	0		
E1, Dark: Relatively uninhabited rural areas, (e.g. national parks, areas of outstanding natural beauty).	0	0	2 / 1
E2, Low district brightness: Sparsely inhabited rural areas (e.g. villages or relatively dark outer suburban locations).	5	2.5	5 / 2
E3, Medium district brightness: Well inhabited rural and urban settlements (e.g. small town centres and suburban locations).	15	5	10 / 5
E4, High district brightness: Town and city centres and other commercial areas with high levels of night-time activity.	25	15	25 / 10

Although zoning is a useful idea for lighting requirements, stakeholders have repeatedly stated that with RULO, the zoning approach is at best of limited use due to the fact that upward light can affect star visibility in other areas over 100km away.

A more stringent approach to light pollution is exemplified by the Low Impact Lighting (LIL) standard, which has especially been promoted by German, Italian and Slovenian members of the European Environmental Bureau. The standard sets out the following requirements:

- Specific energy consumption of 15 kWh/pe/yr for all outdoor public lighting.
- CCT <2200K with less than 6% of total emissions in the <500nm range (except when average illumination is <5 lx, where CCT can rise to 2700K and <500nm emission can rise to 10%).
- ULOR of 0.0% both when new and when dirty.
- Ban on lighting on any roads, exits and junctions outside of settlements.
- Pole distance must be at least 3.7x the pole height.
- Maximum luminance allowed is 0.5 cd/m^2 (i.e. no brighter than an EN 13201 compliant M5 class road).
- Curfew dimming to at least 10% with adaptive technology or to at least 50% with non-adaptive technology.
- Mean time of luminaire failure must be at least 100000 hours or 25 years.
- Luminaire efficacy must be: >50lm/W for lighting less than 1900K, >95lm/W for lighting of 1900-2200K or > 100lm/W for lighting of 2200-2700K CCT (exemptions may apply when mechanical shielding is added to prevent unwanted lighting or when the pole distance:pole height ratio exceeds 6:1).
- Utilisation factor of at least 70% (i.e. 0.70) must be achieved except in cases of narrow cycle or pedestrian paths, where it can be at least 40%.
- Illumination on residential windows cannot exceed 0.01 to 0.50 lx depending on how close the window is to the illuminated public place.

The LIL standard has rules that would not follow the recommendations set out in EN 13201, so procurers interested in such an approach should take care that there is no national or regional legislation that would oblige them somehow to implement the EN 13201 recommendations. The LIL standard clearly prioritises light pollution over energy efficiency but, by advocating lower light levels and curfew dimming, would have a significant beneficial impact on overall electricity consumption of a particular lighting installation – especially when compared to the direct implementations of EN 13201 recommendations for the same area.

The concept of light pollution can broadly be considered as the alteration of natural light levels by human activities, including the emission of artificial light. Light pollution may undermine enjoyment of the night sky (phenomenon skyglow), be harmful to species or be a source of annoyance to people (glare and obtrusive light).

7.1. Ratio of Upward Light Output (R_{ULO} / ULOR)

7.1.1. Background research and supporting rationale

Skyglow

The central argument for having criteria that limit the upward light output ratio is to reduce the artificial brightening of the night sky (skyglow) but also to help limit obtrusive light in built-up urban areas.

For obvious reasons, one of the first stakeholder groups to raise concerns about skyglow from light pollution was astronomers. The Royal Astronomical Society (RAS) in the UK found that 80% of their members could not, or could barely see the Milky Way, having to travel 5-50 miles before being able to find suitable viewing conditions. Falchi et al., (2016) concluded that 88% of land in Europe has a night sky that is considered polluted by astronomers and only 1% that could be considered as "pristine".

LED luminaires typically include glass envelopes, lenses, optical mixing chambers, reflectors and/or diffusers to obtain the desired light distribution. This makes them better suited to deal with ambitious R_{ULO} requirements. With traditional HID cobra-heads there was a trade-off when choosing between drop refractor type lenses and flat glass lenses. Drop lens units were typically used for wider pole spacings and more uniform lighting patterns. Flat glass units usually have less upward light output, better control of light trespass into residential windows, and lower high angle glare. However, flat glass also reduces the total light output or efficiency of the luminaire due to increased internal reflections. Internal reflections can be attenuated by using anti-reflective coatings.

From the point of view of environmental impact and products available on the market there are no grounds to discriminate R_{ULO} requirements according to EN 13201-2 road classes.

Thanks to the use of satellite mounted cameras and sensors, it is possible to have an idea of the actual levels of light pollution across the whole of Europe.

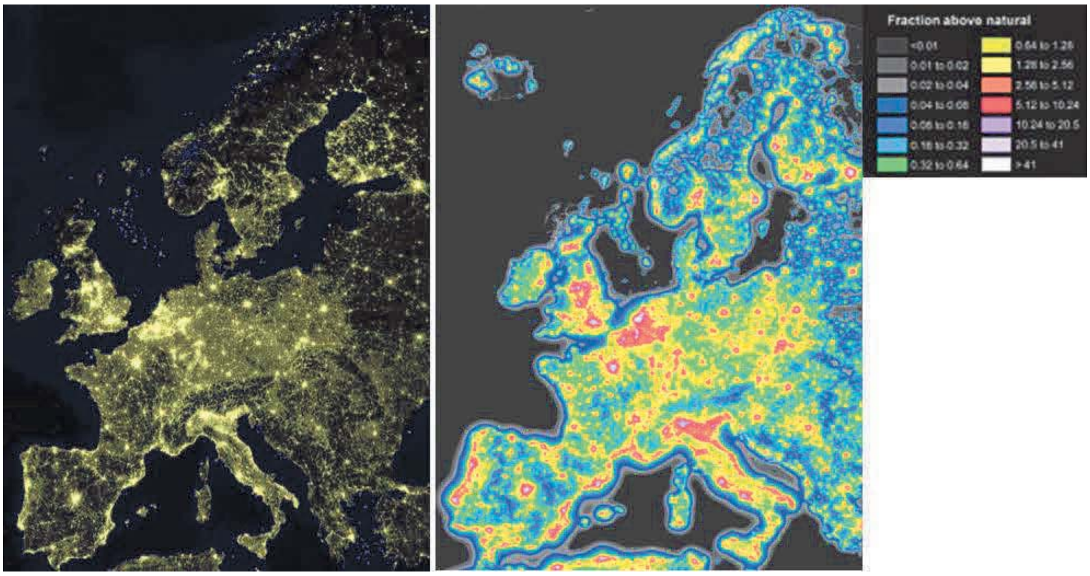


Figure 14. Light pollution in Europe: "Earthlights 2002" published by NASA (left) and a map of skyglow from Falchi et al., 2016 based on VIIRS DNB data from the Suomi NPP satellite (right).

From the images in Figure 14 it is clear that Europe has significant levels of light pollution. The particular impact of major cities can be seen in the cases of Madrid, Paris, London and Rome compared to surrounding areas. The largest areas of consistently high light pollution are in northern Italy, the “low countries” (Belgium and the Netherlands), mid-western England and on the coastline between Lisbon and Porto.

According the data presented by Falchi et al., (2016) only around 7% of the land in Europe suffers from light pollution levels that are high enough to prevent viewing of the Milky Way. However, unfortunately around 60% of the European population live in these polluted areas. Concern was expressed by the authors about a significant amount of light pollution being missed in the future as the many lighting installations shift to LED. The problem is that, unlike traditional sodium lamps, LED emits a significant portion of its light output in the 400-500nm range. The sensitivity of the satellite mounted VIIRS DNB (Visible Infrared Imaging Radiometer Suite Day Night Band) sensor is only useful between 500 and 900nm. So one consequence of a shift to more energy efficient, LED-based street lighting could possibly be that there is a perceived drop in light pollution levels measured by VIIRS DNB that may or may not be true.

Blue light can hinder naked eye astronomic observations by increasing skyglow because it scatters more in the atmosphere and the eye is more sensitive to it at low light levels.

Existing criteria and ambition level

The existing EU GPP criteria, published in 2012, make a distinction between road classes (ME1-ME6, CE0-CE5, S1-7 and roads split by use type (functional or amenity lighting). UOR requirements were much higher, ranging from 3 to 25%.

The best benchmark recommended in EC 245/2009 is to have ULOR at a maximum of 1% for all road luminaires. Because the GPP criteria are voluntary and have the aim of increasing awareness of environmental criteria that can apply in ITTs, it is proposed that all luminaires have a ULOR of 0% when tested in the laboratory and that if the installation requires tilting of the luminaire, that this should not result in upward light output (i.e. shielding of luminaire most be appropriate to cover the tilt angle, which is typically 5 to 15°).

7.1.2. Stakeholder discussion

Stakeholders highlighted the major benefits that were possible in reducing light pollution from road lighting due to reduced upward light output from luminaires, better directed optics using LED technology and curfew dimming. It was pointed out that municipalities would also have to be pro-active in other areas beyond the scope of EU GPP criteria for road lighting if they really wanted to minimise light pollution as much as possible, for example the lighting of monuments, buildings, parks, advertisements, commercial and private properties.

About R_{ULO}

In the TR 1.0, it was proposed that R_{ULO} should be less than 1% for all road classes and lumen outputs for both the core and comprehensive ambition level.

The initial proposal was criticised by stakeholders from several different perspectives. One simple criticism was that the terminologies and acronyms should be updated to reflect recent changes in terminology in international standards (EN 12665:2011 could be considered as a case in point). It was pointed out that R_{ULO} (percentage of total light output above 90°) might address diffuse light pollution to the night sky but does nothing for addressing obtrusive light into adjacent areas. In order to address obtrusive light, procurers should be able to stipulate requirements for certain CIE flux codes at 80° and 70° to the vertical. It was stated that light emitted near the horizontal can scatter for

100km if unobstructed. To better understand these requirements, flux codes should be considered in the context of the flux diagram provided in EN 13032-2. A closer look at what the flux codes actually mean is illustrated in Figure 15.

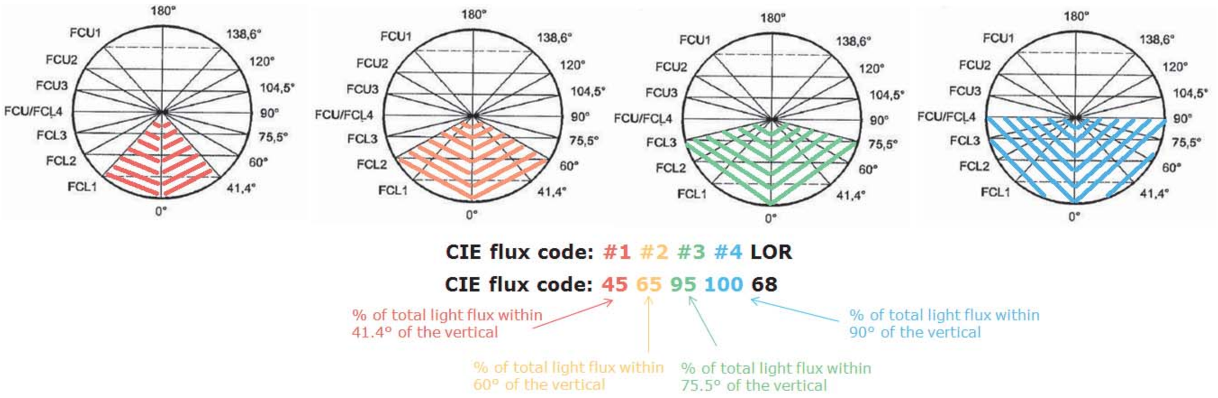


Figure 15. Illustration of illuminated zones applicable to CEN flux codes.

The CIE flux codes are reported in a series of 5 numbers, all of which relate to a certain percentage of the total luminous flux from the light source. First it is worth explaining the last number in the sequence (i.e. 68 in the example above). The number 68 refers to the LOR (Light Output Ratio) and basically means that of all the light produced by the light source, 68% of it actually leaves the luminaire.

The other four numbers all relate to the fraction of that 68% of light leaving the luminaire and within what range of angles to the vertical it falls.

An example requirement for a flux code would be FCL3 >99 for comprehensive level (meaning that 99% of total light output is within the vertical downward 75.5° angle). When dealing with R_{ULO}, it is basically a requirement on FCL4. For example, FCL4 ≥99 is equivalent to a maximum R_{ULO} of 1% while FCL = 100 is equivalent to a R_{ULO} of 0%.

The initial 1% R_{ULO} proposal was considered as unambitious by some stakeholders who added that 0% was particularly easy to achieve for correctly installed LED luminaires. However, it was added by another stakeholder that some degree of upward light output (e.g. 1%) may be desirable in road lighting in old city centre locations with historical buildings. Another comment suggested that a R_{ULO} of 15% could be suitable in areas where vertical illumination is required. One considerable advantage of 0% R_{ULO} was that it prevents the deposition of dirt via the carriage by water droplets during the life of the luminaire. This could also have a positive impact on the maintenance factor of the luminaire.

Another stakeholder in support of the use of flux codes commented that for every 1° tilt upwards in the range of 30° below the horizontal to 30° above the horizontal, luminance to the sky doubles. Regardless, any measurements of R_{ULO} should be based on luminaire data from accredited laboratories (Article 44 of Directive 2014/24) in accordance with the photometric intensity tables in EN 13032-1:2004+A1:2012 and EN 13032-4:2015. Specifically for LED luminaires, measurements according to Annex D of IEC 62722-1 should be considered. It was added that field measurements of R_{ULO} are not practical.

In Italy, one stakeholder made reference to light pollution laws that require fully shielded fixtures for public road lighting and for any light source (public or private) with a light output higher than 1500 lumens. The only exceptions may be with the lighting of monuments or historical buildings.

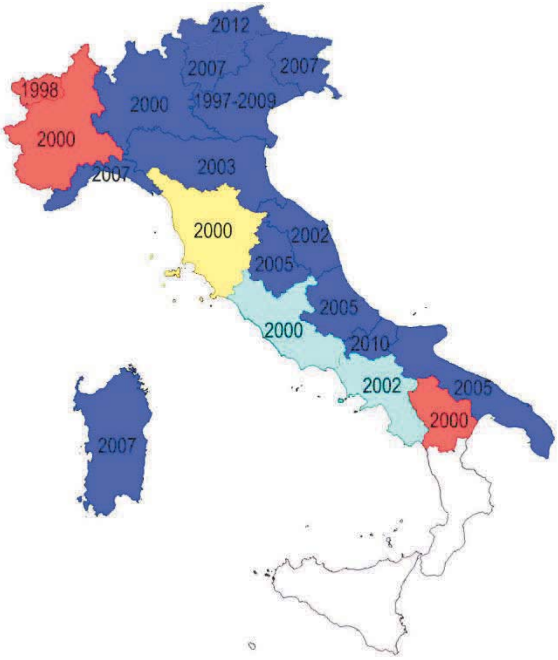


Figure 16 . Regions in Italy where 0% R_{ULO} is required (depicted in blue).

The same stakeholder added that the advantage of 0% R_{ULO} is that it was the one value that can be (relatively) easily verified in-situ although other stakeholders wished to point out that any scientific assessment of R_{ULO} in-situ would need to account for interference of reflected light and direct light from other sources.

One potential problem with restrictions for R_{ULO} was that it might lead to unintended impacts on the energy efficiency (requiring more light points) or, where no extra light points are introduced, on the level of uniformity. Some stakeholders added that they were accustomed to working with glare classes instead of R_{ULO}, although these two considerations do not fully overlap in terms of road lighting design. However, any implementation of GPP criteria related to G classes would be more complex and require additional guidance. Despite this additional complexity, it was stated that Italian GPP criteria currently take G classes into account.

The core and comprehensive criteria have been set out in order to distinguish between situations where the sole concern is to minimise upward light (core, R_{ULO} 0%) and situations where upward light, glare and/or obtrusive light are concerns (comp. R_{ULO} 0%, C3 flux code ≥97).

Other stakeholders complained that 0% R_{ULO} will still not prevent skyglow because light will also be reflected off the road surface. While asphalt generally has a reflectivity coefficient of less than 0.08 (8%), other surfaces such as grass and especially concrete, can have significantly higher reflection rates (see Figure 29 in Technical Annex I).

Although blue light tends to reflect less than redder light, any blue light that is reflected will scatter in the sky much more than higher wavelength light (scattering is a function of the reciprocal 4th power of the wavelength). However, it was countered that such reflection cannot be avoided, that the surface to be lit is not part of the same subject matter of lighting procurement contracts. The biggest wins in reducing skyglow can be made by reducing directly emitted upward light in the first place. Only after direct upward emissions are drastically reduced, would reflected light become more significant.

It was requested that the proposal for 0.0% R_{ULO} also be maintained if the luminaire is to be tilted when installed. If this requires that shielding be added to the luminaire, then so be it.

7.1.3. Criteria proposals for R_{ULO} and obtrusive light

Core criteria	Comprehensive criteria
TS7 Ratio of Upward Light Output (R_{ULO}) and obtrusive light	
(Applicable to all contracts where new luminaires are purchased.) All luminaire models purchased shall be rated with a 0.0 % RULO. If it is necessary to use a boom angle, either to optimise the pole distribution or due to site constraints in pole positioning, the 0.0 % RULO shall be maintained even when the luminaire is tilted at the required angle. **Verification:** The tenderer shall provide the photometric file(s). This shall include the photometric intensity table from which the RULO is calculated according to EN 13032-1, EN 13032-2, EN 13032-4, Annex D of IEC 62722-1 or other relevant international standards. In cases where luminaires are not installed horizontally, the photometric file shall demonstrate that either: - tilting the data by the same tilt angle to be used with the luminaire still results in a 0.0 % RULO, or - additional shielding has been fitted to the luminaire and the shielded luminaire found to show a 0.0 % RULO when tilted at the design installation angle.	***(Applicable to all contracts where new luminaires are purchased. In situations where glare or obtrusive light is a concern, procurers should consider specifying a requirement for C3 flux codes.)*** All luminaire models purchased shall be rated with a 0.0 % RULO and with a C3 flux code of ≥97 according to photometric data. If it is necessary to use a boom angle, either to optimise the pole distribution or due to site constraints in pole positioning, the 0.0 % RULO shall be maintained even when the luminaire is tilted at the required angle. **Verification:** The tenderer shall provide the photometric file(s). This shall include the photometric intensity table from which the RULO is calculated according to EN 13032-1, EN 13032-2, EN 13032-4, Annex D of IEC 62722-1 or other relevant international standards. In cases where luminaires are not installed horizontally, the photometric file shall demonstrate that either: - tilting the data by the same tilt angle to be used with the luminaire still results in a 0.0 % RULO and a C3 flux code of ≥97, or - additional shielding has been fitted to the luminaire and the shielded luminaire found to show a 0.0 % RULO and a C3 flux code of ≥97 when tilted at the design installation angle.

7.2. Ecological light pollution and annoyance

7.2.1. Background research and supporting rationale

The most important aspect of light pollution is the potential harm it may cause to species. Many thousands of years of evolution in harmony with natural photic environments have been disrupted by human settlement and activity. Levels of artificial lighting have increased dramatically in developed countries to the extent that light pollution levels can even be considered as an indicator of economic activity (Henderson et al., 2012). The nature of the photic environment can play an important role on mating behaviour, ease of predation, ease of predator evasion, nesting and foraging behaviours. A growing body of evidence in the academic literature is leading to the conclusions that night time light can seriously disrupt the nocturnal behaviour of many species. The degree of impact on the behaviour of different species and their potential to adapt to artificial lighting may vary significantly. One recently published article (Knop et al., 2017) highlighted the disruption that Artificial Light At Night (ALAN) creates for pollinators (both nocturnal and diurnal) and subsequently on plant reproductive success.

The effect of light on insect behaviour and survival is especially relevant since they play a vital role in food pyramids in all ecosystems. Insects that are attracted by lights can be subjected to different effects, which Eisenbeis (2006) described as:

- The "*fixated or capture effect*", where insects are drawn to the light and so fixated by it that they effectively do not feed, reproduce or attempt to evade predators. They may fly directly to the light, suffering traumas due to burns, overheating, dehydration, wing damage or, if lighting in on bridges, possible drowning.
- The "*crash barrier effect*", where a row of road lights may act as an effective barrier preventing the passage of insects to potentially important food sources and breeding habitats.
- The "*vacuum cleaner effect*", where areas of 50 to 600m may be devoid of certain insect species due to the strength of the draw of artificial light sources.

Two examples worth mentioning are moths and mayflies. Moths are well known to suffer from the "*fixated effect*", flying towards lights and remaining there all night, losing opportunities for feeding and reproduction. Light sources can mask the dim moonlit glows of natural flowers that moths have evolved to feed on. Once distracted by artificial light, moths are less prone to carrying out evasive manoeuvres to avoid predation by bats (Frank, 2006). The attraction of moths to artificial lights greatly increases predation opportunities for bats, birds and spiders but, in the context of road lighting, all of these species are brought closer to the road, were collisions with road traffic would be fatal.

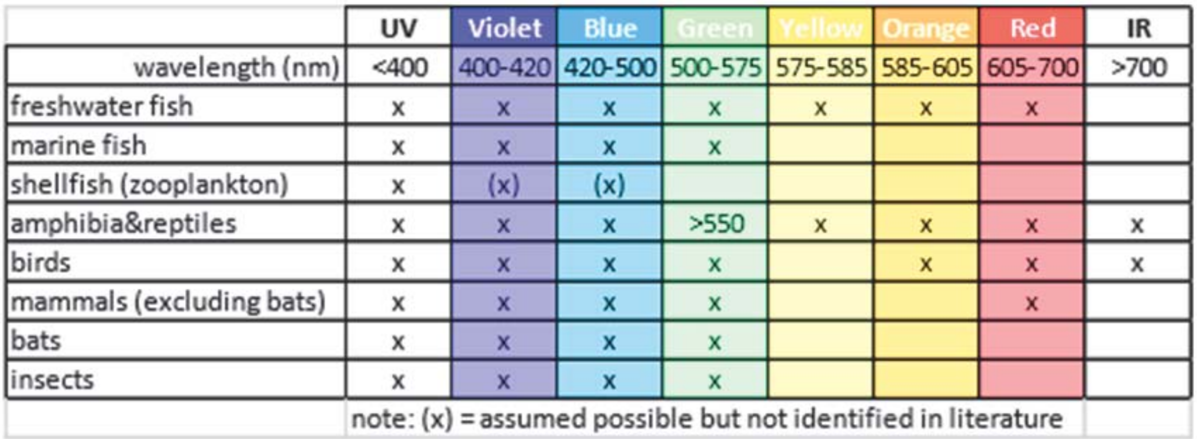
Mayflies, a very important food source for fish in many ecosystems, spend most of their lives underwater but after their final moult, they develop wings and live for as little as 30 minutes or as long as a few days. During this short period, mating occurs and females will lay their eggs on the first surface they land on. The draw to artificial lights will end up with eggs being laid in inadequate locations on many occasions.

The effect of ALAN has been shown to affect the migratory routes of birds (La Sorte et al., 2017). Light-induced grounding and mortality of sea-birds is an especially serious issue that has been observed in petrel and shearwater families, and shown to affect already endangered sea bird species (Rodriguez et al., 2017).

Exposure of loggerhead sea turtles to yellow and orange lights (but not red light) has been shown to cause a reduction in nesting attempts, delay the nesting process of attempts that were made and cause notable disruption and disorientation in sea finding behaviour (Silva et al., 2017). Disruption to sea finding behaviour is especially an issue for sea turtle hatchings. The reflection of moonlight on the sea naturally attracts the hatchlings to the sea. In a recent Brazilian study (Simoes et al., 2017), low moonlight levels alone are sufficient to complicate sea finding for sea turtle hatchlings but that they still moved in the general direction of the sea. When artificial light was present, more than half of the deviations in hatchling trajectory were actually away from the sea and towards the artificial light source.

In cases where lighting is deemed necessary for human activity, the only potential role EU GPP criteria could perhaps play is to encourage dimming as far as possible and/or consider the choice of spectral output from the artificial light source. Although there is much research still to be carried out in this area, a literature review of ecological impacts of light pollution on different types of species has led to the following guidance table (Biodiv, 2015):

Table 13. General guide to effect of different spectral bands of light on different species



	UV	Violet	Blue	Green	Yellow	Orange	Red	IR
wavelength (nm)	<400	400-420	420-500	500-575	575-585	585-605	605-700	>700
freshwater fish	x	x	x	x	x	x	x	
marine fish	x	x	x	x				
shellfish (zooplankton)	x	(x)	(x)					
amphibia&reptiles	x	x	x	>550	x	x	x	x
birds	x	x	x	x		x	x	x
mammals (excluding bats)	x	x	x	x			x	
bats	x	x	x	x				
insects	x	x	x	x				
	note: (x) = assumed possible but not identified in literature							

In general, the table above implies that UV, violet and blue light is more disruptive for ecosystems. Blue light is also a concern that has links to the human circadian system (see section 7.2.3). With the general shift to LED lighting, it is worth noting that the emission spectra can contain high proportions of blue light, although this can vary significantly from one LED model to another (see Figure 17 below).

In areas of high ecological value, dimming or even complete extinction during curfew hours should be considered for road lighting for both ecological and energy efficiency reasons.

Blue rich light

Apart from the much greater skyglow effect of blue light due to Rayleigh scattering, there has been considerable debate about potential health effects of blue light on humans and nocturnal species.

Much recent debate, both in scientific circles and in public news, has referred to impacts of blue light on human circadian rhythm (AMA, 2016). This is related to the recently discovered retinal ganglion cells (ipRGCs), which are intrinsically photosensitive and crucial for delivering light information to parts of the brain controlling the biological clock. Potential health effects on humans are specific to certain wavelengths and not necessarily to broader sections of the blue light region. The Scientific Committee on Health, Environmental and Emerging Risks (SCHEER) recently (July 2017) published its preliminary opinion on potential risks to human health of LEDs (SCHEER, 2017). According to SCHEER, significant further research is needed before it can be determined if the effects of certain short wavelength light on circadian rhythms can be linked to adverse human health effects or not.

However, for road lighting in particular, the exposure time of people is relatively short compared to indoor light sources and so this is a much more relevant discussion for indoor lighting. Of course, this does not apply to wildlife, especially to nocturnal species and, as implied in Table 13, blue light is in general more harmful for ecosystems.

Generic terms such as "*blue light*," "*blue-rich LEDs*," and "*blue content*" used with lighting are not very specific and in fact can be misleading (DOE, 2017). Actual emissions of "*blue light*" require a knowledge of the full spectral distribution of a light source. The general public perception is that white light from LED is associated with a significant proportion of "blue light" in its emission. Today (December 2018) this assumption is generally true because many white LEDs show a significant amount of blue light in their emission spectra.

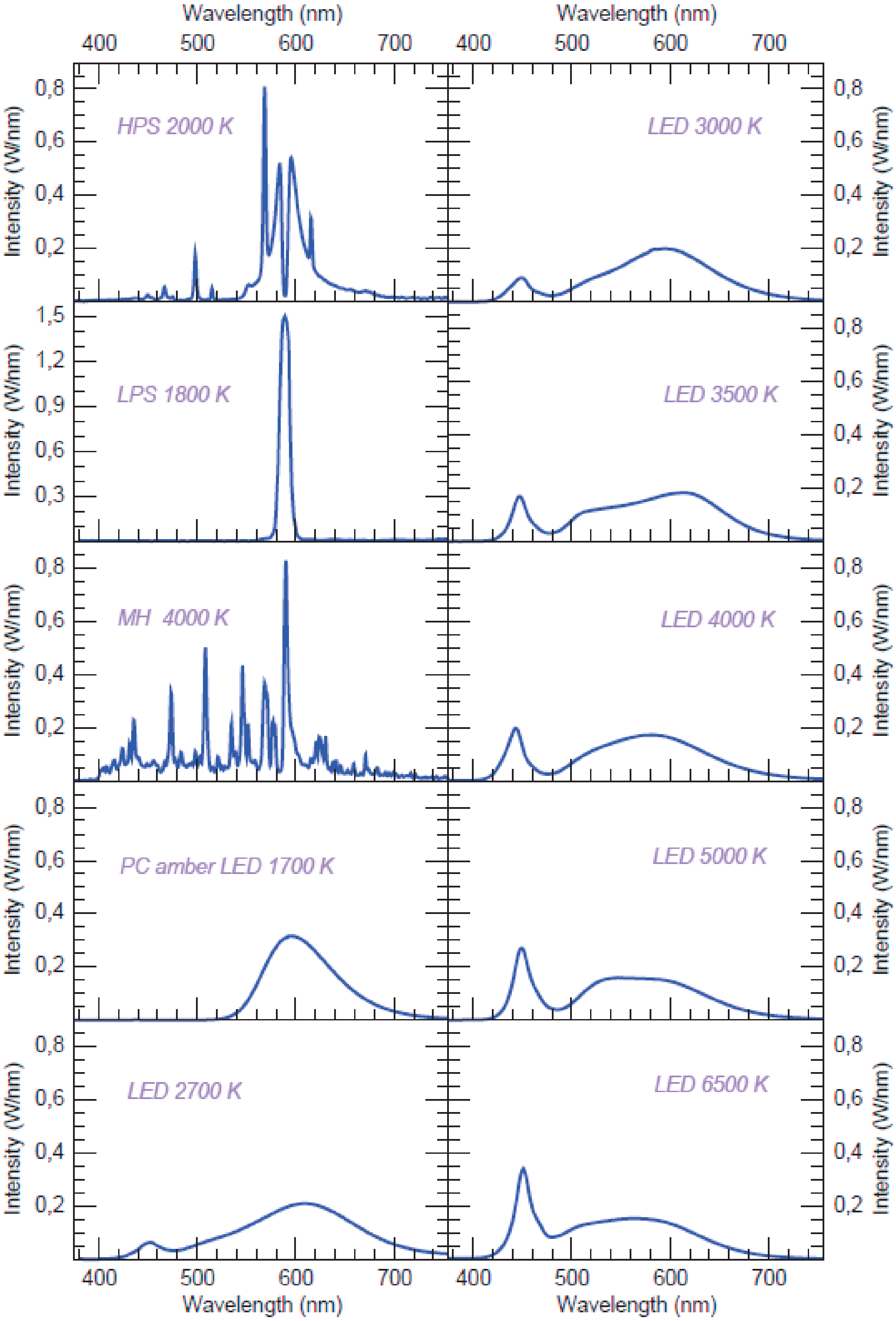


Figure 17. Spectral Power Distributions (SPDs) of different light sources commonly used in road lighting (DOE, 2017b). *PC stands for Phosphor Converted.

As shown in Figure 17, traditional HID lamp technologies can be entirely free of blue light (LPS), have very low "blue light" output (HPS) or have significant output in the blue wavelength ranges (MH). With LED technology, it is possible to tailor the relative outputs of "blue light" and those in the green-yellow-red light ranges. However, the only way to eliminate the blue light output altogether is to convert the blue light emitted from diodes into longer wavelength light (still in the visible spectrum) using a phosphor. Hence the term PC Amber, refers to Phosphor Converted LED with an amber light output (because the blue light fraction has been converted).

However, even for a light source emitting blue light, depending on the other relevant wavelengths emitted, the human eye may perceive it as white or as other colours. There are different blends of white light defined. The perceived "colour" of a white light source by the human eye is most often expressed as the Correlated Colour Temperature (CCT). The term CCT is expressed in units of Kelvin and corresponds to the temperature that a “black body” would need to have in order to emit light corresponding to the same appearance as the light source in question.

In this context, the CCT is an approximate and unreliable metric for gauging the potential health, ecological impact and Rayleigh scattering of a light source, but is a reasonable reflection of human perception. Confusingly, the higher the CCT, the “colder” is the appearance of the light (i.e. more white-blue). So a “warm LED” would actually have a lower CCT than a “cold LED”. This is illustrated in Figure 18. To put the numbers in context, it should be noted that an overcast daylight is typically 6500 K.

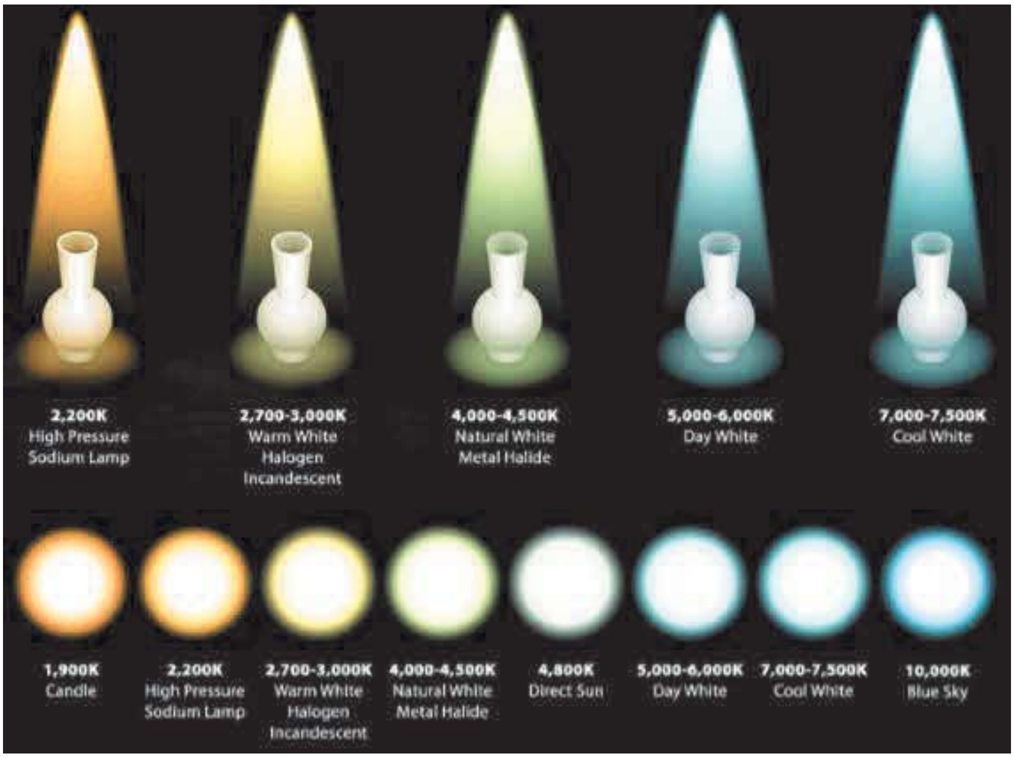


Figure 18. Illustration of different correlated colour temperatures (CCTs).

An advantage of “blue light” is that at very low light levels the human eye is more responsive to blue light due to so-called scotopic vision in comparison to photopic vision (DOE, 2017). The area between or combination of photopic and scotopic vision is called mesopic vision.

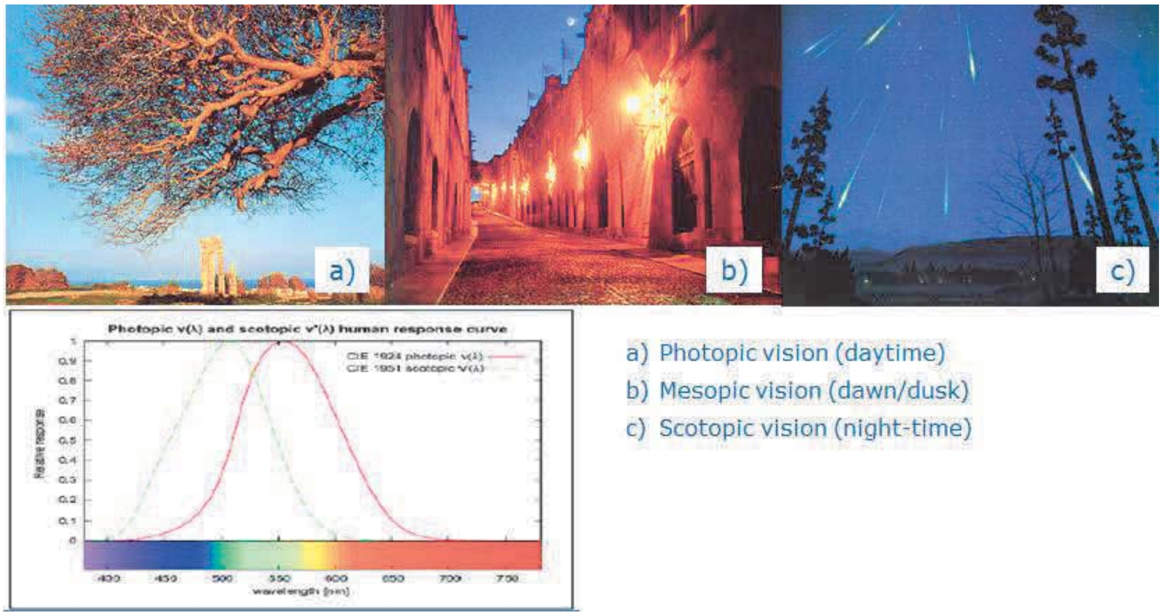


Figure 19. Illustration of the differences in photopic, mesopic and scotopic vision (a-c) and in the response of human photoreceptors in photopic and scotopic environments (Source: presentation titled "Lighting fundamentals").

Cool white (e.g. 5000 K) tend to have more blue in their spectra compared to warm white (e.g. 3000 K). Hence there are advocates to promote cool white light sources with so-called increased mesopic vision. This is acknowledged in the US standard IES TM-12 ‘Spectral Effects of Lighting on Visual Performance at Mesopic Lighting Levels’.

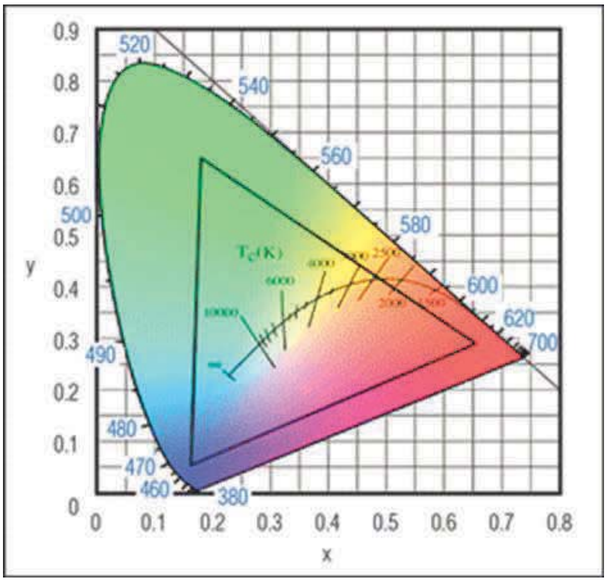


Figure 20. The CIE 1931 x,y chromaticity space showing the colour temperature locus and CCT lines: the lower the CCT, the more red light (Image sourced from this webpage).

When specifying a maximum limit for CCT, it is important to know the availability of products on the market that can meet that requirement. An analysis of the luminaires that were added to the LightingFacts database in 2016 or 2017 as a function of CCT is provided below.

Some general recommendations can be made regarding this topic:

- Do not use the term blue light in any GPP criteria unless relating to spectral emission within a defined wavelength range.

- Only use CCT if the criterion is related to aesthetic requirements relating to light perceived by humans (rather than light perceived by other species).
- If limiting blue light content is an issue, then specific metrics (such as the G-Index or alike) should be used to set thresholds. CCT is a fuzzy and unsatisfactory metric of the blue content of light sources.
- Potential impacts on wildlife and skyglow are sufficient justifications to set restrictions on blue light. This would also have the benefit of addressing concerns with potential effects on human health (a complex matter in which a lot of research is being carried out) because these concerns tend to increase with higher blue light content.

7.2.2. Stakeholder discussion

When prompted, a split opinion was received from stakeholders about photobiological safety of LED light sources. One group felt that this should be addressed by EU GPP criteria while the other group felt that this should be addressed by other means. Reference was made to the following standrds: IEC 62471-1, CIE 62778 (for assessment of blue light hazard), EN 60598 (general requirements for luminaires). One suggestion was to state that EU GPP criteria require that any LED luminaire be compliant with Risk Group 0 or Risk Group 1 limits for light hazards. It is important to clarify that this bears no relation to chronodisruption, but rather to the risk of tissue damage in the human optical system.

An intermediate proposal (between TR 1.0 and TR 2.0) that was discussed amongst a sub-group of the most active stakeholders in the group was to consider light pollution in different ways. For example, one criterion for skyglow (R_{ULO}) and another criterion for the visual quality of the light for humans and nocturnal species (CCT and CRI) impacts of road lighting. However, this intermediate approach did not account for the specific concerns (e.g. higher Rayleigh scattering for skyglow and higher ecological impact on wildlife) that are directly related to blue light output.

Concerns were expressed about any requirements for lower CRI values, as it may result in higher emissions of “blue light” and/or higher levels of illuminance to achieve a given visual acuity for humans.

Some stakeholders were highly critical of justifying higher CCT values in the comprehensive level criterion on the basis of impact on nocturnal species since much research still needs to be done in this area and potential impacts could vary greatly from species to species. A further review of research related to the impact of light on nocturnal species such as birds, bats, insects and aquatic species was requested. Despite these concerns there was some support for criteria related to CCT, but with the nuance that CCT alone will not address concerns about light pollution.

One of the arguments against proposals for low CCT values was that lower CCT LEDs had lower energy efficiency (see Table 7 for a comparison of luminous efficacy vs CCT).

When asked if the criteria for CRI and CCT should be applied always or only in certain situations, most stakeholders agreed that this should be decided by the tenderer. It was commented that the interpretation of guideline CIE 126 (1997) for identifying areas where light pollution is a concern will not be applied in an identical way across different Member States. If requirements on CRI and CCT were to be stipulated in the criteria, they should link to standard methods defined in CIE 13.3:1995 and CIE 15:2004 for CRI and CCT respectively. These parameters are also mentioned in IEC 62717 and IEC 62722 (parts 1 and 2).

It was also added that requirements for lower CCT values is an indirect way of reducing concerns about the emission of blue light from cooler LED lighting. Some stakeholders were in favour of CCTs <3000K being specified in EU GPP criteria while others were opposed to the idea. Those against disputed this assumption that blue light output and CCT are correlated. This prompted one stakeholder to share the graph below.

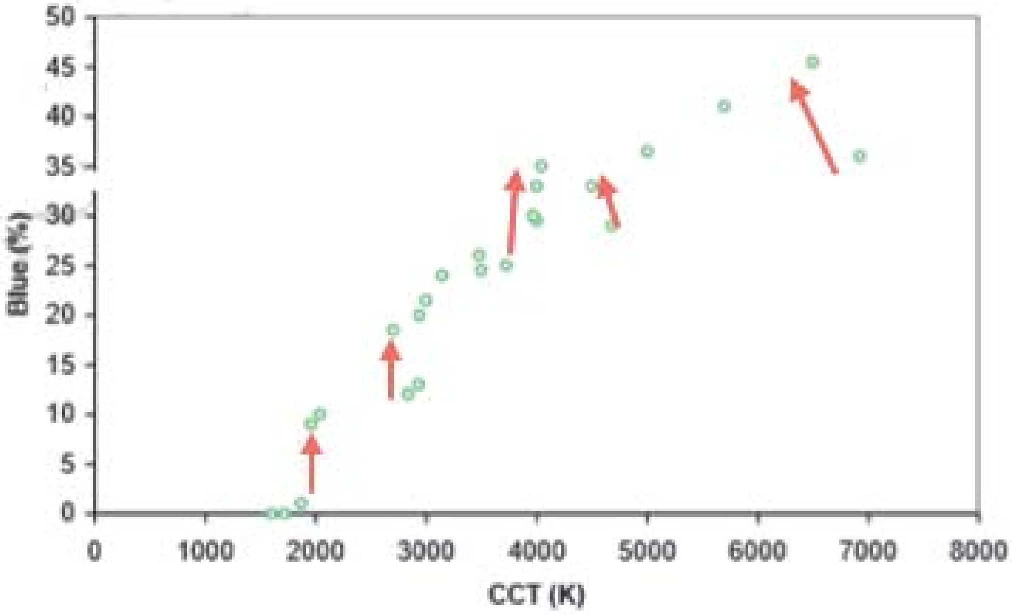


Figure 21. Correlation plot of blue light spectral power output versus CCT for different light sources.

Despite the general correlation shown above, it was repeated that there is no fixed relationship between CCT and the fraction of light output in the "blue" wavelength range (see red arrows as clear examples of the lack of correlation).

Annoyance, glare and obtrusive light

Light is a relatively subjective quality and as public authorities have shifted towards more energy efficient LED road lighting, this has led to a "whitening" of road lighting. There are numerous examples in the news of citizens complaining about the change in "*atmosphere*" in a residential or historic city centre location after sodium lamps have been changed to LED-based light sources.

Common complaints are that the change creates a "*hospital or prison-like feel*" to the lighted area despite the fact that other aspects such as energy efficiency and facial recognition are improved. Procurers should be sensitive to the potential reaction of local residents to any LED-based substitution of HPS or LPS lamps. In cases where objections can be expected or have already been voiced (e.g. historic city centre and residential zones), criteria for CCT ≤3000K are encouraged.

A standard approach for assessing the glare from road lighting is set out in EN 13201-2:2016, which defines intensity classes for the restriction of disability glare and control of obtrusive light G*1, G*2, G*3, G*4, G*5 and G*6 in Annex A. In general, as the glare class becomes more stringent, less light is permitted on the ground coming directions higher than 70°, 80° and 90° below the horizontal.

Light pollution from obtrusive light to humans and the methods for reduction are discussed in guideline CIE 150:2003 'Guide on the limitation of the effects of obtrusive light from outdoor lighting installations'. However, one stakeholder complained about the potential usefulness of this standard since it allows for up to 25 lux (>100x more than a full moon) to shine onto windows during pre-curfew hours in urban zones.

7.2.3. Discussion relating to human health effects of blue light

Due to extensive input from stakeholders following the 2nd AHWG meeting, it was considered necessary to dedicate a sub-section to the points that were raised about the potential human health effects of blue light. The information detailed below is broadly based on SCHEER, 2017. Although the SCHEER preliminary opinion is predominantly based on exposure to blue light from computer screens and indoor lighting, the same potential health effects should also apply to outdoor lighting with the main difference being the lower exposure of people to optical radiation from outdoor lighting. One study suggests that exposure to dim light at night (10 lux) may decrease cognitive performance although 5 lux did not seem to be problematic (Kang et al., 206).

One specific concern with outdoor road lighting is that it is generally more powerful than indoor light sources and short term exposure to very intense visible radiation (i.e. light) can induce cell damage or cell death due to free radical formation via photoreactive pigments such as lipofuscin (Chamorro et al., 2013; Kuse et al., 2014). These effects can apply to exposure to any light in principle.

The higher energy, shorter wavelength light (400-600nm) is capable of penetrating into cell organelles and producing reactive oxygen species in mitochondria, which may lead to apoptosis (Roehlecke et al., 2009) or phototoxic effects (Godley et al., 2005).

The concerns with blue light are more pronounced with older people, due to the accumulation of photoreactive pigments in the epithelium with age, and also with aphakic individuals (who have no lens/lenses to help filter shorter wavelength light).

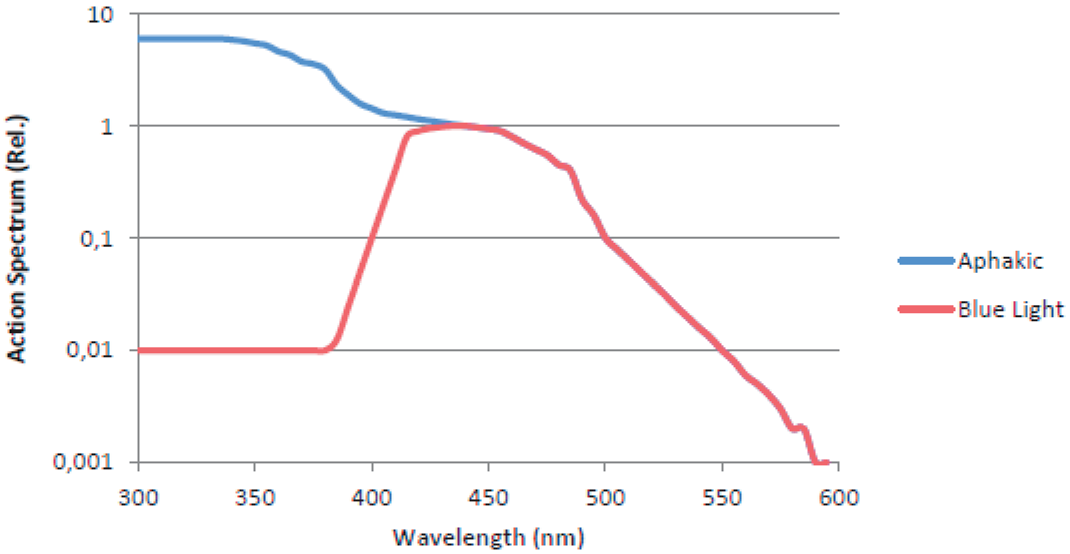


Figure 22. Blue light spectra compared to action spectra for aphakic eyes (from ICNIRP).

The data in Figure 22 clearly show that aphakic members of the population are especially sensitive to the shorter wavelengths of visible radiation (light) and that LED light sources emitting in blue light range would be much more harmful for them than traditional HID type lamps.

While the effects of immediate, short term exposure can be readily demonstrated in scientific studies, it is much more difficult to demonstrate more chronic effects that accrue with gradual exposure over time. Other effects of blue light exposure on human health, especially due to ALAN, may relate to disruption of the circadian rhythm (biological clock). The degree of influence that light may have on the circadian rhythm depends on a number of factors:

- Timing

- Intensity
- Duration
- Spectrum of the light stimulus
- Previous light exposure

Effects can be observed at relatively low intensities (<100 lux) and even for durations of the order of minutes or less (Glickman et al., 2002; Duffy and Czeisler, 2009; Lucas, Peirson et al., 2014).

The fourth point in the list above is particularly relevant. Concerns with blue light are centred on the relatively recent identification of melanospin (within the last 15 years) as the key protein in intrinsically photosensitive Retinal Ganglion Cells (ipRGCs) for carrying out non-image forming functions and for sending signals to various parts of the brain, particularly the suprachiasmatic nucleus, which ultimately affects the production of the hormone melatonin from the pineal gland (Schomerus and Korf, 2005). The melatonin hormone is well known as an important regulator of the human body clock (circadian rhythm).

While *in vitro* experiments clearly show the peak spectral sensitivity of melanospin to be around 480nm (Bailes and Lucas, 2013), the *in vivo* effects are much more complex and may be context dependent (Lucas, Peirson et al., 2014). Nonetheless, it can be generally concluded that the circadian rhythm is most affected by light in the wavelength range 460-490nm (Duffy and Czeisler, 2009; Benke and Benke, 2013). It is worth noting that this coincides almost exactly with the blue peak emission of most LED light sources depicted in Figure 17.

Melatonin is a particularly useful biomarker for monitoring the circadian rhythm and levels can be monitored by analysing saliva, serum or urine. Circadian rhythms do not only affect sleeping and waking cycles but also cognition, immune system and repair mechanisms and numerous physiological processes such as metabolism, endocrine functions and protein expression (Takahashi, 2017).

Research to date has predominantly focussed on circadian disturbance due to indoor light exposure and possible effects on cancer, metabolic health effects and cognitive function (IARC, 2010; Wang, Armstrong et al., 2011; ANSES, 2016; Mattis and Sehgal, 2016). James et al., (2017) presented data suggesting that exposure to outdoor ALAN is a factor contributing to breast cancer. Another study, about the exposure of populations in Barcelona and Madrid to ALAN (indoor and outdoor) and the incidence of prostrate and breast cancer found evidence of a positive association of the blue content of outdoor ALAN and these cancers but not with overall outdoor or indoor ALAN (Garcia-Saenz et al., 2018).

One interesting point is that when looking at the potential broader effects of ALAN on human health, it is impossible to know to what extent "*social jetlag*" might affect results – e.g. the need for individuals to wake up and have breakfast when it is still dark in order to get to work on time. There is also the need to consider the differences between sleep quality and sleep quantity (Joo, Abbott et al., 2017; Magee, Marbas et al., 2016).

Considering all of these complex interactions and the general lack of comparable studies in the literature, it is unsurprising that the preliminary opinion of SCHEER is that:

"The Committee concludes that there is no evidence of direct adverse health effects from LEDs in normal use (lighting and displays) by the general healthy population..."

And

"…Light sources that emit more short-wavelength light, as do some types of LEDs, will have a larger effect on the circadian rhythms at equal optical radiance, duration and timing of exposure. At the moment, it is not yet clear if this disturbance of the circadian system leads to adverse health effects."

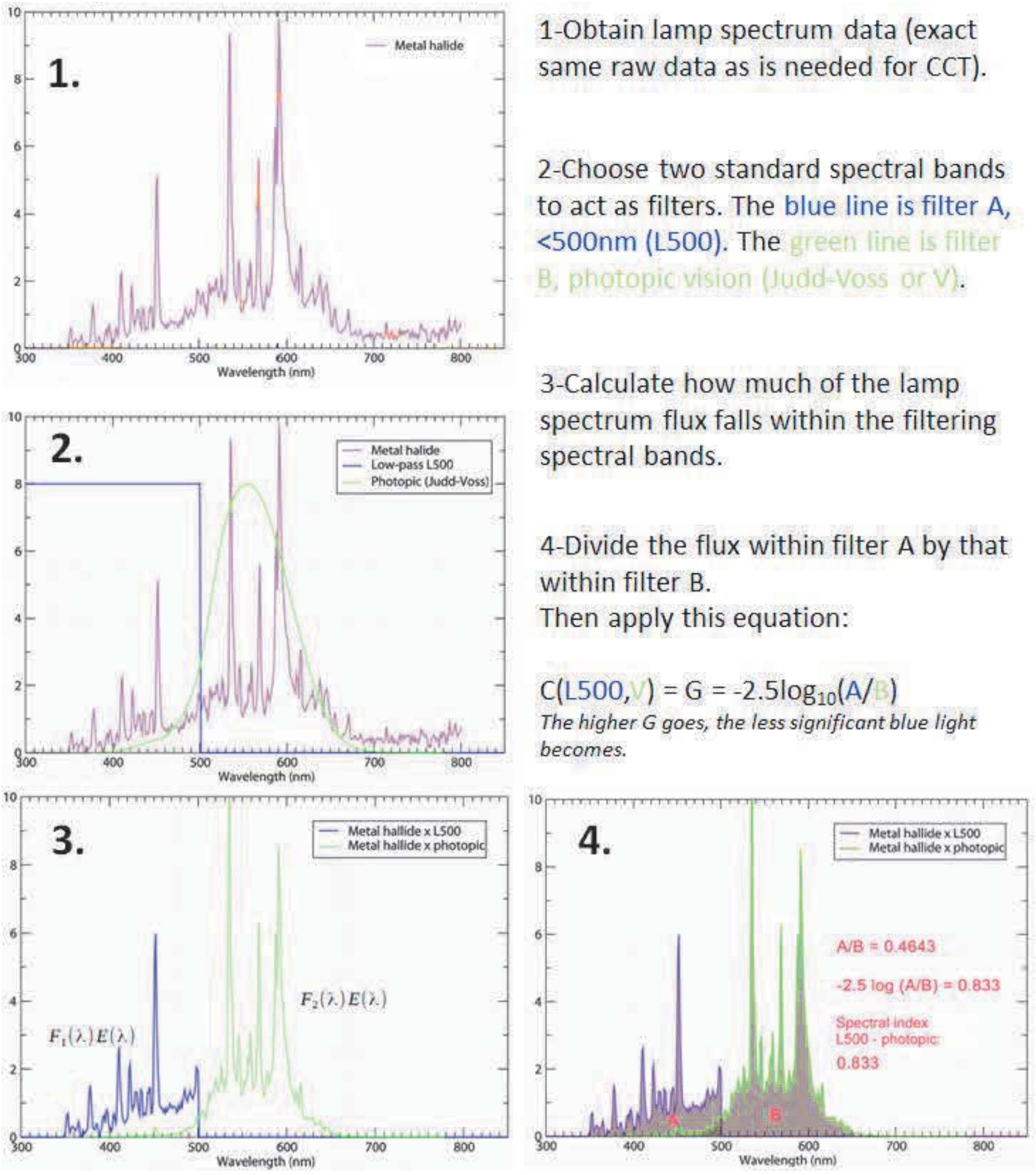
Considering these comments quoted above, it becomes apparent that the effect of blue light on human health is indeed a complex issue which raises a number of concerns (especially for aphakic members of the population), but has not yet been fully understood. Going beyond human health impact, concern with the effect of blue light on nocturnal species and its much higher potential contribution to skyglow are sufficient motives for promoting restrictions on blue light in a number of areas (e.g. parks, gardens, protected areas and intrinsically dark areas).

7.2.4. Discussion about how to quantify blue light output (and limits)

Significant discussion took place regarding the proposals in TR 2.0 relating to limits that were set for CCT and specifically for blue light output. It was already understood that CCT is not a perfect indicator of blue light output (see Figure 21) but it was also argued that this is a metric that many people seem to be able to grasp.

One of the main arguments against CCT was that it only roughly describes the spectra of lamp light output by assuming that the lamp behaves as a black body. While this may have been relevant for incandescent bulbs, it is not relevant to other lighting technologies such as High Intensity Discharge or LED.

An alternative method was proposed that allows the same data that is needed to calculate CCT to be used to calculate a spectral index which expresses the relative importance of light in two bands or wavelength intervals. If these bands are A and B, the related spectral index may be noted in the most general way as C(A,B). For the evaluation of blue light content, it has been suggested to use A as all emissions of wavelength lower than 500nm (L500), and B as the standard curve of photopic vision (Judd-Voss version, for example, V). The resulting C(L500,V) index is already being implemented in some regulations and, following the Andalucian Regulation, it was proposed to label it as the "G index" (in spite of possible minor confusion with glare classes). An example of how the G index is calculated is illustrated below.



1-Obtain lamp spectrum data (exact same raw data as is needed for CCT).

2-Choose two standard spectral bands to act as filters. The blue line is filter A, <500nm (L500). The green line is filter B, photopic vision (Judd-Voss or V).

3-Calculate how much of the lamp spectrum flux falls within the filtering spectral bands.

4-Divide the flux within filter A by that within filter B.
Then apply this equation:

$$C(L500, V) = G = -2.5\log_{10}(A/B)$$

The higher G goes, the less significant blue light becomes.

Figure 23. Example of how the spectral index C(L500,V), or G index, works.

The proponents of the G index cited some of its advantages, which included:

- Simpler basic principles than CCT.
- The index is unit-independent, so the units on the y-axis of any spectral data are irrelevant because the calculation is based only on that same spectrum.
- No external reference sources or standards needed for comparison.
- The G-index units are "magnitudes", the same units that are used in astronomy – directly relevant when considering skyglow.

The approach to calculating the G-index for lamps has already been consulted widely with Spanish stakeholders representing the industry, governments and academia and has been recently published in an academic journal (Galadi-Enriquez, 2018). Computationally, its value is easier to derive than CCT, and using the same initial spectral data. The Andalusian representatives have very recently made available an online calculator or spreadsheet where the input of lamp spectrum data can be directly inserted and the G-index calculated straight away.

In order to better understand how the G-index might compare to CCT data for different lamps, a number of spectra have been analysed for both CCT and the G-index.

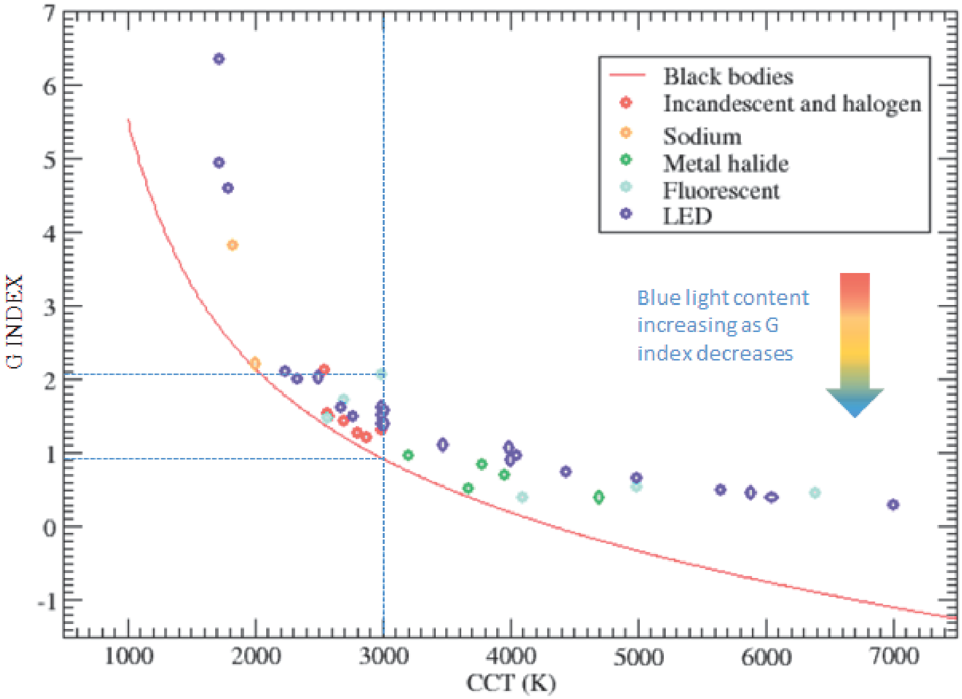


Figure 24. Correlation between CCT and G-index values for different lamps (specific comparison at 3000K highlighted).

The data in Figure 24 show that while the real lamp data, when plotted as G-index versus CCT, generally follows the black body curve, it is far from a perfect fit.

In fact, looking specifically at CCT = 3000K, which is an important threshold that has been much quoted in public debate, there is actually a significant difference in actual blue light content: the G-index can range from around 0.9 for a true black body to 2.1 for a fluorescent lamp. Just looking at 3000K LED lamps, the range was also from 1.3 to 1.6.

It is also worth comparing the G-index approach with the requirements of the Low Impact Lighting (LIL) standard that was summarised at the beginning of section 7. The LIL standard is asking for a very similar thing, but expresses blue light as a % of all light output (not just light within photopic range) and does not formally translate the results into an index value. Although not directly comparable, because the second filter is different (bolometric instead of photopic), the LIL standard would ask for:

- a C(L500,bol) index of >3.05 when blue light should be <6% or
- a C(L500,bol) index of >2.50 when blue light should be <10%.

Due to concerns that the LIL approach may favour light sources that also emit outside of the photopic vision range and into the infra-red region, it is considered more appropriate to continue with the (L500,V) index when setting actual EU GPP criteria.

The LIL criteria set separate requirements on blue light and CCT, which accurately reflects the fact that CCT does not guarantee any control over blue light emissions. Setting criteria on both CCT and blue light at the same time may led to confusion since many people believe CCT would render the requirement on blue light redundant when this is not necessarily the case (see the vertical spread of points on the 3000K line in Figure 24). It is much better to distinguish when and why a procurer may wish to set a limit on CCT and when and why on blue light emissions.

When blue light emission is identified as a concern by the procurer, it is necessary to consider what an appropriate ambition level to set for the G-Index would be. The following levels have been considered:

- G ≥1.5. Almost all light sources with a CCT >3000K would not fulfil this condition. Almost all light sources with a CCT <2700K would fulfil this condition. Light sources with a CCT in between 2700 and 3000K may or may not fulfil this condition.
- G ≥2.0. Almost all light sources with a CCT >2700K would not fulfil this condition. Almost all light sources with a CCT <2300K would fulfil this condition. Light sources with a CCT in between 2300 and 2700K may or may not fulfil this condition.

All LPS, HPS and PC amber light sources could be considered to meet the more stringent requirement of G ≥2.0.

7.2.5. Criteria proposals for ecological light pollution and annoyance

Core criteria	Comprehensive criteria
TS8 Annoyance	
(The CCT value is directly related to human perception and so should be specified when human annoyance is a concern.) *(Same for core and comprehensive criteria.)* In residential areas, in order to reduce the risk of human annoyance, the CCT of light sources shall be ≤3000K and a dimming or switch-off programme shall be implemented*. **Verification:** If requested, the tenderer shall provide the light spectra of all lamps to be provided. The tenderer shall provide measurements of CCT reported in accordance with CIE 15. With dimming, the tenderer shall provide details of the proposed dimming controls and the range of dimming capabilities, which shall at least permit dimming or switch-off based on an astronomical clock. **As per the procurer's specifications (potentially defined in TS3 if that is included in the ITT).*	
TS9: Ecological light pollution and star visibility	
(The G-index value is directly related to blue light content, and so should be specified when light pollution effects on wildlife or on star visibility are a concern.) In parks, gardens and areas considered by the procurer to be ecologically sensitive, the G-index shall be ≥1.5*. A dimming programme** shall be implemented for parks and gardens that are open during night-time hours. A switch-off programme shall apply to any relevant closing hours for parks and gardens. A dimming and/or switch-off programme** shall be implemented for any other	***(The G-index value is directly related to blue light content, and so should be specified when light pollution effects on wildlife or on star visibility are a concern. Procurers should be aware that luminaires complying with this requirement are unlikely to meet TS1 for luminaire efficacy.)*** In parks, gardens, areas considered by the procurer to be ecologically sensitive or any area within a 30km radius of an urban optical astronomy observatory or within a 100km radius of a major optical astronomy observatory, the G-index shall be ≥2.0*. A dimming programme** shall be

ecologically sensitive areas. **Verification:** The tenderer shall provide measurements of the G-index***. **If it is not possible to calculate the G-index, CCT may be used as an orientation, it always being understood that its use as a metric for blue light is not perfect. A G-index of ≥1.5 would generally (but not always) equate to a CCT of ≤3000K.* ***As per the procurer's specifications (potentially defined in TS3 if that is included in the ITT).* ****The G-index can be quickly and easily calculated using the same photometric data used to calculate the CCT via an excel spreadsheet available at this website:* http://www.juntadeandalucia.es/medioambiente/cieloandaluzindiceg	implemented for parks and gardens that are open during night-time hours. A switch-off programme shall apply to any relevant closing hours for parks and gardens. A dimming and/or switch-off programme** shall be implemented for any other ecologically sensitive areas or areas within the defined radii of relevant optical observatories. **Verification:** The tenderer shall provide measurements of the G-index***. **If it is not possible to calculate the G-index, CCT may be used as an orientation, it always being understood that its use as a metric for blue light is not perfect. A G-index of ≥2.0 would generally (but not always) equate to a CCT of ≤2700K.* ***As per the procurer's specifications (potentially defined in TS3 if that is included in the ITT).* ****The G-index can be quickly and easily calculated using the same photometric data used to calculate the CCT via an excel spreadsheet available at this website:* http://www.juntadeandalucia.es/medioambiente/cieloandaluzindiceg