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Revision of the EU Green Public Procurement Criteria for Road Lighting and traffic signals

Technical report and criteria proposal

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Abstract

The EU GPP criteria for road lighting and traffic signals aim to address the key environmental impacts associated with the design, installation and operation of these systems. For road lighting, the criteria are broadly split into three parts: energy consumption, light pollution and durability aspects.

From an LCA perspective, the main environmental impact was found to be related to energy consumption during the use phase. This impact can be reduced in a number of ways, by using luminaire and light source combinations with a high luminous efficacy, by dimming during periods of low road use and by selection of the lowest necessary light class for roads to prevent unnecessary over-lighting in the first place.

Light pollution is another environmental impact of particular relevance to road lighting and traffic signals which is not well addressed by LCA methodologies. In order to reduce the potential for light pollution, EU GPP criteria are proposed based on upward and horizontal light output ratios. Furthermore, limits on Correlated Colour Temperature and blue light output are proposed in order to address concerns about annoyance and ecological light pollution respectively.

The durability of light sources and fittings is not only important to environmental impacts but also to life cycle cost. Consequently, the EU GPP criteria set requirements for minimum warranties, ingress protection, control gear failure rates and reparability - in order to ensure that lighting equipment in winning tenders is of sufficient quality and able to deliver a prolonged service life.

The implementation of these criteria should also help procurers understand better about aspects that should be considered in road lighting system design (e.g. maximum lighting level, dimming capability), the actual products they are procuring (requirements on provision of instructions and labelling), to keep accurate information about their infrastructure (requirement on asset labelling) and to monitor lighting system performance (requirements on metering and AECI).

Overall, a good understanding of road lighting and traffic signal systems and the use of suitable technical specifications in Invitations to Tender should help ensure that the twin benefits of lower environmental impacts and lower life cycle costs for public authorities can be obtained.

1. Introduction

Public authorities' expenditures in the purchase of goods, services and works (excluding utilities and defence) constitute approximately 14% of the overall Gross Domestic Product (GDP) in Europe, accounting for roughly EUR 1.8 trillion annually (EC, 2016).

Thus, public procurement has the potential to provide significant leverage in seeking to influence the market and to achieve environmental improvements in the public sector. This effect can be particularly significant for goods, services and works (referred to collectively as products) that account for a high share of public purchasing combined with the substantial improvement potential for environmental performance.

Green Public Procurement (GPP) is defined in the Commission's Communication "COM (2008)400 - Public procurement for a better environment" as "*…a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured.*"

Therefore, by choosing to purchase products with lower environmental impacts, public authorities can make an important contribution to reducing the direct environmental impact resulting from their activities. Moreover, by promoting and using GPP, public authorities can provide industry with real incentives for developing green technologies and products. In some sectors, public purchasers command a large share of the market (e.g. public transport and construction, health services and education) and so their decisions have considerable impact. In fact, COM (2008)400 mentions that public procurement has the capability to shape production and consumption trends, increase demand for "greener" products and services and provide incentives for companies to develop environmental friendly technologies is clearly emphasised. Many examples of what is being done with GPP can be found online, for example at the Green Public Procurement in Action website or the GPP2020 Procurement for a low-carbon economy website.

GPP is a voluntary instrument, meaning that Member States and public authorities can determine the extent to which they implement it.

The development of EU GPP criteria aims to help public authorities ensure that the goods, services and works they require are procured and executed in a way that reduces their associated environmental impacts. The criteria are thus formulated in such a way that they can be, if deemed appropriate by the individual authority, integrated into its tender documents with minimal editing.

GPP criteria are to be understood as being part of the procurement process and must conform to its standard format and rules as laid out by Public Procurement Directive 2014/24/EU (public works, supply and service contracts). Hence, EU GPP criteria must comply with the guiding principles of: Free movement of goods and services and freedom of establishment; Non-discrimination and equal treatment; Transparency; Proportionality and Mutual recognition. GPP criteria must be verifiable and it should be formulated either as Selection criteria, Technical specifications, Award criteria or Contract performance clauses, which can be understood as follows:

Selection Criteria (SC): Selection criteria refer to the tenderer, i.e., the company tendering for the contract, and not to the product being procured. It may relate to suitability to pursue the professional activity, economic and financial standing or technical and professional ability and may- for services and works contracts - ask specifically about their ability to apply environmental management measures when carrying out the contract.

Technical Specifications (TS): Technical specifications constitute minimum compliance requirements that must be met by all tenders. It must be linked to the contract's subject matter. The ‘subject matter’ of a contract is about what good, service or work is intended to be procured. It can consist in a description of the product, but can also take the form of a functional or performance based definition. Technical specifications must not concern general corporate practices but only characteristics specific to the product being procured. A link to the subject matter can concern any stage of the product's life-cycle, including its supply-chain, even if not obvious in the final product, e.g., not forming a material part of the product. Offers not complying with the technical specifications must be rejected. Technical specifications are not scored for award purposes; they are strictly pass/fail requirements.

Award Criteria (AC): At the award stage, the contracting authority evaluates the quality of the tenders and compares costs. Contracts are awarded on the basis of most economically advantageous tender (MEAT). MEAT includes a cost element and a wide range of other factors that may influence the value of a tender from the point of view of the contracting authority including environmental aspects (refer to the Buying Green guide (EC, 2016) for further details). Everything that is evaluated and scored for award purposes is an award criterion. These may refer to characteristics of goods or to the way in which services or works will be performed. In the latter case they cannot be verified at the award stage since they refer to future events. Consequently, in these cases the criteria are to be understood as commitments to carry out services or works in a specific way and should be monitored/verified during the execution of the contract via a contract performance clause. As with technical specifications, award criteria must be linked to the contract's subject matter and must not concern general corporate practices but only characteristics specific to the product being procured. As with technical specifications, a link to the subject matter can concern any stage of the product's life-cycle, including its supply-chain, even if not obvious in the final product, e.g., not forming a material part of the product. Award criteria can be used to stimulate additional environmental performance without being mandatory, therefore not foreclosing the market for products not reaching the proposed level of performance but at the same time recognising the superior performance of products that can meet a defined higher performance.

Contract Performance Clauses (CPC): Contract performance clauses are used to specify how a contract must be carried out. As with technical specifications and award criteria, contract performance clauses must be linked to the contract's subject matter and must not concern general corporate practices but only those specific to the product being procured. A link to the subject matter can concern any stage of the product's life-cycle, including its supply-chain, even if not obvious in the final product, e.g., not forming a material part of the product. The economic operator may not be requested to prove compliance with the contract performance clauses during the procurement procedure. Contract performance clauses are not scored for award purposes. Compliance with contract performance clauses should be monitored during the execution of the contract after it has been awarded and may be linked to penalties or bonuses under the contract in order to ensure compliance.

For each criterion there is a choice between two levels of environmental ambition, which the contracting authority can choose from according to its particular goals and/or constraints:

> The **Core criteria** are designed to allow for easy application of GPP, focussing on the key areas of environmental performance of a product and aimed at keeping administrative costs for companies to a minimum.
>
> The **Comprehensive criteria** take into account more aspects or higher levels of environmental performance, for use by authorities that want to go further in supporting environmental and innovation goals.

As said before, the development of EU GPP criteria aims to help public authorities ensure that the goods, services and works they require are procured and executed in a way that reduces their associated environmental impacts. Criteria should focus on the products' most significant improvement areas, resulting from the cross-check between the key environmental hot-spots and market analysis. Criteria development also requires an understanding of commonly used procurement practices and processes and taking on board lessons learned from any actors involved in successfully fulfilling contracts.

For this reason, the European Commission has developed a process aimed at bringing together both technical and procurement experts to collate a broad body of evidence and to develop, in a consensus-oriented manner, a proposal for precise and verifiable criteria that can be used to procure products with a reduced environmental impact.

A detailed environmental and market analysis, as well as an assessment of potential improvement areas, was conducted within the framework of this project and was presented in the Preliminary Report on EU Green Public Procurement Criteria for road lighting and traffic signals. This report can be publicly accessed at the JRC website for road lighting and traffic signals. The main findings presented in the Preliminary Report are summarised in the next section.

Based on the findings from the Preliminary report, a first draft of the Technical Report and criteria proposal was produced and presented at the 1st ad-hoc working group (AHWG) meeting held in Seville on 22nd November 2016. Following stakeholder feedback, a second draft Technical Report was published and discussed during the 2nd AHWG meeting (in webinar format) on the 19th and 21st September 2017. After considering this second round of stakeholder feedback and following internal consultation procedures, this final Technical Report has been produced, which presents the final EU GPP criteria (published in Staff Working Document 494 on the 10th December 2018 SWD(2018) 494) and supporting rationale for those criteria.

2. Summary of the Preliminary report

The Preliminary Report provides a general analysis of the product group in question, assessing the relevance of its scope and identifying the most relevant legislation, standards and definitions that apply. As part of the Preliminary Report, a market analysis is also conducted as well as an assessment of the main environment impacts associated with road lighting and the potential for technical improvements to reduce those impacts. These aspects ensure that the Preliminary Report forms the basis for the revision and development of EU GPP criteria in subsequent draft Technical Reports.

2.1. Scope and definitions

The scope of existing EU GPP criteria (published in 2012) for this product group covers two different types of lighting, namely "street lighting" and "traffic signals", whose definitions are linked to EN 13201 and EN 12368 respectively.

An initial scoping questionnaire was circulated to stakeholders at the beginning of the project. The majority of responses supported the removal of traffic signals from the scope based on the consideration that this would normally form a different subject matter in procurement contracts. With regards to the scope for street lighting, respondents generally agreed to link the definition to that of EN 13201-1. However, it was also mentioned that aspects relating to metering and dimming controls could be referred to, even though they are not explicitly included in the EN 13201 definition. Power cables and poles were not considered important and can continue to be excluded from the scope. One other comment was that the term "*road lighting*" should be used instead of "*street lighting*" in order to ensure better alignment with EN 13201.

A number of definitions were included in the Preliminary Report that are of high relevance to the product group and are summarised below:

- **a) M class road areas:** for drivers of motorized vehicles on traffic routes, and in some countries also residential roads, allowing medium to high driving speeds (for EN 13201-1:2014 suggested associated light levels, see Figure 1).
- **b) C class road areas:** for use in conflict areas on traffic routes where the traffic composition is mainly motorised. Conflict areas occur wherever vehicle streams intersect each other or run into areas frequented by pedestrians, cyclists, or other road users. Areas showing a change in road geometry, such as a reduced number of lanes or a reduced lane or carriageway width, are also regarded as conflict areas (for EN 13201-1:2014 suggested associated light levels, see Figure 1).
- **c) P class road areas**: predominantly for pedestrian traffic and cyclists for use on footways and cycleways, and drivers of motorised vehicles at low speed on residential roads, shoulder or parking lanes, and other road areas lying separately or along a carriageway of a traffic route or a residential road, etc. (for EN 13201-1:2014 suggested associated light levels, see Figure 1).
- **d) Adaptive lighting**: temporal controlled changes in luminance or illuminance in relation to traffic volume, time, weather or other parameters (EN 13201-1:2014).
- **e) Luminaire**: an apparatus which distributes, filters or transforms the light transmitted from one or more lamps and which includes, except the lamps themselves, all the parts necessary for fixing and protecting the lamps and, where necessary, circuit auxiliaries together with the means for connecting them to the electric supply (EN 12665:2011).
- **f) Lamp:** a unit whose performance can be assessed independently and which consists of one or more light sources. Therefore it may include additional components necessary for starting, power supply or stable operation of the unit or for distributing, filtering or transforming the optical radiation, in cases where those components cannot be removed without permanently damaging the unit.
- **g) Light source:** a surface or object designed to emit mainly visible optical radiation produced by a transformation of energy. The term 'visible' refers to a wavelength of 380 - 780 nm.

- **h) Light Emitting Diode (LED):** a light source, which consists of a solid-state device embodying a p-n junction of inorganic material. The junction emits optical radiation when excited by an electric current.
- **i) LED package:** an assembly having one or more LED(s). The assembly may include an optical element and thermal, mechanical and electrical interfaces.
- **j) LED module:** an assembly having no cap and incorporating one or more LED packages on a printed circuit board. The assembly may have electrical, optical, mechanical and thermal components, interfaces and control gear.
- **k) LED lamp:** a lamp incorporating one or more LED modules. The lamp may be equipped with a cap.
- **l) Ballast:** a device connected between the supply and one or more discharge lamps which serves mainly to limit the current of the lamp(s) to the required value
- **m) Control gear:** components required to control the electrical operation of the lamp(s). Control gear may also include means for transforming the supply voltage, correcting the power factor and, either alone or in combination with a starting device, provide the necessary conditions for starting the lamp(s).
- **n) Light pollution:** Several different definitions have been provide, including: (i) "*any adverse effect of artificial light including skyglow, glare, light trespass, light clutter, decreased visibility at night, and energy waste*", (Rajkhowa, 2014); (ii) "*the sum-total of all adverse effects of artificial light*" (CIE 126:1997); (iii) "*the introduction by humans, directly or indirectly, of artificial light into the environment*" (UNESCO, IAU and IAC);

2.2. Relevant standards

Road lighting and traffic signals are well defined by their corresponding standards EN 13201 series and EN 12368. Stakeholders expressed such strong opinions about the EN 13201 standard that it is considered worthwhile to add additional information relating to the standard here in this Technical Report, even though it was only provided after the Preliminary Report was published.

The technical report CEN/TR 13201-1:2014 gives guidelines on the selection of the most appropriate lighting class for a given situation. ***The standard only provides recommendations on road class definition and associated lighting levels - it is not legally binding per se***. The decision to light a road or not and, when it is decided to light a road, the actual choice of the lighting level is to be decided by the local authority or road authority and should respect any local or regional planning laws and/or, where relevant, national lighting plans. In order to reduce light pollution, the selection of the class should always be made using the principle "***As Low As Reasonably Achievable***" (ALARA) at any moment of time.

The European standard EN 13201-2:2016 contains performance requirements (light level, uniformity, glare) for different classes (M1….M6, C1….C5, P1….P6). Class M1 requires much higher light levels compared to class M6 (see Figure 1).

Luminance		Illuminance			Illuminance		
							
= see road		= see objects			= see objects		
view point: car driver		view point: any			view point: any		
EN 13201	L,m	EN 13201	E,m	Emin	EN 13201	E,m	Emin
Class	Cd/m²	class	lx	lx	class	lx	lx
		C0	50				
M1	2	C1	30				
M2	1,5	C2	20				
M3	1	C3	15		P1	15	3
M4	0,75	C4	10		P2	10	2
M5	0,5	C5	7,5		P3	7,5	1,5
M6	0,3				P4	5	1
					P5	3	0,6
					P6	2	0,4
Mesopic vision(max)	0,1				Moonlight	0,3	

Figure 1. EN 13201-2 road classes and their required light levels and Mesopic vision boundary and maximum moonlight levels for comparison

In fact, the EN 13201 lighting levels in general are considered as very high by many stakeholders, especially for the higher class roads (i.e. M1 and C0). One of the factors that define a road class in EN 13201 is traffic volume (especially important in M-class roads). Since this is a dynamic property, which will vary from hour to hour and day to day, the recommended light levels also vary dynamically. Thus to accurately follow the recommendations of the EN 13201 standard would require dimming controls (perfectly compatible with LED lamps but less compatible with HID lamps).

A good example of the development of a national standard that embraces the need for dynamic lighting levels is UNI 11248/2016 in Italy. The Italian standard makes an allowance for reducing light levels by up to 4 classes (e.g. M1 → M5 or M2 → M6) in periods when the traffic flow is expected to be lower.

In P-class roads especially, another aspect to consider when deciding on the appropriate light level is the perceived sense of security. Anecdotal evidence from stakeholders suggested that the EN 13201 recommended levels could be reduced by 30-35% without any loss of security perception.

For reference, the light level of a full moon shining through a clear night sky is added. The upper value of 0.3 lux is for a full moon shining directly overhead. At most European latitudes, the maximum full moon illumination value will be closer to 0.1 lux. A number of stakeholders considered that a full moon level of luminance should be the target level, at least for C and P class roads, since it has been reported that pedestrians and cyclists can still navigate at this light level. Figure 1 shows that the lowest EN 13201 lighting threshold for P class roads is more than 6 times higher than the illuminance of a full moon.

EN 13201 Part 3 deals with calculation of performance, Part 4 contains methods of measuring lighting performance and Part 5 defines energy performance indicators that are presented later in proposed EU GPP criteria. The use of standardised calculations and methodology means that designs of different manufacturers are more comparable, which is essential for evaluating competitive offers in procurement.

It is difficult to foresee how the lighting levels recommended by EN 13201 may evolve in the future. The original justifications behind the choice of lighting levels have been questioned and further debate could result in a significantly different approach being taken (Fotios and Gibbons, 2018).

When renovating, there is the risk that an EN 13201 light class is specified that is much higher than the lighting level that the existing installation delivers. Ideally, procurers should be fully aware of what level of light they actually want or need and should embrace the ALARA (As Low As Reasonably Achievable) principle when deciding on light levels.

2.3. Market analysis

The road lighting luminaire sector is a 520 million €/yr industry that provides lighting for some 1.5 million km of roads in the EU28 via an estimated 64 million luminaires. Around 2.38 million luminaires are sold each year in the EU28, with 2.16 million of those (91%) being for the replacement of existing luminaires. This demonstrates the mature nature of the road lighting sector in Europe and suggests a typical luminaire replacement rate of 29 years.

The split in lamp technology amongst existing luminaries on EU roads in 2015 was estimated as shown in Figure 2.

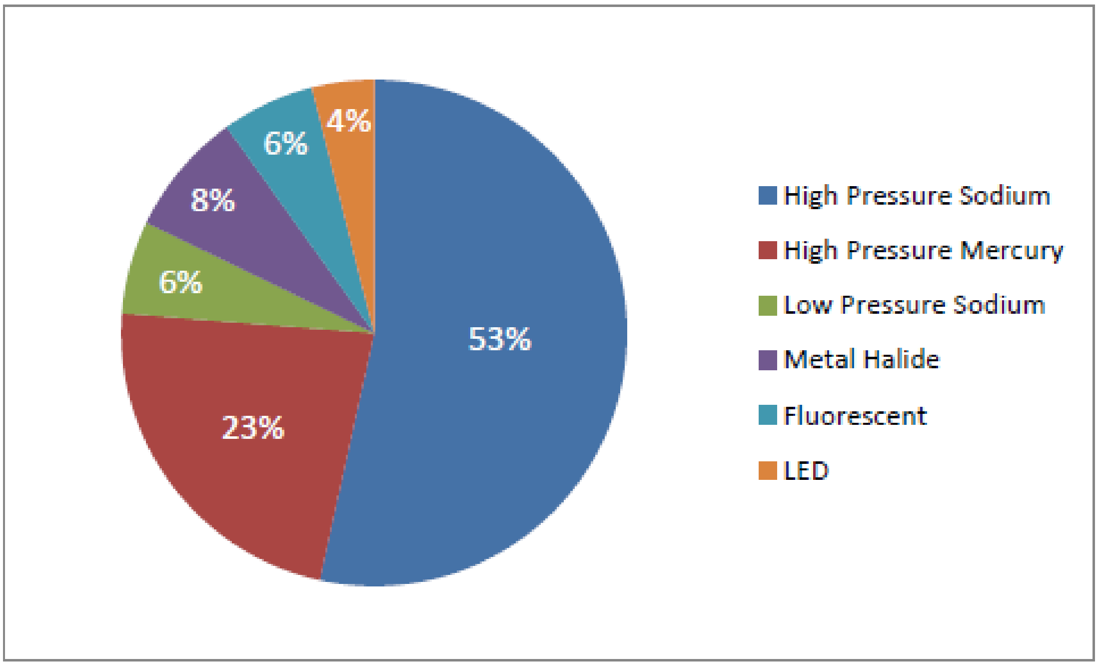

Figure 2. Estimated split of lamp technologies in EU28 road lighting in 2015

Luminaire prices can vary strongly and especially new LED luminaires are substantially more expensive than the average 220 euro, but the price of LED packages for use within luminaires has decreased significantly and is expected to continue decreasing in the future (see Figure 3).

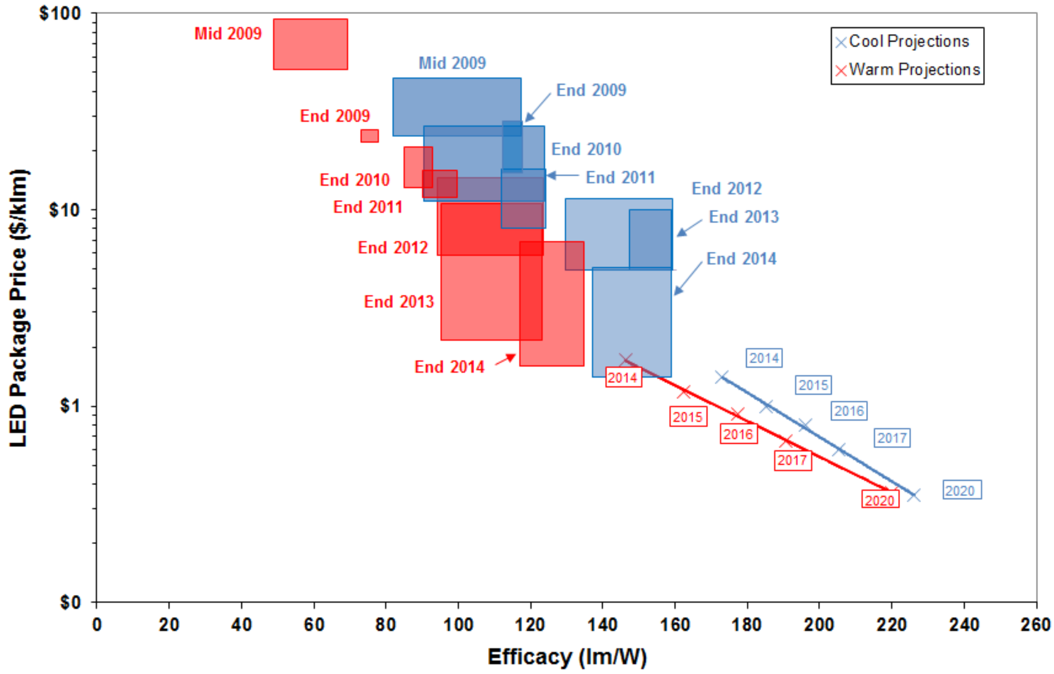

Figure 3. Price-efficacy trade-off for LED packages at 1 W/mm^2 (equiv. 35 A/cm^2) and 25°C (DOE, 2015).

The data in Figure 3 not only demonstrates the decrease in prices but also the increase in lumen efficacy, which will result in lower operating costs for a given necessary light output. However, in order to avoid unrealistic expectations about how low the cost of LED luminaires will become in the future, it is worth highlighting here that the LED package price only accounts for around 10-15% of the total cost of an LED luminaire.

When considering the split of lamp technologies in existing road lighting installations in Europe in 2015, shown in Figure 2, and how this split will look in the near future, there are three key points to consider:

- High Pressure Mercury lamps (HPM) have been phased out since April 2015 as per Regulation 245/2009, so this 23% share will eventually drop to 0%.
- 2015 was a breakthrough year for LED technology in road lighting applications. New sales of road lighting lamps and luminaires have since been dominated by LED technology and so the current 4% share will increase significantly in the next few years.
- Typical service lives of non-LED lamps are of the range of 2-8 years whereas LED lamps may last >15 years.

Consequently, it is widely accepted that LED technology will quite quickly become the dominant road lighting lamp technology in Europe.

2.4. Environmental analysis

2.4.1. LCA-modelled impacts

The environmental impacts associated with the road lighting installations have been investigated by conducting a review of relevant LCA studies published in the literature.

Despite the many nuances that apply to LCA studies, such as the appropriate choice of functional unit, scope and boundaries, assumed product lifetime, inventory data and the different impact categories that can be reported on, the literature was unanimous in showing that the use phase was the dominant source of all LCA impact categories as a direct result of electricity consumption. This is not surprising when it is considered that approximately 1.3% of all electricity consumed by the EU25 in 2005 (35 TWh) was by road lighting installations.

It was also clear that the importance of the manufacturing stage is going to increase if road lighting becomes more energy efficient and/or a low emission electricity mix is used. The lifetime of LEDs becomes relevant because of the higher influence of the manufacturing phase compared to more traditional light sources. All LCA studies were done including assumptions on LED luminaire life time (>15 years). Therefore, from an LCA perspective, the most important parameters that have to be considered in the GPP criteria are the *energy efficiency, durability and lifetime*.

2.4.2. Non-LCA-modelled impacts

The main "non-LCA-modelled" impact associated with road lighting is light pollution. While there are several different definitions of light pollution, it is clear that they all refer to unnatural light caused by anthropogenic activities. The potential adverse impacts of man-made light pollution can be split into the following:

- Skyglow, specifically man-made skyglow (as per CIE 126:1997) with particular importance given to light emitted between the horizontal and 10 degrees above the horizontal. Blue rich light scatters more in the night sky than red light and hence can contribute more to skyglow. Blue rich light tends to have a higher Correlated Colour Temperature.
- Obtrusive light (as per CIE 150:2003) that causes annoyance, discomfort glare or distraction glare which can affect residents in their homes, drivers trying to look ahead and drivers trying to read traffic signals.
- Ecological impact, in the sense that artificial lighting has been shown to affect a wide range of behavioural traits and biological processes including metabolism, foraging, displacement, reproduction, predator-prey dynamics and migrations, across a large number of taxa. The spectrum of the light (visible electromagnetic radiation) emitted may be important.

One key factor for combatting light pollution is to avoid over-lighting roads. A central concept to consider when a lighting level has been decided for a particular road section is that of "***As Low As Reasonably Achievable***" (ALARA) and this may include the possibility to dim lights during low traffic periods.

2.5. Technical analysis

A review of the key components and technology involved in road lighting installations was carried out and the main points are summarised below and are related to the main lamp technologies which are:

- Light Emitting Diodes (LEDs);
- High Intensity Discharge lamps (HID), which include Metal Halide (MH), High Pressure Sodium (HPS) and High Pressure Mercury (HPM); Low Pressure Sodium (LPS) and Compact Fluorescent Lamps (CFLs).

2.5.1. Ballast/control gear/drivers

The purpose of ballasts and control gears is to limit the current supplied to the lamp – this is especially important for HID and LED lamps which cannot be directly connected to a 230VAC source. Ballasts or control gear can be of the magnetic or electronic type. LED lamps require electronic ballasts while HPS and MH lamps can use either electronic or magnetic ballasts. Electronic control gears can offer better power control and lamp ignition for HID lamps, which may be linked to improved lamp survival factors (LSF/F_{LS}) and lamp lumen maintenance factors (LLMF/F_{LLM}). However, the lifetime of magnetic ballasts is very long (30-50 years possible) whereas the failure of the weakest individual component in an electronic control gear (e.g. electrolytic capacitors) can bring about the abrupt failure of a perfectly functioning lamp.

All ballasts for HID cause a loss of some power, which tends to be more significant when the rated lamp power is lower and when smaller loads are applied in dimmable lamps. Minimum ballast efficiencies have been set in the Ecodesign Regulation 245/2009 and also in the existing GPP criteria published in 2012.

2.5.2. Dimming and control systems

Dimming of light output will always reduce the energy consumption of a lighting installation although energy reductions are not perfectly proportional to light reductions because of standby power needs and the operation of control circuits.

It is possible to retrofit dimming systems between an LED module and its control gear. Besides the obvious benefits of reduced energy consumption, dimming controls allow greater flexibility to prevent over-lighting during certain periods of the night. Another possibility with dimming controls is to allow for overdesigned light sources to be used with initial dimming used to prevent over-lighting from new light sources. As the light source output gradually decreases with ageing, the dimming can likewise be decreased to compensate for this. This is also often referred to as constant light output (CLO) control and/or virtual power output (VPO) control.

There are several different control systems available for dimming controls. These controls can operate independently based on a simple timer and programme or feedback from sensors present in the installation or be linked to communication systems that permit remote control by operators. At the more sophisticated end of the spectrum, dimming controls and two-way communication linked to other sensors at the individual luminaire level could play a vital role in intelligent lighting systems as part of smart city networks.

2.5.3. Lamps and light sources

The market analysis revealed the main lamp technologies used in road lighting (i.e. LED, HID, MH, HPS, HPM, LPS and CFL). The key technical considerations for a particular lamp or light source are:

- The luminous efficacy (i.e. light output divided by power consumption)
- The lamp survival factor (i.e. how many abrupt failures in a certain time)
- The lamp lumen maintenance factor (i.e. gradual reduction of light output with ageing of the light source).

Other considerations relate to the colour rendering index and the correlated colour temperature of a lamp but these will be presented in more detail as supporting rationale and background research for proposed light pollution criteria later in this report.

3.5.3.1 Luminous efficacy (η)

The luminous efficacy of light sources tends to increase as the lamp rated power increases. However, while this relationship is clear for HID lamps, it is only partially true for LED lamps. Regulation (EC) No 245/2009 sets minimum luminous efficacy requirements as a function of (i) lamp technology, (ii) nominal lamp wattage and in some cases (iii) if the lamp is "clear" or not (i.e. if frostings or coatings are used to reduce glare) and (iv) the colour rendering index (Ra).

The existing GPP criteria published in 2012 follow the same approach as the requirements of Regulation (EC) No 245/2009 by setting minimum luminous efficacy requirements in core and comprehensive criteria.

When comparing discharge lamp technologies for luminous efficacy, LPS performs very well with 140-170 lm/W (for rated power of 26-66W), CFL produces around 81 lm/W (for a rated power of 36W) and HPM lamps produced only 51 lm/W (for a rated power of 250W).

LED can be considered to perform well in comparison to discharge lamp technologies, with efficacies of 100-175 lm/W for lamps and 100-140 lm/W when considering control gear and optical losses. However, there are also poor examples of LED lamps on the market where the luminous efficacy can be as low as 50 lm/W. One possible reason for this was cited as the reuse of LED chips that had been rejected from high level performance group production lines. Such concerns lend greater value to quality monitoring schemes for LED products like ENEC+ (an independent and pan-European third party certification scheme jointly developed by LightingEurope and the ENEC Mark for the verification of LED-based products). Further advances in LED efficacy can be expected to continue in the near future. A theoretical maximum efficacy of around 300 lm/W for white light is achievable with LED and it would not be unrealistic to expect future road lighting installations to be equipped with luminaires delivering light with an efficacy of >200 lm/W.

3.5.3.2 Lamp Survival Factor (LSF/F_{LS} for HID lamps, Cz for LED lamps)

The terms in the title above refer to the abrupt failure of light sources. Survival factors are expressed as decimals (e.g. 0.8 = 80% unit survival and 0.99 = 99% unit survival) after a defined time period. The term "survival" is considered as not experiencing abrupt failure of the lamp. Abrupt failure can be related to problems with electrical components and circuitry or with the light source itself. An operating period of 1 year for road lighting typically corresponds to 4000h.

Regulation (EC) No 245/2009 sets minimum LSFs for MH (0.8 at 12000 hours) and HPS (0.9 at 12000 hours or 16000 hours depending on the rated wattage). Current BAT is estimated to greatly exceed these minimum requirements (i.e. 0.99 at 16000 hours for both MH and HPS).

For LED technology the term Cz is used instead of LSF/F_{LS}. The Cz term is also linked to a defined time (the abrupt failure fraction as per IEC 62717). A value of C10 at 60000h would mean that after 60000 hours of use, 10% of the lamps have failed.

Actual Cz values for the survival of LED lamps are difficult to predict due to the rapidly developing nature of the technology but in general, LED lamps survive considerably longer than other technologies. This has meant that predictions of LED survival have to be based on extrapolations of test results and should not be considered independently of failure of other components (i.e. control gear components).

<u>3.5.3.3 Lamp Lumen Maintenance Factor (LLMF or F_{LLM} for HID lamps, LxBy for LED lamps)</u>

The terms in the title above refer to the gradual decrease in light output as the light source ages. With the LLMF/F_{LLM} term, values are expressed as a decimal (e.g. 0.8 = 80%) and linked to a specific operating time. A LLMF/F_{LLM} value of 0.85 after 16000 hours means that the light output has decreased by 15% after 16000 hours operation purely due to ageing of the light source.

With LED technologies, the term LxBy is used instead of LLMF/F_{LLM} and is also linked to a defined operating time. A value of L70B50 at 50000h means that after 50000h of operation, 50% of the LED light sources will fail to meet 70% of the initial light output.

2.5.4. Luminaires and Luminaire Maintenance Factor (LMF or F_{LM})

The luminaire is the collective housing for all lamps and light sources, together with any necessary control gear and connections. The luminaire will last longer than any of the components it houses (with the possible exception of magnetic ballasts).

Beyond the fundamental requirement to provide a product that is safe to handle and operate, the two primary functions of the luminaire are to:

i. Distribute the light from the lamp(s) in a manner that fits the lighting installation design needs.
ii. Protect the lamp(s) from potentially damaging external environments (e.g. water ingress and dirt).

The light distribution from a luminaire can be adequately assessed by the provision of a full photometric file. The ability of the luminaire to protect its contents from the environment can be assessed by a standard methodology that results in an "Ingress Protection" (IP) rating being provided (see Annex 5.3 of Preliminary Report for more details).

Luminaires will gradually build up a layer of dust or dirt on its housing which will restrict light output efficacy. With normal discharge lamp technologies, because the lamp needed to be replaced every 2-4 years, cleaning was normally carried out in conjunction with lamp replacement. However, with longer lasting LED lamps, dedicated cleaning cycles will need to be somehow incorporated into the maintenance schedule.

This luminaire pollution effect is taken into account with the Luminaire Maintenance Factor (LMF or F_{LM}) (CIE 154), frequent cleaning and a high IP rating will help to maintain the light output and also results in energy saving. Finally, the Maintenance Factor (MF or F_M) for road lighting is a combination of the lamp maintenance factor F_{LLM} and luminaire maintenance FLM (F_M=F_{LLM}xF_{LM}) (CIE 154).

One key aspect to consider is the reparability (or serviceability) of an LED luminaire. The primary distinction between a repairable and non-repairable LED luminaire is the ability to open the luminaire with normal service tools and to remove and replace electronic components and the lamp itself.

3. Summary of main changes from previous TRs

The purpose of this section is to explain to readers how the draft Technical Report (TR) evolved during the revision process.

Table 1. Comparison of criteria structure in TRs 2.0, 3.0 and 4.0.

TR 2.0	TR 3.0	TR 4.0
Road lighting	**Road lighting**	**Road lighting**
		Preliminary assessment
		CPC1 – Assessment of road lighting infrastructure and ancillary equipment
Selection criteria	**Selection criteria**	**Selection criteria**
SC1 – Competencies of the design team	Same as TR2.0	Same as TR2.0
SC2 – Competencies of the installation team	Same as TR2.0	Same as TR2.0
CPC1 - Assurance of adequately qualified staff responsible for project	Same as TR2.0	CPC2 (Same as TR2.0)
Energy efficiency	**Energy efficiency**	**Energy efficiency**
TS1 – Luminaire luminous efficacy	Same as TR2.0 but with distinction of ambition level based on light output.	Same as TR2.0. Distinction of ambition level based on light output removed.
AC1 – Enhanced luminaire luminous efficacy	Same as TR2.0	Same as TR2.0
CPC2 - Provision of originally specified lighting equipment	Same as TR2.0	Deleted as already covered by CPC5.
TS2 – Dimming control capability	Same as TR2.0	Same as TR2.0
TS3 – Minimum dimming performance	Same as TR2.0	Same as TR2.0
CPC3 – Dimming Controls	Same as TR2.0	Same as TR2.0
TS4 – PDI	Deleted	Deleted
TS5 – AECI	Now TS4. Same as TR2.0	Same as TR2.0
AC2 – Enhanced AECI	Same as TR2.0	Same as TR2.0
TS6 – Metering	Now TS5. Same as TR2.0	Same as TR2.0
		TS 6 Power Factor
CPC4 - Commissioning and correct operation of lighting controls	Same as TR2.0	Same as TR2.0
CPC5 - Provision of originally specified lighting equipment	Same as TR2.0	Same as TR2.0
CPC6: Compliance of actual energy efficiency and lighting levels with design claims	Same as TR2.0	Same as TR2.0
Light pollution	**Light pollution**	**Light pollution**
TS7 – Ratio of Upward Light Output	Now TS6. Same as TR2.0 plus flux code requirement	Now TS7. Same as TR 3.0. Flux code req. now comp. only.
TS8 – Ecological light pollution and annoyance	Now TS7. Same as TR2.0 plus G-Index requirement	Now TS8 and just about annoyance (CCT).
		Now TS9 and just about ecological light pollution and (for comp. level, star visibility).
Lifetime	**Lifetime**	**Lifetime**
TS9 – Provision of instructions	Same as TR2.0	Same as TR2.0
TS10 – Waste recovery	Same as TR2.0	Same as TR2.0
CPC7 – Commitment to waste recovery and transport to suitable sites	Same as TR2.0	Same as TR2.0
TS11 – LED lamp product lifetime, spare parts and warranty	Same as TR2.0	Same as TR2.0 but reference to IEC 62722 and 63013 removed.
AC3 – Extended warranty	Same as TR2.0	Same as TR2.0
TS12 - Reparability	Same as TR2.0	Same as TR2.0 but reworded.
TS13 – Ingress Protection (IP rating)	Same as TR2.0	Same as TR2.0
TS14 – Failure rate of control gear	Same as TR2.0	Same as TR2.0
	TS14 – Labelling of LED luminaires	Now TS16. With G-Index added to list.
	CPC8 – Labelling of LED luminaires	Same as TR 3.0.
Traffic signals	**Traffic signals**	**Traffic signals**
TS1 – Life Cycle Cost	Same as TR2.0	Same as TR2.0
AC1 – Lowest Life Cycle Cost	Same as TR2.0	Same as TR2.0
TS2 – Warranty	Same as TR2.0	Same as TR2.0 but reference to IEC 62722 and 63013 removed.
AC2 – Extended warranty	Same as TR2.0	Same as TR2.0
		AC3 – Dimming controls

From TR 1.0 to TR 2.0

The main differences between TR 1.0 and TR 2.0 can be explained both at the level of the criteria structure and at the level of the criteria content.

In TR 1.0, criteria were grouped by project stage (e.g. design, installation, lighting equipment etc.) whereas now they are grouped by criteria area (i.e. selection criteria, energy efficiency, light pollution and lifetime).

The scope was reworded to specifically exclude certain applications such as tunnel lighting and car parks, which are covered by specific technical standards.

With selection criteria, the main change was that requirements were detailed better in TR 2.0 and set to apply to the person from the contractor who signs off the project (i.e. takes responsibility). It was considered unfair to set minimum requirements for all staff working for the contractor as it would limit opportunities for new staff to get involved. A CPC was inserted to make sure that the competencies are actually available within the contractor team to cover cases when staff changes between the award of the contract and execution of the works may occur.

The approach to PDI and AECI was completely reworked and a new way of linking luminaire efficacy, maintenance factor and utilance was established that would allow for a simplified calculation of PDI. No actual reference values were set for PDI as it was left up to the procurer to define this (it would be influenced by factors such as road width and luminaire efficacy).

For luminaire efficacy, the major change was to move away from a single fixed value to a reference value that would be raised every 2 years in order to reflect the continuing improvements in LED luminaire efficacies.

With regards to light pollution, in TR 1.0 requirements were set for RULO <1% and, for comprehensive level, that CCT would be <3000K and CRI <70. In TR 2.0, the RULO requirements were tightened to 0% and CCT was set at <3000K (core) or <2700k (comprehensive). Furthermore, a limit of blue light output was set for the comprehensive criterion. A greater emphasis on dimming was evident in TR 2.0 by not just requiring compatibility with dimming but to actually install dimming controls (except under limited circumstances).

With lifetime criteria, the warranty of 10 years set out as a TS in TR 1.0 was split into a shorter warranty TS in TR2.0 but complemented by an AC for longer warranties – which would allow those producers offering longer warranties to be more competitive.

The award criterion for life cycle costing was removed because, depending on how financial offers are submitted, it could result in double rewarding of the cheapest offer. In any case, it is recommended that the basis for any investment in lighting installations should be supported by a strong case for delivering lower life cycle costs than a business as usual scenario.

From TR 2.0 to TR 3.0

The main differences between TR 2.0 and TR 3.0 were related to the nuancing of ambition levels for luminaire efficacy (lower ambition level for low power LED luminaires), the removal of a dedicated criterion for PDI (now simply a table of reference PDI values is provided), a new requirement for CIE flux code #3 being at least 95 (to encourage better luminaire shielding that reduces risk of glare and skyglow and may improve the actual maintenance factor) a different requirement relating to blue light content (the G-Index is proposed because CCT is not a perfect measure of blue light) and the requirement for labelling of LED luminaires (to ensure that public authorities can keep track of installed LED infrastructure as the technology continues to evolve rapidly).

From TR 3.0 to TR 4.0

A number of changes have been incorporated into TR 4.0 based on feedback received during the written stakeholder consultation. The main changes are summarised below.

An improved explanation of the different types of work which are relevant to the application of these GPP criteria has been provided in this chapter.

With the luminaire efficacy requirements in chapter 7, a reassessment of the LightingFacts database, focussing especially on the data from 2016-2018, has shown that there is no statistically significant relationship between light output and LED luminaire efficacy. Results for low powered lamps were predominantly associated with much older data (and thus less efficient data). The new analysis therefore contradicts the conclusion reached following the data analysis in TR 3.0 and justifies the removal of any nuancing of luminaire efficacy ambition level as a function of light output. The tiered approach to increasing the ambition level remains in place with core level being set at 120 lm/W in 2018-19 and comprehensive level being set at 130 lm/W in 2018-19. The ambition levels then increase by 17-18 lm/W every two years.

The reference PDI values (and thus the AECI reference values) have changed slightly due to some adjustments to the utilance factors associated with both core and comprehensive level.

The reassessment of the LightingFacts database clearly showed that warmer LED with CCT <2700K is significantly less efficacious than LED >2700K (about 20 lm/W lower (ca. 20%). Consequently, if lower than 2700K light sources are specified, the luminaire efficacy or AECI criteria should be revised downwards by at least 20%.

Decorative luminaires appeared to show an even greater energy penalty (about 30-45 lm/W lower, or ca. 30-45%) than low CCT light sources but this observation was mainly due to pre-2017 data. Looking at the 2017 and 2018 data only, there seems to be no significant distinction between the efficacies of standard and decorative luminaires. Consequently, it is no longer recommended to exempt decorative luminaires from the criteria relating to luminaire efficacy or AECI.

With regards to light pollution criteria, the RULO criterion (TS6) has been reworded to make it clear that the 0.0% limit applies to the luminaire in the position in which it is to be placed, whether that is horizontal to the road surface or with a tilt angle.

The criterion for "Ecological light pollution and annoyance" (TS7), which contained an "and/or" approach to CCT and the G-Index has been split into two parts:

- TS7: Annoyance (with a requirement on CCT and suggestions on dimming – since these are both directly related to the perception of humans).
- TS8: Ecological light pollution (with a requirement on the G-Index and suggestions on dimming – since these are both directly related to impact on nocturnal species).

With lifetime criteria, the term B_y has been removed from requirements relating to L_xB_y since L_x is the most important aspect. For the same criterion, testing according to IEC standards for projected data has been removed from the assessment and verification text since this is no agreed procedure is in place for extrapolating the data. The term L_0 has been removed from the L_0C_z requirements since it is considered redundant. These changes have also been applied to the equivalent criteria for traffic signals.

4. Scope of criteria

Stakeholder discussion

Initial stakeholder input about the scope was received in the form of responses to the initial scoping questionnaire. Some of the main findings were:

Table 2. Summary of responses from questionnaire (16 responses)

Scoping question	Yes	No	No opinion
Should the scope continue to be aligned with EN 13201?	9.5	5.5	1
Should the scope continue to include traffic signals?	4	4	8
Should there be specific criteria for LED retrofit situations?	10	6	0
Should there be criteria for poles?	3	12	1
Should there be criteria or power cables?	1	11	4
Should there be criteria for metering or billing?	10	5	1
Should there be specific criteria for LED luminaires?	15	1	0

A minority of stakeholders wanted to extend the scope of the product group beyond EN 13201 to include other applications such as parking lots and other areas in commercial and industrial zones. However, when discussing issues such as the calculations for PDI and AECI values for energy efficiency, it quickly became apparent that it would be complicated to set particular ambition levels for energy efficiency for these types of lighting installations.

Some stakeholders criticised the alignment with EN 13201 in the scope because they felt that the standard encourages over-lighting of roads when compared to current typical practice in many EN Member States. However, JRC emphasised that the alignment of the scope with EN 13201-2 does not in any way imply that the EN 13201-1 guidance for setting lighting levels for each road class are to be followed or complied with by procurers who wish to apply the EU GPP criteria. EN 13201-1 simply provides guidance for how to define what class of road you have and then suggests minimum lighting levels for each road class. The choice of lighting levels is ultimately up to the procurer and will be influenced by local, regional or national planning rules. Lighting levels will always be nuanced by site specific factors such as the need for vertical lighting and facial recognition, pole heights, the use of decorative luminaires in residential areas and historical areas and the potential for obtrusive light. The JRC encourage that procurers wishing to follow the EU GPP criteria follow the ALARA (As Low As Reasonably Achievable) principle when deciding on required lighting levels.

Most respondents had no opinion on whether to include traffic signals in the scope or not. All specific comments from respondents on this matter are presented below:

Table 3. Comments about traffic signals received from respondents

<table>
<tr><th>For traffic signals in scope</th><th>Against traffic signals in scope</th></tr>
<tr><td rowspan="3">Yes, sadly, there still seems to be a market for halogen traffic signals among municipalities, perhaps due to controls or some other factor. This also allows for a detailed review and further improvement in the criteria, including for example efficacy, materials, lifetime and so-on which would no longer be addressed if they were taken out of scope.</td><td>I would remove traffic signals as street lighting is quite different area.</td></tr>
<tr><td>Yes, it would be better to have specifications for street lighting in one (standing alone) document because of different technical system.</td></tr>
<tr><td>Too many documents will increase the complexity and make it harder to keep the document actual.</td></tr>
</table>

Discussions with stakeholders during the project so far have revealed that experience of the group is almost exclusively with road lighting applications instead of traffic signals. While it was quite clear that traffic signals is a separate area of expertise from road lighting and that the background research for one is not automatically valid for the other, the impacts associated with energy consumption of traffic signals was not insignificant (see C40 cities and COMPETENCE references). This fact, coupled with the knowledge that there is no other product group where traffic signals would be included in the foreseeable future led to the decision to keep traffic signals in the scope.

Other feedback revealed that there was a strong demand for criteria specifically about LED luminaires and that there should be no criteria for poles and cables. There was also a reasonable level of support to include criteria for metering and for LED luminaire retrofit situations. New criteria have been proposed for LED luminaires and metering.

The evolution of scope proposals for the product group in versions 1.0, 2.0, 3.0 and 4.0 of the TR are presented in Table 4 below.

Table 4. Scope for existing EU GPP criteria

<table>
<tr><th>Road lighting and traffic signals</th><th>Road lighting</th></tr>
<tr><td colspan="2">Technical report 1.0 (October 2016)
Road lighting: fixed lighting installation intended to provide good visibility to users of outdoor public traffic areas during hours of darkness to support traffic safety, traffic flow and public security according to standard EN 13201-2 road classes on road lighting including similar applications as used for car parks of commercial or industrial outdoor sites and traffic routes in recreational sports or leisure facilities”
Traffic signals: red, yellow and green signal lights for road traffic with 200mm and 300mm roundels according to EN 12368. Portable signal lights are specifically excluded.</td></tr>
<tr><td colspan="2">Technical Report 2.0 (July 2017)
Road lighting: In accordance with EN 13201-2, the term road lighting refers to fixed lighting installations intended to provide good visibility to users of outdoor public traffic areas during hours of darkness in order to support traffic safety, traffic flow and public security.
Specifically excluded are lighting installations for tunnels, toll stations, canals and locks, parking lots, commercial or industrial sites, sports installations, monuments and building facades.
Traffic signals: red, yellow and green signal lights for road traffic with 200mm and 300mm roundels according to EN 12368. Portable signal lights are specifically excluded.</td></tr>
<tr><td colspan="2">Technical Report 3.0 (March 2018)
Road lighting: The scope of these criteria covers the procurement of lighting equipment for road lighting in new lighting installations, for retrofitting of existing lighting installations, or the replacement of light sources, lamps or luminaires on a like-for-like basis in existing lighting installations.
In accordance with EN 13201-2, the term road lighting refers to fixed lighting installations intended to provide good visibility to users of outdoor public traffic areas during hours of darkness in order to support traffic safety, traffic flow and public security.
Specifically excluded are lighting installations for tunnels, toll stations, canals and locks, parking lots, commercial or industrial sites, sports installations, monuments and building facades.
Traffic signals: red, yellow and green signal lights for road traffic with 200mm and 300mm roundels according to EN 12368. Portable signal lights are specifically excluded.</td></tr>
<tr><td colspan="2">Technical Report 4.0 (June 2018)
Road lighting: The scope of these criteria covers the procurement of lighting equipment for road lighting in new lighting installations, for retrofitting of different luminaires to existing lighting installations, retrofitting of different light sources to existing luminaires or the simple replacement of light sources, lamps or luminaires on a like-for-like basis in existing lighting installations.
In accordance with EN 13201-2, the term road lighting refers to fixed lighting installations intended to provide good visibility to users of outdoor public traffic areas during hours of darkness in order to support traffic safety, traffic flow and public security.
Specifically excluded are lighting installations for tunnels, toll stations, canals and locks, parking lots, commercial or industrial sites, sports installations, monuments and building facades.
Traffic signals: red, yellow and green signal lights for road traffic with 200mm and 300mm roundels according to EN 12368. Portable signal lights are specifically excluded.</td></tr>
</table>

The final scope text published in the SWD(2018) 494 is as follows:

Road lighting: *These criteria cover the procurement of lighting equipment for:*

- *road lighting in new lighting installations;*
- *retrofitting of different luminaires to existing lighting installations;*
- *retrofitting of different light sources or controls to existing luminaires; or*
- *the simple replacement of light sources, lamps or luminaires on a like-for-like basis in existing lighting installations.*

In accordance with standard EN 13201-1, the term 'road lighting' refers to fixed lighting installations intended to provide good visibility to users of outdoor public traffic areas during the hours of darkness to support traffic safety, traffic flow and public security.

It specifically excludes lighting installations for tunnels, toll stations, canals and locks, parking lots, commercial or industrial sites, sports installations, monuments and building facades.

The following technical definitions are provided to help apply the criteria (please refer to the technical report for details and further technical definitions):

'luminaire efficacy': ratio between luminous flux output from the luminaire (in lumens) and power consumption (in Watts)

***Traffic signals**: Red, yellow and green signal lights for road traffic with 200mm and 300mm roundels, in line with standard EN 12368, are included. Portable signal lights are specifically excluded.*

By referring to EN 13201-1 in the product group scope, it is implied that all of the road classes defined therein are included. The standard splits roads into three broad classes (M, C or P) and grades (e.g. M1-M6, C0-C5 and P0-P5) based on the main types of road user, the volume of traffic, speed limits for vehicles and road geometries.

4.1. Different applications for road lighting criteria

All municipalities and road authorities require road lighting to some degree and public procurement activities may cover one or more of the following areas:

a. **New installation:** Where a lighting installation is put in place for a newly built outdoor public traffic area (road or pathway).

b. **Refurbished installation:** Where the number of poles, the pole positioning and luminaire/light sources of an existing lighting installation are significantly modified for the lighting of an existing outdoor public traffic area.

c. **Luminaire retrofit:** Where the existing poles and wiring remain in place but existing luminaires are removed and replaced with new luminaires (and usually new light sources too). (If the new luminaires have a different power rating than the old luminaires, then changes to the power supply components external to the luminaire may also be necessary).

d. **Light source retrofit:** Where the existing poles and luminaires remain in place but lamps/light source are removed from the luminaires and replaced with a different type of lamp/light source. (If the new lamp/light source has a different power rating than the old lamp/light source, then changes to the power supply components within or external to the luminaire may also be necessary).

e. **Lighting control retrofit:** Where the existing light sources, lamps and luminaires remain in place but additional controls are installed (e.g. for dimming, for constant light output, daylight monitors, for remote data reporting or switches linking to motion sensors). Lighting controls may also be added as part of luminaire or light source retrofits.

f. **Lamp replacement:** Where existing lamps are replaced on a like for like basis.

For new installations, the approach is quite straight-forward in the sense that a design will be needed which will specify the optimum placement of poles and the luminaire mounting heights and tilt angles. When specifying luminaires and light sources, it is enough to simply look at what are the better performing products on the market and set the energy efficiency criteria accordingly. The design of a new system may be carried out by the contracting authority's in-house staff, by a street lighting contractor or by an independent lighting designer. The installation work is usually carried out by a contractor.

Existing installations will represent the vast majority of procurement exercises in Europe. Due to the continual improvements in energy efficiency of LED lighting technology in the last 5 years and rapidly decreasing costs, procurers with HID lamps in their lighting installations are under pressure to consider alternatives (i.e. points b, c or d above) instead of simply buying the same lamps as before to replace old ones (i.e. point e above).

The overall approach to the EU GPP criteria is illustrated in Figure 4. In cases where the road lighting installation already exists, the procurer is recommended to do a quick preliminary estimation of the luminous efficacy or PDI or AECI of existing installed road lighting light sources and/or luminaires. If the result is that the existing light sources have a very high luminous efficacy already, this may be sufficient justification to simply relamp the installation. However, in cases where there are doubts about the energy efficiency of the existing installation, any relamping scenario should be costed and checked against life cycle costs of LED retrofitting or redesigns using estimated energy efficiency data. These preliminary assessments do not form part of the EU GPP criteria themselves but may be of high importance to installations with a history of poor record-keeping and management.

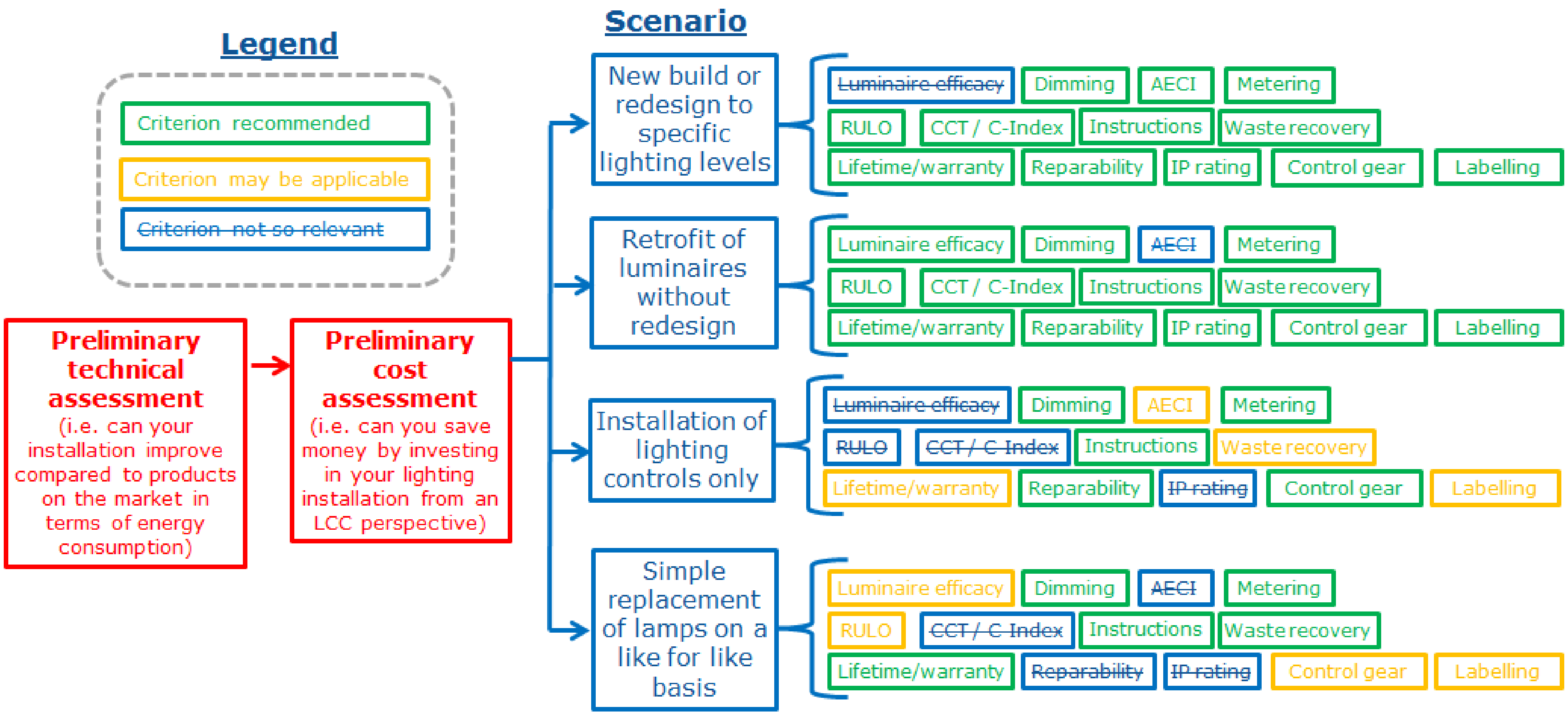

Figure 4. Overview of approach to GPP criteria for the product group "road lighting"

The preliminary assessments aim to first know how energy efficient the current installation is and second, to determine what kind of savings (energy and cost) are possible with the different options (i.e. redesign with new luminaires, luminaire replacement or only light source/controls replacement).

As can be seen in Figure 4, there are three main options for procurement. For each option, criteria are split into one of three groups: Energy Efficiency, Product Lifetime and Light Pollution. Criteria in green are considered as being highly relevant, those in orange as potentially relevant and those in blue and strikethrough as not so relevant, depending on the situation.

The top option is the most comprehensive because a lighting design (or redesign) is required. This option is most likely for any new roads and major renovation of existing roads which are heavily trafficked and where speed limits and conflict areas represent a sufficient risk to road users. In countries and regions where road lighting classes are specified for the road in question, then a re-design will inevitably be required.

The middle and bottom options are more likely to apply to smaller roads and P class roads (i.e. predominantly for pedestrians) with lower required lighting levels or where minimum lighting classes and other characteristics defined in EN 13201 are not stipulated by regional or national legislation.

The criteria for road lighting are split into three broad criteria groups: energy efficiency, light pollution and product lifetime and durability.

For a given criteria area, minimum technical specifications and/or award criteria are provided together with any notes that explain in what situation these should apply/not apply. When there is an obvious need for a contract performance clause (CPC), a suggested CPC is also provided.

Each criterion is preceded by sections about relevant background research, supporting rationale and stakeholder discussion. Closely related criteria may be grouped together with a common background research and stakeholder discussion.

4.2. Lighting infrastructure preliminary assessment

The lighting networks of municipalities and many road authorities have evolved in a piecemeal fashion over several decades. The typical lifetime of road lighting poles and some luminaires can exceed 30 years. The replacement of HID lamps is a much more frequent operation and there are only a limited number of standard wattages available (e.g. 50W, 70W, 110W). The replacement of individual lamps due to abrupt failures and the gradual shift towards LED lamps of varying wattages and dimming programmes makes it a real challenge for authorities to keep up to date with the current status of their lighting assets.

To compound this problem, most authorities do not have dedicated metering or billing for electricity consumed by the lighting infrastructure.

In order to optimise investment in new lighting equipment, it is crucial for the public authority in question to have a clear understanding of existing asset performance. The clearer this understanding, the more accurate will be any cost-benefit exercise of different management strategies and procurement activities related to road lighting.

An overall picture is needed for the entire road lighting network as well as each sub-installation. Basic information should be the number of light points, luminaire specifications (efficacy, upward light output, year of installation), lamp details (technology, rated power, CCT, model, year of installation) and auxiliary electrical equipment (ballast/driver, dimming controls etc.).

While all public authorities will have a reasonable idea of the status of their currently installed lighting assets, this preliminary assessment is particularly recommended in cases where road lighting specific metering and billing for consumed electricity is inadequate.

The scope of this preliminary work would be limited to the existing asset assessment alone and not be directly linked to any Invitation to Tender for the procurement of road lighting equipment.

CPC1 Preliminary assessment of existing lighting infrastructure and installation of dedicated metering.
(Same for core and comprehensive criteria.) ***(This contract should be considered a standalone preliminary procedure. It is not directly linked to any subsequent procurement exercises for the purchase of road lighting equipment or to the EU GPP criteria set out later in this document. This preliminary assessment should apply only when the procuring authority identifies the need to improve knowledge about their existing installed road lighting assets; when there is a need to install road lighting-specific electricity metering; or when the procurer decides not to use in-house staff to carry out this assessment.)*** The currently installed road lighting assets identified by the procurer within a defined area must be assessed for the following aspects: • mapping of light points and assignment of unique light point ID numbers (if not already done); • luminaire model, efficacy, ratio of upward light output and year of installation (where information is available); • lamp technology, rated power, correlated colour temperature (CCT) and year of installation; • presence/absence of dimming controls. The entire lighting network shall be split into sub-areas (if not already previously done by the procuring authority) and each sub-area shall be assessed to determine if specific metering of road lighting electricity consumption is in place. In cases where specific metering is not in place, new meters and, if necessary, junction boxes shall be installed. Once the appropriate metering has been installed, records shall be kept of the electricity consumption attributable to road lighting operation in each defined sub-area. This information shall then be used by the procurer as a basis for any future cost-benefit analyses when considering the procurement of new lighting equipment.

4.3. Contracting of lighting or energy services

The traditional approach to road lighting procurement has been that municipal authorities or road authorities procure the road lighting equipment and take ownership of the infrastructure. These same authorities take ultimate responsibility for maintenance of the lighting assets, which is carried out either by in-house skilled staff or sub-contractors.

The installation of new lighting poles and associated electrical infrastructure is normally a significant cost that appears as relatively minor when included in much larger projects such as new road construction or the development of commercial or residential areas.

However, the situation with existing road lighting infrastructure is different. The combination of tightening public annual expenditure budgets, limited availability of capital and the potential for major long term energy savings via significant investment in new LED technology has made a new procurement approach attractive: **the procurement of lighting services**.

Key terminology such as LaaS (Lumens as a Service) and ESCO (Energy Services COmpany) may be used. These types of contract tend to focus on the retrofitting of existing installations and would, as a minimum, need to define the following aspects:

- Design light levels to be achieved, how to monitor them in-situ and actions to take if light levels are too high or too low.
- Minimum luminaire efficacy requirements or maximum installed capacity allowed.
- Duration of the contract.
- Price per lumen on the road.

The price per lumen on the road would be the factor that is used to identify the winning tender. For the tender to be acceptable, it would need to result in cost savings for the public authority. A direct comparison with operating costs for the lighting installation for the old and the new system is not completely fair. The avoided capital investment for the public authority should ideally be factored in.

Monitoring of the in-situ light level is an important consideration because there will be a natural incentive to dim as much as possible during curfew hours for both parties, but it is important that the contractor must not dim to lower light levels than the procurer has asked for without their express permission.

There are a number of specific technical factors that may, if defined by the procurer, limit the availability of products that tenderers can choose from, potentially compromising their ability to deliver the lowest price per lumen.

- Minimum requirements on luminaire efficacy will have an effect on the price per lumen because there is a direct relationship between energy consumption and price per lumen. However, too strict a requirement may result in higher prices if more expensive lamps or luminaires are needed to meet them.
- Minimum requirements on light pollution could have a significant effect on price per lumen because they will limit the availability of products to choose from but not deliver any operational cost savings that can be translated into a lower price per lumen.
- Minimum requirements on product durability could have some effect on the price per lumen because they will limit the availability of products to choose from and more durable products tend to be associated with higher quality components that will be more expensive. However, the choice of ESCO contract duration would have a much clearer impact than any product specific durability requirement.

Especially with any light pollution-related technical requirements, in order to continue incorporating these in lighting or energy service-based procurement models, it would be recommended to include these as award criteria.

5. Selection Criteria

As stated earlier in the introduction, selection criteria apply to the tenderer and should focus on aspects related to the capability of the tenderer to meet to the requirements of the contract, should they be successful in the bidding process. Selection criteria presented here focus on technical aspects.

5.1. Background research and supporting rationale

For lighting installation design teams

In order to properly design a road lighting installation, a thorough knowledge of the current market and underlying trends, the EN 13201 standard series, lighting design software and installation practices is needed. Furthermore, a good understanding of the planning and approval processes of outdoor lighting installations will be needed. These processes will be subject to national spatial planning and road legislation and which may fall under the responsibility of municipalities or other authorities. Therefore, this criterion requests evidence to prove that the tenderer will meet clear minimum requirements that will help demonstrate that they have the required know-how and range of competencies to successfully design a new or renovated lighting system. It is also worth highlighting the recent introduction and recognition of the degree of European Lighting Expert in several countries, which could potentially be used as a reference in relevant countries.

For teams installing lighting equipment

The same rationale as for the selection criteria for the design team applies to the selection criteria for the installation team. In order to properly install a road lighting installations, the team should have a good knowledge of how to open, place and connect lighting fixtures and how to commission a controlled lighting point. Therefore this criterion searches for evidence to prove that the required skills are available for the service requested.

Aspects common to designers and installers

In both selection criteria, requirements should not be too stringent as to present a barrier to the market for new or emerging companies. For this reason, the minimum requirements for experience are limited only to the senior member of staff working for the tenderer who will ultimately sign off any final design or approve the adequacy of any installation works.

The level of experience can be misleading if only considered in terms of time. Thus it is also important to allow for the recognition of the number of projects and scale of projects as part of experience in tenderer teams.

In some cases, a successful tenderer may sub-contract a more experienced consultant to check and approve their design. In such cases, the tenderer may simply commit to contracting such a consultant should they be awarded the contract but without knowing precisely who that consultant would be yet. Even if a sufficiently qualified member of staff is already directly employed by the tenderer, they may leave the company before the contract is undertaken. For these reasons, it is important that the selection criteria are also covered by a contract performance clause.

5.2. Stakeholder discussion

One point that was raised was the lack of any mention of specific lighting design software when stating minimum experience and requirements for the design team or designer. It was added that in some cases the use of different software for the same design can generate variations in the final results although the scale of these variations is uncertain.

One of the basic principles of EU GPP criteria is to try to remain impartial with respect to selection criteria and so it would not be recommendable to stipulate a specific software program and not another one that can be used for the same purpose. However, if the procurer has a history of working with designs using particular software, then they are of course free to specify this in their individual ITT – but one particular piece of software cannot be promoted over others in EU GPP criteria.

Another discussion point was to try to be more specific about the quantity of relevant experience for installers and designers. The need to strike the right balance between a certain minimum experience and unintentionally creating barriers to potential tenderers was emphasised. One potential solution is to place quite stringent requirements only on the person who will finally check, approve and sign off the lighting design / installation work.

An earlier proposal of requiring a minimum amount of time in the job (i.e. 3 years) was criticised because it does not guarantee that lots of relevant project experience has been gained. The other proposal to require a minimum number of completed projects is not perfect either, allowing the possibility that 2 small short-term projects are valued more than 1 major long-term project. For this reason, a clause has been inserted to allow the procuring authority to accept experience in a lower number of projects if they are of a sufficient scale.

Support was expressed for recognising the membership of professional bodies as it ensures that the individuals undergo continuous professional development and can easily be checked. Nonetheless, other experience and qualifications should not be ruled out. One example mentioned was the Lighting Certificate course run by the UK Lighting Industry Association. However, the usefulness of asking for experience with validating software according to CIE 171 was questioned because it deals with indoor lighting and daylight conditions but not with road surface reflectance and thus luminance calculations.

The other main discussion point was the risk that tenderers insert the names of highly qualified individuals simply to pass the selection criteria but then, if awarded the contract, they would then go and employ someone less qualified, either to save costs or due to the unforeseen unavailability of the original person/people. For this reason, a contract performance clause covering this potential situation has been inserted.

5.3. Proposed selection criteria

Core criteria	Comprehensive criteria
SC1 - Competencies of the design team	
(Applies when a lighting design is requested in the procurement exercise.) *(Same for core and comprehensive criteria.)* The tenderer shall demonstrate that the design will be checked and approved by staff with the following minimum experience and qualifications: • at least three years' experience in lighting design, dimensioning of electrical circuits and electrical distribution networks, • involvement in the design of at least three different outdoor lighting installations, • a certified level of competency in the use of lighting design software for power density indicator (PDI) and annual energy consumption indicator (AECI) calculations (e.g. European Lighting Expert certificate), • experience with the use of validated lighting calculation software (e.g. according to CIE 171, road surface reflectance tables or other relevant standards), • holding a suitable professional qualification in lighting engineering or membership of a professional body in the field of lighting design. **Verification:** The tenderer shall supply a list of the person(s) who will be responsible for the project should the tender be successful, indicating their educational and professional qualifications, relevant design experience in real projects and, if relevant, experience in and the name of any lighting design software used. This should include persons employed by subcontractors if design work is to be subcontracted. The procuring authority, at its own discretion, may accept experience in less than three lighting installation designs if the scale of the design project(s) was sufficiently large (i.e. amounting to at least 70% of the scale of the design project that is the subject of the invitation to tender), and the duration was sufficiently long (i.e. amounting to at least three years).	

Core criteria	Comprehensive criteria
SC2 - Competencies of the installation team	
(Applies when responsibility for installation is not assumed by the procuring authority's own maintenance staff.) *(Same for core and comprehensive criteria.)* The tenderer shall demonstrate that the installation works will be planned, checked and approved by personnel with the following minimum experience and qualifications: • at least three years' relevant experience in the installation of outdoor lighting systems, • involvement in the installation of at least three different installation projects, • a suitable professional qualification in electrical engineering and membership of a professional body relevant to the work they are undertaking (e.g. certified lighting technician). The list of relevant installed lighting systems with the relative 'scale of the project' should be reported. **Verification:** The tenderer shall supply a list of person(s) responsible for the installation works should the tender be successful, indicating their educational and professional qualifications,	

training logs and relevant installation experience in real projects. This should include persons employed by subcontractors if installation work is to be subcontracted. The procuring authority, at its own discretion, may accept experience in less than three lighting installation works if the scale of the works was sufficiently large (i.e. amounting to at least 70 % of the scale of the design project that is the subject of the invitation to tender), and the duration was sufficiently long (i.e. amounting to at least three years).	
Core criteria	**Comprehensive criteria**
CPC2 – Assurance of adequately qualified staff to carry out contracted tasks	
(Applies to SC1 and SC2.) *(Same for core and comprehensive criteria.)* The successful tenderer (contractor) shall ensure that the personnel mentioned in the documentation provided to demonstrate compliance with SC1 and/or SC2 are indeed involved in the works covered by the contract. In cases when the personnel originally assigned to the project are not available, the contractor must communicate this to the procuring authority and provide a substitute or substitutes of equivalent or higher experience and competency. Proof of the qualifications of any substitute personnel shall be submitted in the same manner as described in SC1 and/or SC2, as appropriate.	

6. Energy consumption criteria

For any given lighting level requirement in an installation, there is a clear link between environmental benefits and improved energy efficiency of light sources and luminaires. Cost saving is also a clear driver for improved energy efficiency although in this respect care has to be taken to focus on life cycle costs and not simply operational costs. As the market for LEDs in outdoor lighting matures, capital costs are decreasing all the time and, as electricity costs continue to increase, the relative importance of energy efficiency in life cycle cost calculations increases too.

Due to the importance of energy efficiency criteria on both environmental and economic aspects, a minimum cut-off requirement is proposed as a technical specification and an award criterion is proposed in order to encourage tenderers to go further.

A potential contract performance clause is also provided to ensure that the lighting installation actually delivers on the minimum energy efficiency and lighting requirements stated in the winning tender. Arguably the best way to ensure compliance with predicted energy consumption performance is to have a metering system for the lighting installation split by defined zones or even to monitor power consumption at the level of the individual luminaire which could be reported automatically to a remote system.

Apart from more efficient lighting, attention must be paid to the potential savings via the use of dimming controls to reduce light output, and thus energy consumption, during programmed periods of expected low road use. The importance of dimming is reflected in a technical specification for compatibility of light sources and luminaires with dimming controls and minimum % dimming capabilities.

For each energy efficiency criterion, a note is placed to explain under which circumstances the criterion should be applied, e.g. when designing new installations, re-designing existing installations or simply re-lamping of an existing installation.

The importance of energy efficiency

There is broad agreement in the life cycle assessment literature that the dominant source of LCA environmental impacts associated with road lighting is electricity consumption during the use phase. The outputs of studies in the literature generally follow the same tendency as given below in Figure 5.

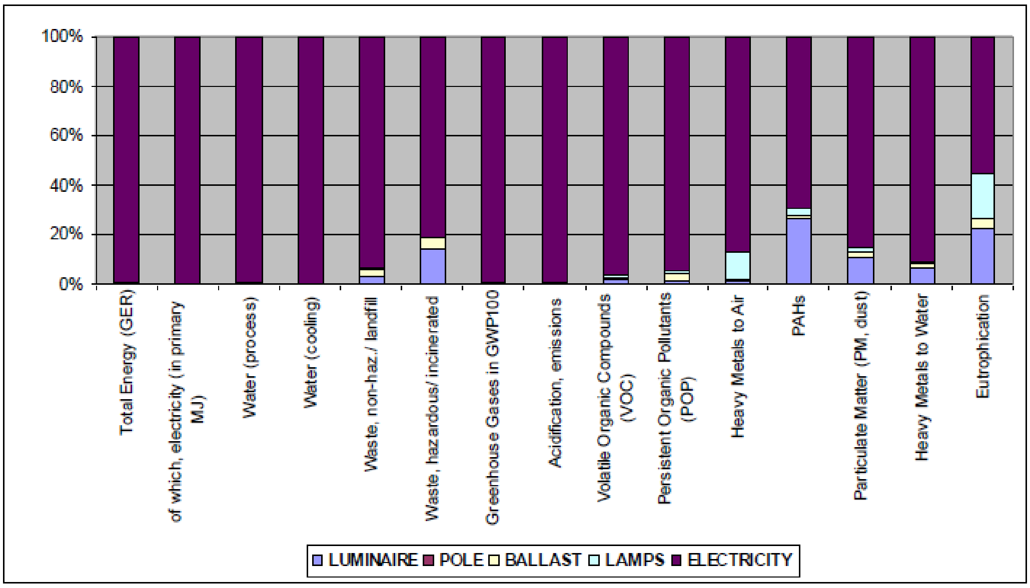

Figure 5. Breakdown of the life cycle environmental impacts of road lighting (Van Tichelen et al., 2007)

Despite this clear relationship, it is worth noting that as lamp technologies become more energy efficient, impacts associated with materials used may become relatively more important. This will ultimately depend on the environmental footprint of the specific materials used, the lifetime over which the lamp and other components can be expected to last and the potential for reuse and recycling of materials.

Per capita energy consumption of municipalities and regions

During stakeholder discussion, the possibility of setting an EU GPP criterion based on the per capita energy consumption of public lighting was raised. The indicator has been promoted via the Covenant of Mayors (COM) initiative. The indicator is quite simple and is calculated by dividing the total annual power consumption (kWh) of public lighting by the population of the same region. It is possible that in areas where energy bills are not well disaggregated, some assumptions will be made based on the installed power of public lighting (kW) and on assumptions about their operating conditions made (e.g. number of hours per day and average dimming).

Although the JRC dismissed the idea of inserting such a criterion in ITTs for a number of reasons, it was agreed that it could be interesting to investigate this subject further in order to gain an understanding of how per capita electricity consumption due to public lighting can vary in different regions. Data provided by stakeholders was as follows:

- Spain: national average 116 kWh/pe/yr
- France: national average 86 kWh/pe/yr
- Germany: national average 43 kWh/pe/yr
- Graz (AT): 15-20 kWh/pe/yr
- Milan (IT): 40 kWh/pe/yr

The JRC consulted comprehensive public data about installed lighting installations in Andalucia (Spain) which was available for the years 2005 and 2008-2013. Data was available for over 700 towns and villages, although data for the larger cities, such as Sevilla, Cordoba and Malaga was not included.

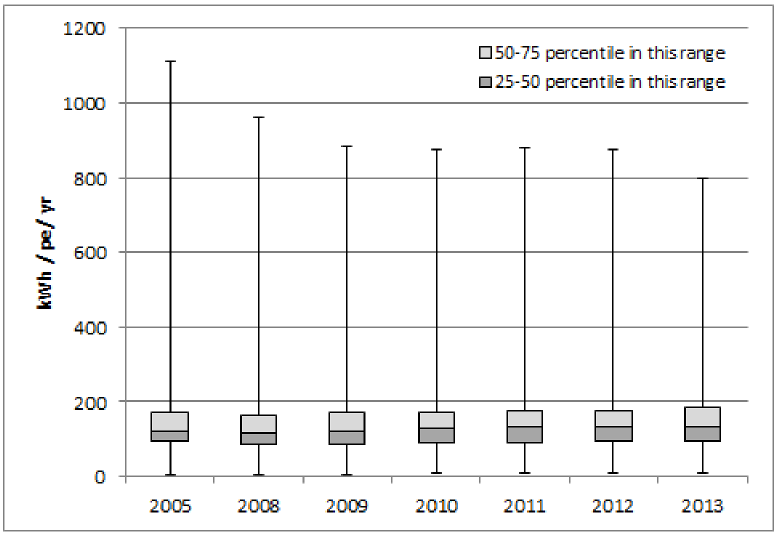

Figure 6. Summary of per capita energy consumption by public lighting in over 700 Andalucian towns and villages

From the almost 5000 data points, it was necessary to delete around 20 values due to them being unrealistically high (e.g. 2000-7000 kWh/pe/yr) and not keeping in line with data for other years in the same town or village.

The raw data available was basically installed power for public lighting (in kW) and the population (in pe). Consequently it was necessary to assume a certain operating period (11 hours per day, 4015 hours per year) and that no dimming took place (a reasonable assumption since significant LED uptake not expected prior to 2013).

Looking at the overall data there is no clear trend except that the most extreme consumers have decreased between 2005 and 2009. Although difficult to see in the graph due to its scale, the middle 50% of performers (i.e. between the 25th and 75th percentiles) were consistently in the range of 85 to 185 kWh/pe/yr.

At the level of individual towns and villages there was a huge range of % changes in per capita energy consumption for public lighting in different years. The 4 best performers were Benahadux, Paterna de Rivera, Belmez de la Moraleda and Tarifa, where consumption was reduced by more than 80% between 2005 and 2013. However, at the other extreme, Cabra, Atarfe, Chimeneas, Ezcuzar and Carboneros showed per capita energy consumption for public lighting increased by 250-450% between 2005 and 2013. Specific mention of Pedroche is also merited, where the increase was around 4000% during the same period.

Previous EU GPP criteria for energy efficiency

In the 2012 EU GPP criteria, minimum requirements for luminous efficacy were defined for different lamp technologies when *lamps, ballasts or luminaires were being purchased*. Apart from the effect of different lamp technologies, the minimum required luminous efficacies varied as a function of the rated wattage because the power rating has an influence on the energy efficiency of the main lamp technologies used in 2012 (i.e. HID type technologies). Energy losses due to ballasts were treated separately.

This was a far from ideal solution because simply replacing existing lamps and ballasts with more energy efficient ones may simply result in over-lighting while the energy consumption remains the same.

When considering criteria for *new lighting installations or renovation of existing installations*, the 2012 EU GPP criteria did make some attempt to link energy efficiency to the lighting level of class C and class P roads:

- Maximum 0,044 W/(lux·m²) if E ≤ 15 lux
- Maximum 0,034 W/(lux·m²) if E > 15 lux

However, energy efficiency requirements linked to only two lighting levels (above or below 15 lux). This is not appropriate now considering that EN 13201-1:2014 sets 12 different lighting level thresholds for C and P class roads are set at 0.4, 0.6, 1.0, 1.5, 2.0, 3.0, 7.5, 10, 15, 20, 30 and 50 lux (see Figure 1).

The rise of LED lighting technology means that there are now many options for improving the energy efficiency of road lighting installations and that energy efficiency criteria do not need to be nuanced for power rating.

Key terms and definitions from EN 13201-5

In order to ensure a consistent approach to defining the energy efficiency of a road lighting installation, it is recommended to follow the definitions and methodology provided in EN 13201-5: 2016 "Road lighting – energy performance indicators". This standard introduces several key definitions:

- **Luminous efficacy** (η), expressed in lm/W.
- **Power Density Indicator** (PDI) expressed in W/(lx.m²).
- **Annual Energy Consumption indicator** (AECI) expressed in kWh/(m².y).
- **Operational profile**: the number of hours the lighting installation will be switched on for each day and at what percentage of full power it will operate at for each hour.
- **Road profile**: the layout of the road, including any sidewalks and other areas intended to be lit and excluding any intermediate areas, such as vegetated strips and central reservations, not intended to be lit.

The key terms for measuring energy efficiency of an installation are PDI and AECI, although these cannot be calculated without first knowing the luminaire efficacy, road profile and operational profile.

6.1. Luminaire efficacy

Contracting authorities should also be aware of the fact that public procurers for central government institutions are obliged, under Article 6 of the Energy Efficiency Directive, to purchase only products that comply with energy efficiency benchmarks specified in implementing measures if a product is covered by such an implementing measure under the Ecodesign Directive.

With regards to road lighting, Regulation 245/2009 is currently in force and will be later repealed by a new Commission Regulation (under public consultation until December 2018). The current draft proposal does set luminous efficacy requirements for LED lighting (120 lm/W) that are not more stringent than those specified in the EU GPP criteria.

6.1.1. Background research and supporting rationale

The luminous efficacy is basically how much useful light (in lumens) can be produced by a given unit of power (1 Watt). Luminous efficacy can be defined at various different levels: of the light source, of the luminaire containing the light source or the installation containing all the luminaires. Definitions of light source or luminaire efficacy can be simply measured in the laboratory as the ratio of light output (in lm) to power input (in W). The most complicated definition is luminous efficacy at the level of the entire installation which, as per EN 13201-5:2016 is as follows:

$$\eta_{inst} = C_L \, x \, F_M \, x \, U \, x \, R_{LO} \, x \, \eta_{ls} \, x \, \eta_P$$

Where:

- η_{inst} is the installation luminous efficacy in lm/W
- C_L is the correction factor where a design is based on luminance or hemispherical illuminance instead of illuminance
- F_M is the overall maintenance factor of the lighting installation (this is a combination of individual maintenance factors for decreased lumen output from the light source and for dirt gathering on the housing), it is the product of F_{LLM} and F_{LM}.
- U is the utilance of the installation (i.e. the fraction of light output reaching the target area)
- R_{LO} is the optical efficiency of the luminaire (i.e. how much of the light output of the light source leaves the luminaire)
- η_{ls} is the luminous efficacy of the light source alone (in lm/W)
- η_p is the power efficiency of the luminaire (i.e. accounting for power losses in control gear).

Data provided by lighting equipment manufacturers about luminous efficacy will provide information about the light output and power consumption of the light source alone and when mounted in the luminaire. Power losses in control gear may or may not be reported separately, although this should not be important for the currently proposed EU GPP criteria so long as the combined overall power consumption figure is provided.

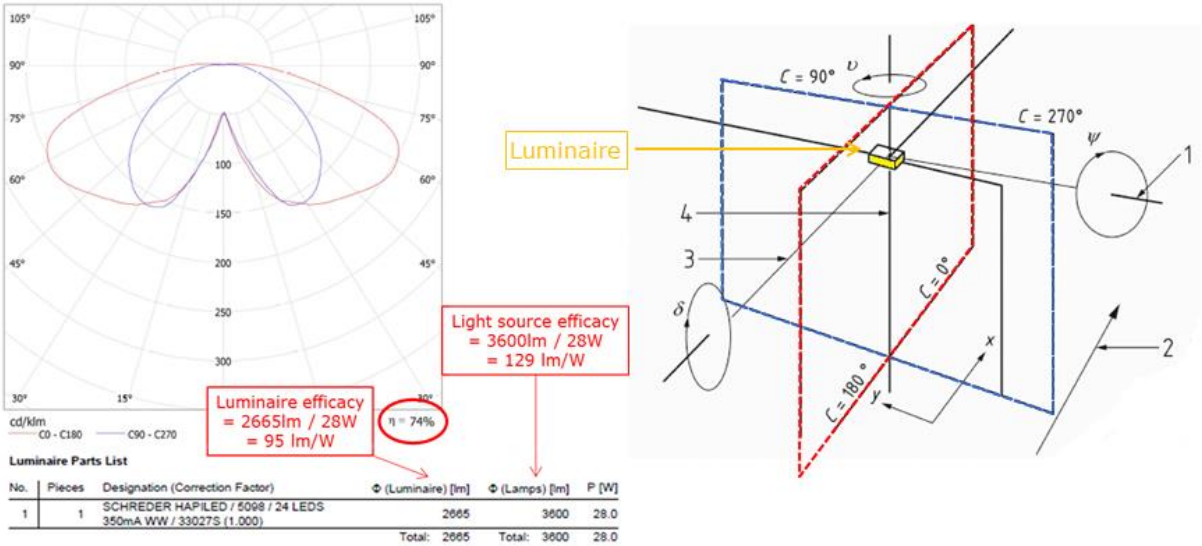

Figure 7. Example of light output and power consumption data provided in a luminaire manufacturer data sheet (left) and, adapted from EN 13201-3, a 3-D illustration of the 0-180 and 90-270 axes (right).

In the above case, a luminaire data sheet for SCHREDER HAPILED/5098/24 LEDS 350mA WW/33027S, the optical efficiency (R_{LO}) of the luminaire was 74% (or 0.74) and the luminaire efficacy (the product of R_{LO}, η_{ls} and η_p) was around 95 lm/W. The step from luminous efficacy of luminaire to the luminous efficacy of the installation is quite a big one and involves the consideration of the utilance factor and the maintenance factor (these are described later in section 7.3.1 and in Technical Annexes I and II).

DesignLights Consortium (DLC)

An example of a tiered approach to luminous efficacy can be seen from the DesignLights Consortium, as illustrated in Figure 8 below. The first tier is between minimum requirements for a "*standard Qualified Products List (QPL)*" (of 90-100 lm/W) and of a "*premium QPL*" (of 110-120 lm/W).

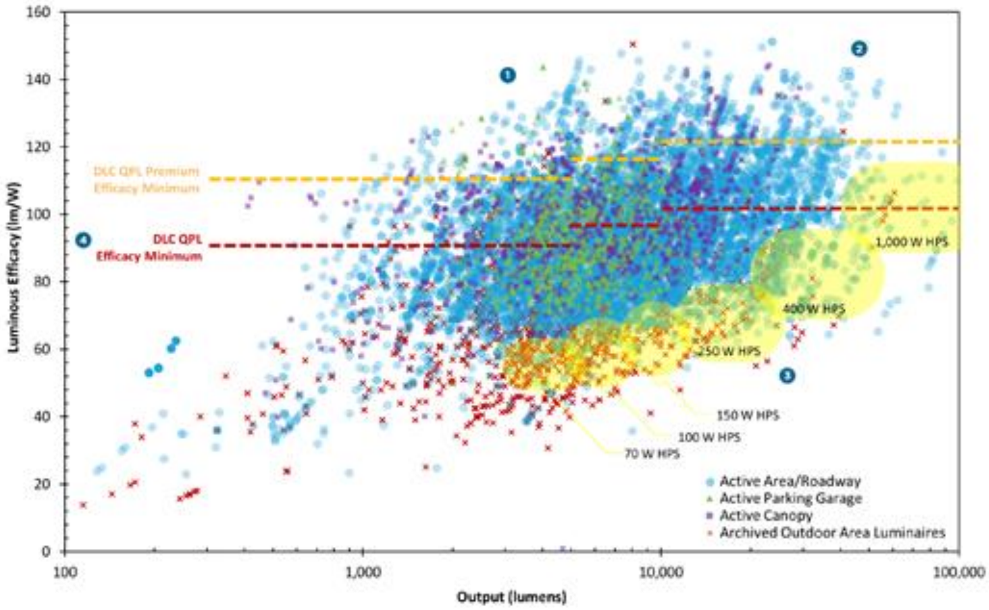

Figure 8. US DOE Lighting Facts database (2016) of road lighting luminaires with luminaire output (lumens) versus luminaire efficacy (source DOE, 2016)

Figure 8 shows that while the typical luminaire efficacies of HPS lamps (indicated in yellow areas) depend on the lumen output and wattage, the LED data for area/roadway lighting (blue points) is effectively independent of power rating and lumen output – except perhaps when output drops below 500 lumens. The DLC have recognised some minor relationship between luminous efficacy and lumen output for LED by stepping the minimum requirements for luminaires to appear on their Qualified Products List in 2016 by setting minimum requirements of:

- 90 lm/W up to 5000 lumen output,
- 95 lm/W for 5000-10000 lumen output
- 100 lm/W for >10000 lumen output

Figure 8 also highlights how much LED-based luminaires for road lighting (blue points) can exceed HPS-based luminaires (yellow areas) in terms of luminous efficacy for outputs between 3000 and 30000 lumens. This increase in efficacy of HPS-based luminaires as the light output increases is clear from Figure 8. This tendency was well reflected for all HID type lamps in the current GPP criteria published in 2012. However, with LED technology there is no technical reason to introduce weaker requirements for luminaires with a lower wattage and/or road illuminance. When comparing the minimum requirements for the DLC QPL (Qualified Products List), it is clear that only high power (1000W) HPS lamps could meet the requirements.

Initial proposal in TR 1.0

In TR 1.0, it was proposed to have some minimum requirements for luminaire efficacy (105 lm/W for core level and 120 lm/W for comprehensive level). The main justification for this criterion was that it forms the basis for any calculations of energy efficiency of the installation (i.e. PDI or AECI) and is much easier to verify, with data readily available from suppliers. In projects where a detailed design is not specified for whatever reason, especially when light sources are to be retrofitted to existing luminaires, the luminaire efficacy will be the main point to promote the energy efficiency of the installation.

Proposal in TR 2.0

In TR 2.0, the core and comprehensive criteria were revised to 102 lm/W and 112 lm/W respectively and linked to the years 2016 and 2017. For later years, a tiered approach was defined where every two years the ambition level would rise by 17-18 lm/W. This was based on projected trends from historical data in the LightingFacts database during the period 2012-2016. Exemptions from the stated ambition levels were mentioned for decorative luminaires with any light source and for any luminaire with light sources that were <2100K.

Proposal in TR 3.0

In TR 3.0, a closer analysis of the LightingFacts database suggested that there was a decrease in luminaire efficacy as the light output of LED luminaires decreased. This also followed a similar logic as the DLC approach that is illustrated in Figure 8. Consequently, the same tiered approach was maintained as in TR 2.0 but with some lower efficacy ambition levels for luminaires of lower light outputs (i.e. 0-1000, 1000-3000 and 3000-11000 lumens). The same ambition levels as in TR 2.0 were maintained for luminaires with light output >11000 lumens.

Proposal in TR 4.0

Following stakeholder feedback and a reassessment that only focuses on the data in 2016-2018, it became apparent that there was no obvious relationship between light output and LED luminaire efficacy. The re-analysis confirmed that there was however a statistically significant decrease in luminaire efficacy for any LED luminaire when the light source is <2700K. There also appeared to be an even more significant decrease in efficacies for decorative LED luminaires however, when looking only at 2017 and 2018 data, it appears that now there is no significant decrease for decorative luminaires. Consequently, the lower ambition levels for lower light output was removed, the lower ambition level for decorative luminaires was not incorporated and the lower ambition level for warmer light sources was set at <2700K.

6.1.2. Stakeholder discussion

The main criticism of criteria for luminaire efficacy was that a good efficacy value does not guarantee an energy efficient road lighting installation. However, the counter argument is that it is extremely difficult, if not impossible, to deliver an energy efficient road lighting installation using luminaires with a poor luminous efficacy.

It was felt by some stakeholders that ambition levels should not be varied for different types of luminaire but, paradoxically, concern was expressed that the current proposals would only allow for luminaires with white LED light sources, effectively excluding warm LED and low wattage HPS. Other stakeholders felt that a clear distinction must be made between efficacies for "pure" road lighting luminaires and efficacies in urban areas where luminaires may also have some sort of decorative design and also need to provide amenity lighting as well as road lighting. It was suggested that a more reasonable luminaire efficacy to ask for in amenity applications would be 80-85 lm/W.

Italian GPP approach

It was claimed that in Italy, a distinction is indeed made between "pure road lighting" and road lighting for pedestrian walkways and in historic city centres. National legislation has been introduced to support the implementation of a Parameterized Energy Index for Luminaires (IPEA) – essentially a labelling system for road lighting luminaires that is largely based on luminous efficacy that results in labels from A+++++ (A5+) to F.

This label is scaled according to the relevant reference luminaire efficacy, which varies according to the lamp wattage and the road type as shown below.

Table 5. Italian reference values for luminaire efficacy for different outdoor lighting applications

Rated Power	Luminaire efficacy reference values				
	Road lighting	Area lighting, roundabout, parking lot	Pedestrian area, bike lane	Green area lighting	City centre with historic lantern
P < 65	73	70	75	75	60
65 < P < 85	75	70	80	80	60
85 < P < 115	83	70	85	85	65
115 < P < 175	90	72	88	88	65
175 < P < 285	98	75	90	90	70
285 < P < 450	100	80	92	92	70
450 > P	100	83	92	92	75

Dividing the actual luminaire efficacy by the reference luminaire efficacy generates the IPEA value. The higher the IPEA value, the higher the performance label assigned to the actual luminaire. For example, "G" is <0.40, "F" is 0.40-0.55, "E" is 0.55-0.70, "D" is 0.70-0.85 and "C" is 0.85-1.00. The B (1.00-1.10), A (1.10-1.20), A+ (1.20-1.30), A++ (1.30-1.40).

Looking specifically at the reference efficacy values for "road lighting", the different luminaire efficacies required to achieve a particular IPEA label can be easily calculated.

Table 6. Translation of Italian IPEA values into luminaire efficacies for different labelling classes for "road lighting".

Rated power (W)	Reference Luminaire efficacy (lm/W)	IPEA labelling class										
		A5+	A4+	A3+	A2+	A+	A	B	C	D	E	F
<65	73	116.8	109.5	102.2	94.9	87.6	80.3	73	62	51.1	40.1	29.2
65-85	75	120	112.5	105	97.5	90	82.5	75	63.8	52.5	41.3	30
85-115	83	132.8	124.5	116.2	107.9	99.6	91.3	83	70.6	58.1	45.7	33.2
115-175	90	144	135	126	117	108	99	90	76.5	63	49.5	36
175-285	98	156.8	147	137.2	127.4	117.6	107.8	98	83.3	68.6	53.9	39.2
285-450	100	160	150	140	130	120	110	100	85	70	55	40
>450	100	160	150	140	130	120	110	100	85	70	55	40

In terms of ambition level, minimum requirements for EU GPP criteria would fall somewhere between A+ and A5+, depending on the installed power. The above levels and classes apply only for "road lighting", but the reference luminaire efficacy values for different roads, such as pedestrian paths, cycle paths and historic city centres is included in Table 5 for comparison.

According to Italian stakeholders, the IPEA values above were developed based on EN 13201, 245/2009/EC and 347/2010/EC as well as market enquiries and field experience. From the Italian experience, it is clear that city centre lighting is considered as less efficient than road lighting but that lighting of bike lanes and pedestrian areas can be more efficient.

For pure road lighting luminaires, one stakeholder felt that the proposed efficacies in TR 1.0 (i.e. 105 and 120 lm/W) could be made even more ambitious. There is a plethora of market data for LED-based luminaire efficacy from the US. Therefore it is worthwhile to consider ambition levels in the context of this market data.

From an EU GPP perspective, the main drawbacks of the Italian approach are related to the labelling going well beyond A class and complications with updating the reference levels to account for technological progress. The reference to a national level energy labelling system, which has presumably not been developed in accordance with the Energy Labelling Directive (2010/30/EU), is not recommended in EU GPP criteria published by the Commission. However, the actual numbers linked to the labels for luminaire efficacy (IPEA) and PDI (IPEI) could be used to support particular ambition levels for lighting in different use environments.

Stakeholders generally acknowledged that any fixed minimum requirement for energy efficiency in GPP criteria would need to be reassessed as LED technology continues to rapidly improve. Due to the fact that GPP criteria are fully revised every 5 to 6 years but not periodically updated, the best way to do this would be to introduce a tiered approach to the PDI or luminous efficacy reference values, which could then be increased in a tiered approach.

Stakeholder proposal based on LightingFacts data

Three tiers of luminaire efficacy were proposed based on LED luminaire efficacy data trends between 2012 and 2018 and with the intention of targeting the top 75% of LED luminaires on the market for core level and the top 50% for comprehensive level.

An analysis of luminaire efficacy data from the US DOE (Department of Energy) database was submitted by one stakeholder to justify the tiered approach. The data covered around 7700 street light luminaires for models on the market from 2012 to 2018.

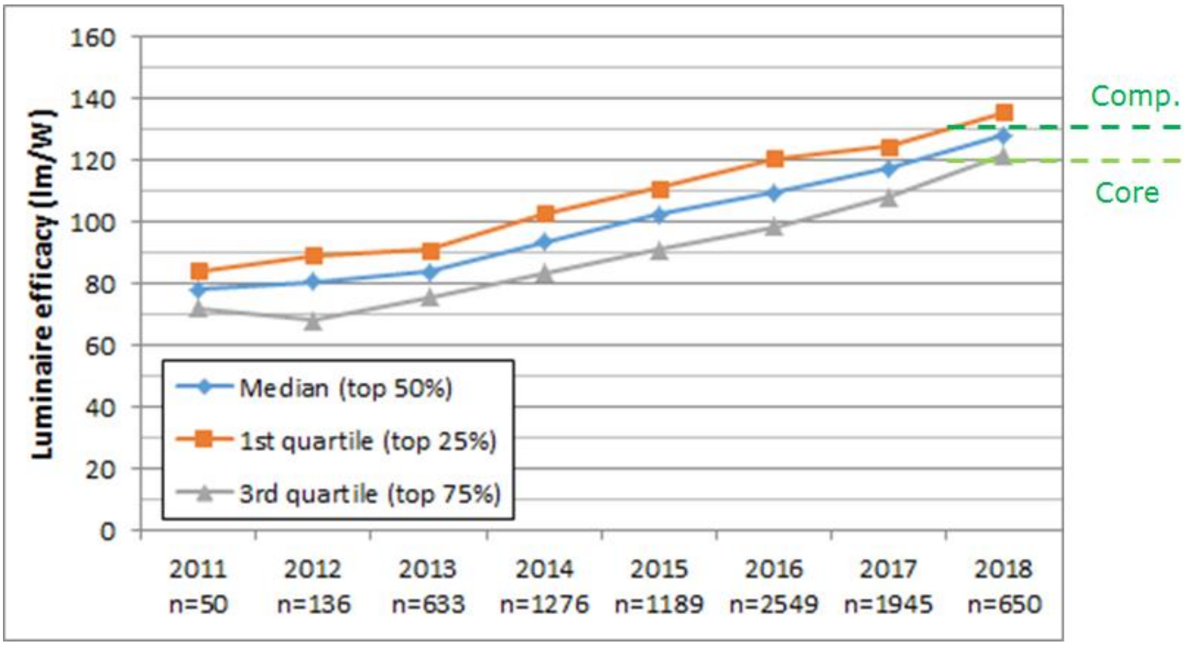

Figure 9. Luminaire efficacy data from 2011-2018 in the Lighting Facts database (US DOE, 2018). N=number of products approved in that year. 2018 data is for Q1 only.

Since 2013, when numbers of products approved began to exceed 500 per year, the trendline shows an average annual increase in median efficacy of around 8.5 lm/W. This confirms that the trends assumed in TR 2.0 when proposing the tiered approach to the ambition level for luminaire efficacy continue to be valid.

It was proposed that the ambition level be set to 120 lm/W (core) and 130 lm/W (comprehensive) and run until 2020. After that, the ambition level would increase by 17 lm/W and in 2022, it would increase by another 17 lm/W. It was agreed that any reference values for luminous efficacy should be set at the level of the luminaire, so that any optical losses from luminaires and power losses from ballasts and control gear are accounted for.

On the other hand, some stakeholders expressed concern that too high a level of ambition might essentially exclude low wattage HPS and warm LED as possible options. While it was generally accepted that this ambition level was suitable for "pure road lighting" (i.e. M class roads), it was doubted that this would work for lighting in historic areas in city centres, it is possible that luminaires have a decorative function which would limit their luminous efficacy. It was also questioned if areas with warm lighting (i.e. low CCT light sources) would be able to comply with these values. This led to a further analysis of the Lighting Facts database to determine to what extent luminaire efficacy decreased with decreasing CCT.

In order to investigate how well stakeholder concerns were reflected by the LightingFacts data, an analysis was carried out for a) luminaires with light sources of different CCTs for luminaires approved in 2016 and 2017 and b) decorative luminaires.

Table 7. Median and 3rd quartile luminaire efficacies as a function of style of luminaire and CCT of light source (From 2016 and 2017 approved products on the Lighting Facts database).

	Decorative luminaire	All luminaires	Correlated Colour Temperature (K) range				
			≤2500	2500-3499	3500-4499	4500-5499	≥5500
Number of products	n=254	n=4494	n=12	n=1029	n=1658	n=1409	n=386
Median (top 50%)	93.8 LPW	114.9 LPW	72.3 LPW	110.7 LPW	115.7 LPW	115.2 LPW	122.1 LPW
3rd quartile (top 75%)	85.6 LPW	104.8 LPW	70.3 LPW	100.5 LPW	105.2 LPW	107.2 LPW	108.0 LPW

With the different CCT ranges, the lowest CCT range (≤2500K) had a significantly lower efficacy (30-50 LPW lower) than the other CCT ranges. There were no statistically significant differences between the data in the other CCT ranges although there was a very minor increase in median and/or 3rd quartile values as CCT ranges increased in value. So the stakeholder concerns about lower efficacies for low CCT light sources also appear to be well founded, at least when CCT is <2500K. However, it must also be pointed out that there was only a very small sample size for the ≤2500K CCT range (n=12). Of the 1029 luminaires listed between CCT 2500 and 3499K, only 2 were ≤2700K. Consequently, the median and 3rd quartile numbers for CCT ≤2700K are virtually identical to those for CCT ≤2500K.

Looking at the average luminaire data for 2011 to 2018, concerns about decorative luminaires having lower efficacies appear to be well founded. Comparing the 2nd and 3rd columns in Table 7, it is clear that decorative luminaires have an efficacy that is around 20 LPW lower than the entire range of luminaires.

A closer look at the luminaire efficacy data for decorative luminaires is presented below with the aim of better understanding its evolution.

Table 8. Evolution in median luminaire efficacies for standard and decorative luminaires (from LightingFacts database)

		2011	2012	2013	2014	2015	2016	2017	2018
Standard luminaires	Median	78.1 LPW	80.5 LPW	83.8 LPW	93.4 LPW	102.4 LPW	109.5 LPW	117.6 LPW	127.9 LPW
	Year on year increase	n/a	+2.4LPW (3.1%)	+3.3lpw (4.1%)	+9.6LPW (11.4%)	+9.0LPW (9.6%)	+7.1LPW (6.9%)	+8.1LPW (7.4%)	+10.3LPW (8.8%)
	N=	50	136	633	1276	1189	2549	1945	601
Decorative luminaires	Median	71.3 LPW	68.0 LPW	62.6 LPW	85.8 LPW	87.5 LPW	90.3 LPW	114.6 LPW	131.4 LPW
	Year on year increase	n/a	-3.3LPW (4.6%)	-5.4LPW (8.9%)	+23.2LPW (37.1%)	+1.7LPW (1.9%)	+2.8LPW (3.2%)	+24.3LPW (26.9%)	+16.8LPW (14.7%)
	N=	1	2	1	4	18	204	50	44

The LightingFacts database reveals that there has been a significant year on year increases between 2013 and the first quarter of 2018 but that, due to the very limited numbers of decorative luminaires in the database in earlier years, only the trends from 2016 and 2018 should be considered. During those two years, a combined +44% increase in efficacy was evident.

The numbers in Table 8 show that decorative luminaires have consistently lower median efficacies during the years 2011 to 2016. However, the data from 2011 to 2014 represents very few decorative luminaires and thus may not be representative. In the last two years (2017 and 2018) the numbers imply that decorative luminaires have successfully closed the gap to when compared to the entire database median efficacy.

In conclusion, the concerns about poor efficacies of decorative luminaires compared to normal luminaires appeared to be valid at least until 2016 although data from 2017 and 2018 suggest that now decorative luminaires can be just as efficacious as standard ones.

Regarding which format the photometric file should be provided in, stakeholders mentioned EU lumdat (.ldt) and (.xls). However, the most important point was that the file format was compatible with common light planning software such as Dialux, Relux or Oxytech freeware. The software called "Lighting Reality" was also mentioned.

6.1.3. Criteria proposals for luminaire efficacy

<table>
<tr><th>Core criteria</th><th>Comprehensive criteria</th></tr>
<tr><td colspan="2">TS1 Luminaire efficacy</td></tr>
<tr><td>
(Applicable when light sources or luminaires are to be replaced in an existing lighting installation and no redesign is carried out. These ambition levels should not be applied when light sources are also requested to be rated with CCT ≤2700K.)
The lighting equipment to be installed shall have a luminaire efficacy higher than the relevant reference value stated below.
<table>
<tr><th>Year of ITT*</th><th>Efficacy (lm/W)</th></tr>
<tr><td>2018-19</td><td>120</td></tr>
<tr><td>2020-21</td><td>137</td></tr>
<tr><td>2022-23</td><td>155</td></tr>
</table>
Verification:
The tenderer shall provide a standard photometric file that is compatible with common light planning software and that contains technical specifications on the light output and energy consumption of the luminaire, measured by using reliable, accurate, reproducible and state-of-the-art measurement methods. Methods shall respect relevant international standards, where available.
*Due to the rapid technological developments in luminaire efficacy of LED-based lighting, it is proposed that the reference values stipulated here for invitations to tender (ITTs) should increase over the next 6 years, to avoid them becoming obsolete before the EU GPP criteria are due for revision again.
</td><td>
(Applicable when light sources or luminaires are to be replaced in an existing lighting installation and no redesign is carried out. These ambition levels should not be applied when light sources are also requested to be rated with CCT ≤2700K.)
The lighting equipment to be installed shall have a luminaire efficacy higher than the relevant reference value stated below.
<table>
<tr><th>Year of ITT*</th><th>Efficacy (lm/W)</th></tr>
<tr><td>2018-19</td><td>130</td></tr>
<tr><td>2020-21</td><td>147</td></tr>
<tr><td>2022-23</td><td>165</td></tr>
</table>
Verification:
The tenderer shall provide a standard photometric file that is compatible with common light planning software and that contains technical specifications on the light output and energy consumption of the luminaire, measured by using reliable, accurate, reproducible and state-of-the-art measurement methods. Methods shall respect relevant international standards, where available.
*Due to the rapid technological developments in luminaire efficacy of LED-based lighting, it is proposed that the reference values stipulated here for invitations to tender (ITTs) should increase over the next 6 years, to avoid them becoming obsolete before the EU GPP criteria are due for revision again.
</td></tr>
<tr><td colspan="2">AC1: Enhanced luminaire efficacy</td></tr>
<tr><td colspan="2">
(Applies to TS1.)
(Same for core and comprehensive criteria.)
A score of up to X points shall be awarded to tenderers that are able to provide light sources or luminaires which exceed the minimum luminous efficacy defined in TS1.
Maximum points (X) will be awarded to the tender with the highest luminous efficacy value and points will be proportionately awarded to any other tenders whose light sources or luminaires exceed the minimum requirements of TS1 but do not reach the value of the highest efficacy tender.
</td></tr>
</table>

6.2. Dimming controls

6.2.1. Background research and supporting rationale

Dimming the light output of a road lighting installation saves energy. The relationship between dimming and power consumption is almost directly proportional for LED-based luminaires.

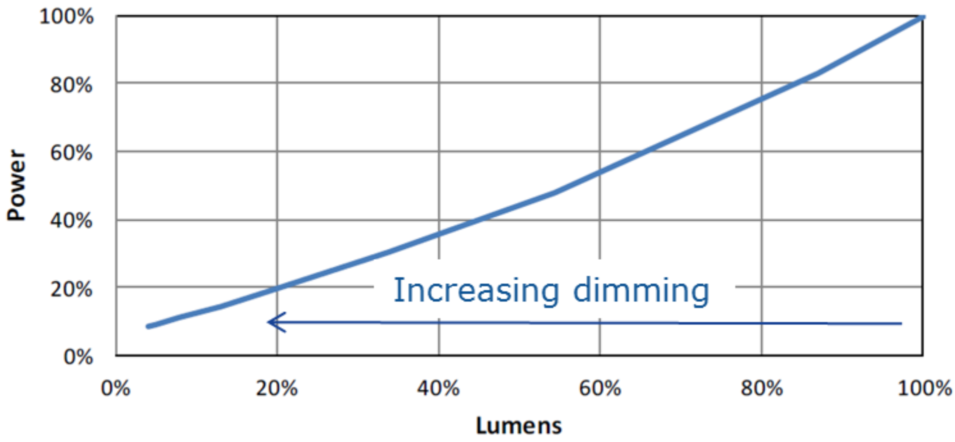

Figure 10. Relationship between power consumption and dimming of light output (Source, NEMA, 2015)

Many dimming controls can easily go down to 10% of maximum light output and some can even go to 1%. However, as the dimming levels increase, the basic low-level power consumption of the drivers and control units becomes increasingly significant, as can be demonstrated when the plotting luminaire luminous efficacy for the same luminaire under different dimming conditions.

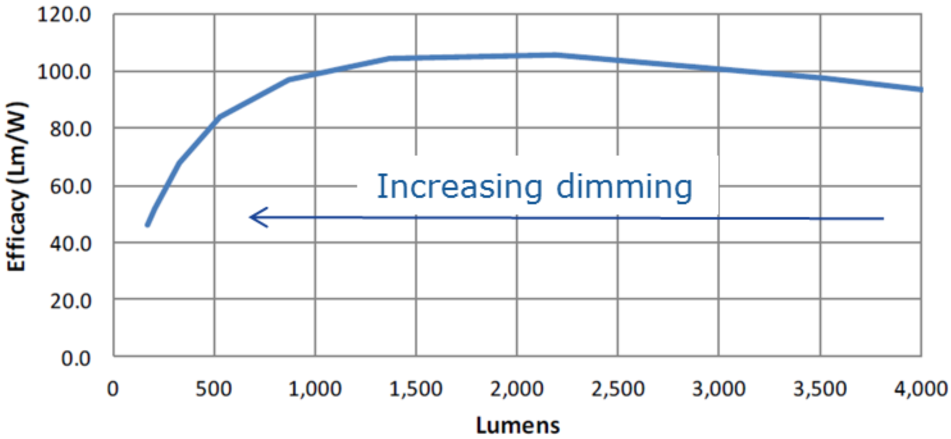

Figure 11. Relationship between luminaire efficacy and dimming of light output (Source, NEMA, 2015).

When considering the data from Figure 10 and Figure 11, it is clear that all dimming is beneficial in terms of reduced costs and environmental impacts related to energy consumption. However, it should be noted that when dimming to extremely low levels (i.e. dimming to less than 20% of maximum light output), the luminous efficacy of the luminaire will reduce.

Another benefit of dimming is that it is possible to minimise light pollution on demand. In some cases, where a more efficient lamp has been retrofitted without the control drivers and ballast being modified or replaced accordingly, it is possible that the new lamp uses the same power input to simply generate more light, even if this is more than was desired. Dimming controls can correct for this.

Existing EU GPP criteria

Annex VII of Ecodesign Regulation EC/245/2009, which provides benchmarks for luminaires, states that:

"*Luminaires are compatible with installations equipped with appropriate dimming and control systems that take account of daylight availability, traffic and weather conditions, and also compensate for the variation over time in surface reflection and for the initial dimensioning of the installation due to the lamp lumen maintenance factor*."

The same wording is used as a comprehensive level award criterion in the current GPP criteria (published in 2012). It is worth noting that the criterion only requires "compatibility" with dimming and not the installation of dimming controls as such.

Without dimming controls, it is possible that lighting installations are either over-designed to produce excessive lighting at the beginning (before lumen output depreciation) or that they will sooner fail to meet the initially designed lighting levels (again due to lumen output depreciation).

The gradual depreciation in lumen output is a common issue for all lighting technologies and is related to both decreased output due to the light source itself and also due to dirt gathering on the luminaire.

Operational profile

In order to reduce costs, local authorities are increasingly looking at the possibility of dimming during curfew hours (i.e. periods of low road use, typically midnight to 6am). The recognition of dimming is reflected in the EN 13201-5 standard (Road lighting Part 5 – Energy Performance Indicators), which defines the term "*operational profile*".

The operational profile refers to how long the lighting installation is powered up on a daily basis. With dimming controls, the alteration of the level of power creates the possibility for many different operational profiles. Some examples of operational profiles are provided in Figure 12 below.

Figure 12. Examples of different operational profiles for road lighting installations during period a) evening peak hours, b) off-peak hours and c) morning peak hours (adapted from EN 13201-5). Consumption figures included refer to a 100kW installation

The top profile in Figure 12 refers to a simple on/off scenario for a lighting installation where the start and end time are programmed – this is typical of most existing installations and in this particular case, would consume 1200 kWh/d.

The middle profile in Figure 12 shows the implementation of a dimming scenario, where light output is reduced by 50% during the expected hours of low use (in this case from 0000 to 0600) – resulting in a consumption of 900 kWh/d – 25% less than the same undimmed installation.

The lower profile refers to a situation where the default light output is the same as in the middle profile, but only when sensors indicate that road use is above a certain minimum level. If road use is lower than this defined level, the lighting output will be automatically decrease from the default lighting level (from 100% to 50% during peak times or from 50% to 10% during off-peak times). Although the exact energy savings will vary from day to day, the road traffic pattern used in the assumption for Figure 12 resulted in a consumption of 650 kWh/d – almost 30% less than the simple curfew dimmed installation and almost 46% less than the same undimmed installation.

Possible cases where dimming control might not payback

Given the major operational cost savings that are possible with dimming controls, it seems unlikely that such an investment would not pay for itself. However, attention must be paid to the capital costs of dimming controls and the power rating of the luminaire. As the power rating decreases, the capital costs become more significant.

One example is with a low wattage luminaires where the extra cost for dimming controls (estimated around 50 euro) does not outweigh the savings. A quick calculation shows that for a 20W luminaire, the cost saving by reducing average energy consumption by 30% through dimming for 20 years is similar to the extra cost of the controls:

$$0.3\ x\ 20W\ x\ 4000h.yr^{-1}\ x\ 20yr\ x\ 0.11€.kWh^{-1} = 52.80€$$

The factor 0.3 corresponds to an easily achievable 30% energy saving due to implementing an operational profile that accounts for a 50% dimming during curfew hours (e.g. midnight to 6am) and prevents over-lighting of the newly installed luminaire which was specified to allow for gradual reductions in lumen output.

Future increases in electricity prices and future decreases in the costs of dimming controls will make dimming control more attractive from an investment perspective. In order to be able to take advantage of these potential future trends, and especially considering that many LED luminaires installed today will be expected to continue to operate for 10-20 years without any replacement, it is recommended that all installed luminaires and light sources are at least compatible with dimming controls.

Before deciding on whether to invest in dimming controls or not, procurers are encouraged to use the preliminary check based on LCC costing prior to launching any ITT.

6.2.2. Stakeholder discussion

Stakeholders were in general in favour of dimming controls being promoted, even in core criteria, where the installation of simple controls based on an astronomical clock could be specified. However, opinions differed about how exactly dimming should be promoted in the criteria.

However, stakeholders were cautious about any promotion of specific control systems at the installation level because this is highly unlikely to be requested for any contract that only refers to sub-regions of a network when network-wide control systems are already in place.

Regarding presence detectors, one stakeholder referred to a project where 1 in 5 presence detectors were found to be performing inadequately after only 1 year of operation, resulting in increased energy consumption. Consequently, it would not be recommended to install these types of controls without metering of electricity consumption (ideally at the level of individual luminaires linked to remote data recording systems).

Further research into possibilities to specify "self-commissioning" luminaires in EU GPP criteria was requested. Such self-commissioning would involve automatic in-situ checks against a defined set of operational parameters that can be defined and adjusted if needed. However, initial feedback revealed that such systems would be cost-prohibitive at least when compared to normally operating road lighting installations.

In the proposal in TR 1.0, degrees of dimming were addressed indirectly simply by adjusting the CL factor in the equation that was proposed to measure the AECI. A CL factor of 1.1 was proposed for LED-based lighting in order to account for initial over-design to account for lumen output depreciation. It was proposed to reduce this factor from 1.1 to 0.85 (core) or to 0.75 (comprehensive). In order to maintain a constant AECI value, this would essentially require dimming of around 23% and 32% for core and comprehensive criteria respectively.

The assumptions behind these indirect dimming ambition levels were questioned. Different opinions were expressed about the degree of dimming that would be allowable in certain situations. However, it is possible that procurers will already have clear ideas about what dimming scenarios they wish to implement (if any) and this could be specified in the Invitation to Tender (ITT) as a dimming ratio for the average illuminance with dimming divided by the average illuminance if no dimming was applied (e.g. E,m_{dim} / E,m_{nodim}). A similar idea was also suggested about the desire to see procurers specify AECI values with and without dimming.

For the purposes of calculating the impact of dimming on energy consumption tenderers should ideally provide the power curve for the luminaire with light output plotted against power consumption. The relationship is generally proportional except in high dimming scenarios where standby power consumption by control gear would become important.

Due to the multiple benefits of dimming, dimming controls must be installed in all cases unless, in exceptional circumstances, it can be demonstrated that the total cost of ownership would increase by installing dimming controls. The EN 13201 standard itself recognises that the required lighting levels are dynamic in nature and an appropriate lighting level at all times can only be ensured with adequate dimming control during off-peak hours. Dimming has obvious environmental benefits via energy consumption and reduced light pollution. Furthermore, dimming can enhance the lifetime of LED luminaires due to a reduced risk of overheating, which is the principal cause of abrupt LED failure.

In feedback to TR 3.0, it was requested that the dimming controls should also be specified that would facilitate simple implementation of switch-off policies. These have been commonly implemented in parts of the UK (mainly motivated by cost-reductions). In France, it was stated that some 6000 of the 36000 towns and villages implement switch-off policies between midnight and 0500.

When considering possible dimming scenarios, one suggestion was to make different recommendations depending on the use. For example, dimming to 70% of peak time light output in cities, dimming to 50% of peak time light output in motorways and dimming to 50%, then 10% of peak time light output in parks and gardens based on a 2-level dimming programme.

The proposal in TR 1.0 about dimming was perhaps not so visible to procurers, so stand-alone criteria were proposed in TR 2.0 and 3.0. In TR 4.0, in order to ensure that the cheaper and simpler dimming controls are always considered, the note before the technical specification was modified to require dimming controls in all cases unless concerns about a higher total cost of ownership were justifiable. This wording should help ensure that cheaper astronomical clock based dimming controls are not excluded simply via association with more sophisticated and more expensive dimming controls.

6.2.3. Criteria proposals for dimming

Core criteria	Comprehensive criteria
TS2: Dimming control compatibility	
(Applicable to all calls for tender.) *(Same for core and comprehensive criteria.)* The lighting installation shall be compatible with dimming controls and allow for programmed switch-off during periods of low night-time road use intensity. **Verification:** The tenderer shall explain how the proposed lighting installation is compatible with programmed dimming and switch-off. This explanation should include any relevant documentation from the manufacturer(s) of the light sources and luminaires proposed	

for use by the tenderer. In cases where controls are not integrated into the luminaire, the documentation should state what control interfaces can be used for dimming. The documentation shall also state what dimming methods are compatible, for example: • dimming based on pre-set period of expected low night-time road use intensity, • initial dimming of over-designed lighting installations to compensate for gradual decreases in lumen output, • variable dimming to maintain a target illuminance in variable weather conditions.	
TS3: Minimum dimming performance	
(Applicable to all calls for tender, unless it is clear that dimming controls would lead to a higher total cost of ownership. Procurers should clearly define the desired dimming performance in the ITT.) All light sources and luminaires shall be installed with fully functional dimming controls that are programmable to set at least one pre-set level of dimming down to at least 50 % of maximum light output. **Verification:** The tenderer shall provide documentation from the manufacturer(s) of the light sources and luminaires that are proposed for use by the tenderer, showing that they are compatible with dimming controls. The documentation shall also state what dimming controls are incorporated, for example: • pre-set dimming, or • variable dimming based on weather conditions or traffic volume. The documentation shall also clearly provide a power curve of light output versus power consumption, state the maximum dimming possible and provide instructions about how to programme and re-programme the controls.	***(Applicable to all calls for tender, unless it is clear that dimming controls would lead to a higher total cost of ownership. Procurers should clearly define the desired dimming performance in the ITT.)*** All light sources and luminaires shall be installed with fully functional dimming controls that are programmable to set at least two pre-set levels of dimming, down to at least 10 % of maximum light output. **Verification:** The tenderer shall provide documentation from the manufacturer(s) of the light sources and luminaires that are proposed for use by the tenderer, showing that they are compatible with dimming controls. The documentation shall also state what dimming controls are incorporated, for example: • pre-set dimming, or • variable dimming based on weather conditions or traffic volume. The documentation shall also clearly provide a power curve of light output versus power consumption, state the maximum dimming possible and provide instructions about how to programme and re-programme the controls.
CPC3: Dimming control	
(Applies to TS2 and TS3.) *(Same for core and comprehensive criteria.)* If, for whatever reason, the contractor changes the light sources and/or luminaires from those specified in the successful tender, the new light sources and/or luminaires shall be at least • equally compatible with dimming controls as the originals, • have the same programmable flexibility,	

- be able to achieve at least the same maximum dimming, and
- have a similar power curve.

Agreement on this matter shall be settled by the provision of similar documentation from the manufacturer(s) of the new light sources and/or luminaires that would justify the selection of the new luminaires and/or light sources.

6.3. Annual Energy Consumption Indicator (AECI)

6.3.1. Background research and supporting rationale for AECI

When a new design is carried out for a lighting installation, either because it is a new site or a complete refurbishment of an existing site, it is possible to specify in the tender some design details such as the Power Density Index (PDI) and, by knowing the illumination level required, the AECI. In TR 2.0, two criteria were set for these situations, one for a maximum PDI and one for a maximum AECI.

One major criticism of the approach in TR 2.0 was that procurers will not easily understand the standard calculations for PDI and AECI and that a simpler approach is needed. In the same way, it was questioned if procurers really needed to specify any PDI value, since this only forms a part (albeit a very important one) of the AECI calculation.

The AECI is considered as a more intuitive indicator for procurers than PDI or luminaire efficacy since it effectively expresses the final electricity consumption of a particular road lighting installation. The AECI takes into account over-lighting and dimming.

Consequently, the approach in TR 3.0 focuses purely on a single criterion for AECI and the aim of the background research is to explain how this calculation can be broken down into distinct factors and directly linked to PDI.

The same explanation of how to calculate PDI that was provided in TR 2.0 has been moved to Technical Annex I. In TR 3.0 and 4.0, a table of PDI reference values has been included in Technical Annex II, together with an explanation of how these values are influenced by the luminaire efficacy, maintenance factor and utilance.

The main difference between TR 3.0 and 4.0 is that the distinction of PDI values as a function of light output (and thus road class) has been removed. This changed stemmed from perceived differences in the luminaire efficacy in LED lighting of different light output. However, focussing only on the more recent data (2016-2018), it is evident that such a distinction does not apparently exist.

Consequently, in TR 4.0, the PDI reference value only varies as a function of road width and ambition level (different luminaire efficacies and utilance factors for core and comprehensive level). The tiered approach to PDI values remains in place, reflecting the background research that justified such an approach for luminaire efficacy.

The one variable that is not specified in the AECI criterion is the illumination level, which is something that the procurer must define (illumination should also take into account any dimming factors too). For reference only, we have also included some indicative AECI reference values for C and P class roads (in Technical Annex II).

Standard calculation of AECI

The EN 13201-5 standard calculation is defined in the text box below.

Calculating AECI (W/(m2.yr)

The standard calculation defined in EN 13201-5 is not directly linked to the PDI calculation and so does not consider lighting levels or PDI, only power consumption, taking into account all the periods when power consumption is different:

$$D_E = AECI = \frac{\sum_{j-1}^{m}(P_j \; x \; t_j)}{A}$$

Where P_j is the operational power required (in W) in the j^{th} period of operation, t_j is the length of time (in hours) during a one year period that the j^{th} period is in operation, A is the area that is lit (m^2) and m is the number of periods with different operational power.

Simplified calculation of AECI

When trying to examine what is the suitable "reference AECI" for a particular road lighting installation, it is arguably better to calculate AECI in such a way that the "reference PDI" is directly included in the calculation and that the influence of illumination on the AECI value can be clearly seen:

$$AECI = PDI \, x \, E_m \, x \, F_D \, x \, T \, x \, 0.001$$

Where, AECI is in units of $kWh.m^{-2}.yr^{-1}$

PDI is in units of $W.lx^{-1}.m^{-2}$

E_m is the maximum maintained illuminance (lx),

F_D is the dimming factor for any programmed dimming.

T is the operating time ($h.yr^{-1}$)

0.001 is the number of kW in 1W

It is clear that the higher the average light level (E_m x F_D) or the longer the lights are on (T), the higher will be the AECI.

A closer look at the PDI variable

The PDI is the other major variable and, as initially described in TR 2.0, a breakdown of the factors that affect PDI values is provided so that readers can understand why a fixed PDI value for all roads cannot be used:

$$PDI_{ref}(W.lx^{-1}.m^{-2}) = \frac{1}{\eta_{lum} \, x \, F_M \, x \, U}$$

Where:

- η_{lum} is the luminaire efficacy (in lm/W).
- F_M is the maintenance factor (unitless, accounting for both lamp lumen depreciation and dirt on the luminaire housing, i.e. F_{LLM}xF_{LM}).
- U is the utilance (unitless, expressing the % of total light output that lands on the target areas).

<u>*Luminaire efficacy*</u>

With regards to luminaire efficacy, the reader is referred to the background research carried out for TS1 (see section 0). The main points are that the LED technology is improving at such a rate that it would be necessary to increase the ambition level every 2 years.

Factors that affect the luminaire efficacy for LED are the year it was produced (as rapid developments continue) and if the CCT is ≤2700K or not.

<u>*Maintenance Factor*</u>

A maintenance factor of 0.85 (subtracting 0.10 for lamp lumen depreciation, F_{LLM} and 0.05 for dirt accumulation, F_{LM}) is suggested here but this can be altered by the procurer. The maintenance factor can be considered as the combined effect of all factors that decrease the light output from the luminaire (i.e. lamp lumen output depreciation and dirt accumulation on the luminaire). The latter factor will be influenced by the degree of atmospheric pollution (especially particulate matter), proximity to vegetation, luminaire housing geometry (e.g. flat or rounded), the luminaire housing material and the cleaning frequency. Local authorities have often used general calculation tables to estimate the maintenance factor.

Table 9. Example of a table to estimate the maintenance factor for road lighting (Sanders and Scott, 2008).

Cleaning interval (months)	Luminaire maintenance factor (F_{LM})								
	IP2X			IP5X			IP6X		
	High pollution	Medium pollution	Low pollution	High pollution	Medium pollution	Low pollution	High pollution	Medium pollution	Low pollution
12	0.53	0.62	0.82	0.89	0.90	0.92	0.91	0.92	0.93
24	0.48	0.58	0.80	0.87	0.88	0.91	0.90	0.91	0.92
36	0.45	0.56	0.79	0.84	0.86	0.90	0.88	0.89	0.91
48	0.42	0.53	0.78	0.76	0.82	0.88	0.83	0.87	0.90

High pollution is generally considered to occur in large urban or heavily industrialised zones. Medium pollution is attributed to semi-urban, residential or light industrial zones and low pollution is attributed to rural areas.

It is clear from Table 9 that the Ingress Protection rating will also have a major effect, at least between IP2X and IP5X. Other GPP criteria mentioned later (see TS12) recommend a minimum IP5X in some cases and IP6X in the majority of cases.

However, the traditional rules of thumb for luminaire maintenance factors in the UK were shown to be overly conservative by Sanders and Scott (2008). A more appropriate approach was to consider mounting height and to split areas into different "environmental zones".

Table 10. Actual observed data of maintenance factor for IP65 luminaires in UK

Cleaning interval (months)	E1: national parks, areas of outstanding natural beauty		E2: generally outer urban and rural residential areas		E3: generally urban residential areas		E4: generally urban areas having mixed residential and commercial use with high night time activity	
	≤6m	≥7m	≤6m	≥7m	≤6m	≥7m	≤6m	≥7m
12	0.98	0.98	0.98	0.98	0.94	0.97	0.94	0.97
24	0.96	0.96	0.96	0.96	0.92	0.96	0.92	0.96
36	0.95	0.95	0.95	0.95	0.90	0.95	0.90	0.95
48	0.94	0.94	0.94	0.94	0.89	0.94	0.89	0.94

The data collected by Sanders and Scott reveals that in general, the lumen depreciation due to dirt accumulation is much lower than previously assumed. This may be due to improved emission control on vehicles, decreased industrial activity in the UK or other factors. Interestingly, the data also revealed that mounting height had no effect on luminaire maintenance factors in areas of low pollution but did have an effect in areas of higher pollution.

Regardless, the main purpose of showing these tables is to explain that the choice of maintenance factor is important. While the F_{LLM} is confirmed by the lighting equipment manufacturer, the F_{LM} is very much up to the procurer to define and may use overly conservative rules of thumb that led to overdesign in the lighting installation.

Factors that influence the MF include: light source performance (product specific) and local environment, luminaire housing, pole height and cleaning frequency (site specific).

The Utilance Factor

The utilance is determined according to road width, pole placement, luminaire height and the ability of the optics to focus light on the target area while minimising the spillage of light outside of the target area. Experience shared by stakeholders implied that road width was the most important influence on utilance. The utilance factors that have been used to calculate the reference PDIs listed in Technical Annex II are as follows:

Table 11. Utilance factors as a function of road width and ambition level

Road width	Core level	Comprehensive level
≥ 9m	0.70	0.75
8-9m		
7-8m	0.63	0.70
6-7m	0.56	0.60
5-6m	0.49	0.55
≤ 5m	0.42	0.50

This is the general guide to follow unless the procurer decides to choose their own utilance based on site specific freedoms or restrictions for optimising the lighting design. For reference, the highest utilance that can be realistically considered today would be around 0.78, and that is only when there are no constraints on the placement of poles and mounting heights of luminaires. In sites where there are lots of constraints on optimising the optical design, a utilance factor as low as 0.35 may be justifiable even for roads that are wider than 5m.

The utilance factors recommended in Table 11 show that the comprehensive level requirements consistently ask for slightly better optics and/or luminaire placement than the core level. For both ambition levels, the relationship with road width is the same. For narrow roads the utilance can improve by some 10-20% for every metre that the road widens at least up to a width of 8m. Beyond widths of 8m, the achievable utilance factor can be assumed to be relatively constant.

Factors affecting utilance are the road width, luminaire optics, luminaire tilt angle and pole positioning.

6.3.2. Stakeholder discussion

Comments about AECI vs PDI

Although it was agreed that PDI and AECI are closely related to each other, there was considerable discussion about whether or not criteria should be set for PDI.

The main argument against PDI was that it was an additional complexity that procurers might not understand properly.

The main argument in favour of PDI criteria is that it ensures that the design delivers enough light to the road for a certain amount of power consumption.

One stakeholder stated that the usefulness of the PDI criterion really depends on how interested the procurer is in minimum lighting levels and design performance – which can vary depending on the nature of the road. For example:

- Where details of road layout, lighting level or dimming are not specified by the procurer in sufficient detail and there is little or no flexibility in the design, the calculation of PDI is not so valuable and only AECI linked to a defined reference PDI would be necessary.
- When sufficient details are provided and flexibility in the design is possible, there is a real opportunity to optimise PDI (and thus AECI) by good design. So in this case, a PDI criterion could be specified and allowed to be used in the AECI calculation.

However, other stakeholders felt that so long as the influence of PDI was clearly demonstrated on AECI, the simplest approach would be to set AECI ≤ PDI_{ref} x E,m. Then it would simply be up to the procurer to define either:

- the AECI that they want (the tenderers then have to see what light level is possible and how much dimming would be needed to respect that AECI) or
- the light level (E,m) that they want (the tenderers have to see what luminaire efficacy, maintenance factor and utilance they can justify in their design for the lowest AECI at that E,m).

For this new approach to work, it is necessary to justify a series of PDI_{ref} values that can be used as a basis. As mentioned earlier, the luminaire efficacy, maintenance factor and the utilance are the variables affecting PDI.

For consistency, when constructing the PDI reference tables in Technical Annex II, the same numbers for luminaire efficacy that are stated in section 6.1.3 have been used. A single maintenance factor of 0.85 has been used for all situations (procurers may change this if they wish when setting minimum PDI_{ref} values). The utilance factor is defined as a function of road width (higher utilance for higher road widths) but the assumed utilance is also more ambitious in the comprehensive level requirements.

In the same table where PDI reference values have been defined in Technical Annex II, they have been translated into what is termed "AECI base values". These are basically the translation of the equivalent PDI reference value into AECI but not yet accounting for the light level (which the procurer should specify).

Finally, and still in the same table, specific AECI values have been inserted based on the average maintained illuminance levels required for a number of different road lighting classes.

The relationship between the 3 sets of values in the table in Technical Annex II can be explained as follows:

- PDI reference ($W.lx^{-1}.m^{-2}$) is based on luminaire efficacy, maintenance factor and utilance factor.
- AECI base value ($kWh.lx^{-1}.m^{-2}.yr^{-1}$) is basically the PDI reference multiplied by operating time ($h.yr^{-1}$), multiplied by any dimming factor (unitless, =1.00 for core and 0.73 for comprehensive) and converting W into kW (i.e. x 0.001kW/W).
- Specific AECI value ($kWh.m^{-2}.yr^{-1}$) is basically the AECI base value multiplied by the average maintained illuminance (lx) that the procurer wants.

The illuminance levels are all that needs to be specified for C and P class roads. For M class roads, it would also be necessary to convert illuminance into luminance, which would require an assumption to be made about the surface reflectivity of the road. Since this reflectance value can vary significantly, it was decided not to propose any specific AECI values for M class roads just in case procurers mistakenly presume that all roads have whatever reflectance value that would have been used as an assumption in developing the AECI reference values for M class roads for EU GPP criteria.

6.3.3. Criteria proposals for AECI

<table>
<tr><th>Core criteria</th><th>Comprehensive criteria</th></tr>
<tr><td colspan="2">TS4 Annual Energy Consumption Indicator (AECI)</td></tr>
<tr><td colspan="2">(Applicable when a new lighting installation is being designed or when a redesign is required due to the refurbishment of an existing lighting installation or the retrofitting of new luminaires. Procurers should pay particular attention to the numbers submitted for the maintenance factor and utilance from the designer/tenderer and make sure that they are realistic and justifiable.)
(Same for core and comprehensive criteria, although PDI reference values are higher for comprehensive level approach – see Technical Annex I.)
The procurer shall provide technical drawings of the road layout, together with the areas to be lit and the illuminance/luminance requirements.
For M-class roads, the procurer shall define the surface reflectivity coefficient of the road, which tenderers should use in their luminance calculations.
To aid tenderers in their assumptions for design maintenance factors, the procurer should define with what frequency the luminaires will be cleaned.
For the average maintained illuminance/luminance defined by the procurer, the AECI of the design shall comply with the equation below:
$$AECI_{design} \leq PDI_{ref} \times E_m \times F_D \times T \times 0.001$$
Where:
PDI is the power density indicator, in units of $W.lx^{-1}.m^{-2}$
E_m is the maximum maintained illuminance (lx)
F_D is the dimming factor for any programmed dimming
T is the operating time $(h.yr^{-1})$
0.001 is the number of kW in 1W
The PDI_{ref} value used shall depend on the road width and year as listed in Technical Annex I. Lower PDI_{ref} values than those listed in Technical Annex I are justified in cases where light sources with CCT ≤2700K are also specified.
Verification:
The tenderer shall state what lighting software has been used to calculate the PDI value and provide a clear calculation, where the values for the luminaire efficacy, maintenance factor and utilance factor of their proposed design are visible. The calculation results must include the measurement grid and calculated illuminance/luminance values.</td></tr>
<tr><td colspan="2">AC2: Enhanced AECI</td></tr>
<tr><td colspan="2">(Applies to TS4.)
(Same for core and comprehensive criteria.)
A score of up to X points shall be awarded to tenderers that are able to provide designs that result in a lower AECI than the maximum limit defined in TS4.
Maximum points (X) will be awarded to the tender with the lowest AECI value and points shall be proportionately awarded to any other tenders whose designs are lower than the maximum limit in TS4 but do not reach the value of lowest energy consuming tender.</td></tr>
</table>

6.4. Metering

6.4.1. Background research and supporting rationale

As shown in the Preliminary report (PR), the operational costs of electricity are the major source of environmental impacts. The purchase of electricity is a major contributor to the total cost of ownership of road lighting installations and can represent a significant fraction of total electricity costs for municipalities.

As mentioned in the PR (section 3.3.3), more and more cities understand that a metering system for a road lighting network may play a strategic role in energy consumption and CO_2 emission reduction measures. A metering system could potentially be added to the existing road lighting system, even if non-LED technologies are in place.

The electricity has to be billed and purchased for road lighting, but in a lot of cases there are no meters to count the electricity consumption. In those cases it usually means that the bill to pay is estimated by the lamp power and the operation time without considering the real consumption, which may vary especially if dimming and CLO drivers are used. With traditional HID lamp technologies and operating practices, this was not a major issue because lamps only came in a limited number of power ratings (e.g. 50W, 70W, 110W), the same type of ballasts were used and operational profiles did not account for CLO, curfew dimming or user dimming based on motion-sensor calculated traffic volume.

However, with the rise of LED technology, lamps are available in a much wider range of power ratings. The use of CLO drivers to avoid excessive power consumption and over-lighting of installations during initial operation is increasingly being considered. For municipalities and road authorities under budgetary pressure or wishing to reduce light pollution, the ability to dim light output during defined periods of low use is essential.

If dimming control programs that activate different dimming levels based on real life, in-situ variations in daylight or traffic are used (see bottom option in Figure 12), it will be impossible to accurately predict electricity consumption. In these cases especially, the metering of electricity consumption at the luminaire level, or at least at the level of the installation responding to these dimming controls, is the only way to ensure that the billing for electricity is accurate and to also know how these dynamic dimming controls perform compared to simpler fixed curfew dimming controls or to no dimming control.

Metering at the level of the luminaire could provide valuable information about the lifetime performance of the light source and control gear and, if reported remotely, would also identify any abrupt failures. Such data could also be valuable if attempting to identify the cause of abrupt failures (e.g. during storm periods, accidents or pinpointing an act of vandalism). Long term metering data could provide valuable feedback to manufacturers as well, to complement the laboratory data they already have.

Reference to the Measuring Instruments Directive (MID) was made in the criteria proposed in TR 1.0 and such a reference is maintained in the TR 2.0 and TR 3.0 proposals. However, due to the costs and effort involved in complying with the requirements of the MID, this condition should only apply to a meter installed at the sub-station for a lighting installation and not to individual luminaire level meters.

6.4.2. Stakeholder discussion

The interest in metering was highlighted by a request to consider the creation of a database with the real electricity consumption of the road lighting by authorities in each city. Ideally data should be based on meter readings dedicated to lighting installations and networks. However, it would still be possible to report data based on the MWh consumption that is simply billed and the number of lighting points/km of lit road/inhabitants covered by that bill.

Stakeholders confirmed that metering of electricity consumption in road lighting installations is not common practice. Consumption is often estimated for billing purposes by multiplying the number of luminaires by the typical luminaire power consumption and factoring in any dimming scenarios. Some extreme examples in the UK were cited where billing for electricity consumption was simply based on a fixed cost per luminaire and did not account for any lower consumption due to higher efficacy light sources or dimming. It was questioned if metering was actually a "green" criterion although it would be very useful in providing direct positive feedback to road network managers on any measures taken to improve energy efficiency.

A distinction was made between metering at the level of the installation and at the level of the individual luminaire. The main problems with installing metering systems for installations were related to the need to comply with different regulations, additional costs and, in urban areas at least, limited space for new electrical cabinets and/or limited space in existing cabinets.

At the individual luminaire level, it is possible to specify control gear that is at least compatible with metering and that remote reporting of electricity consumption offers significant potential in monitoring operational performance, especially if linked to constant light output controls but also to detect abrupt failures in some or all of the light sources in a particular luminaire.

Considering the potential to embrace smart lighting principles, some stakeholders were in favour of introducing individual luminaire reporting compatible with remote systems as an award criterion, since it would entail additional costs. However, any attempts to promote metering at the level of the individual luminaire would have a major cost impact. Some ball-park figures quoted for the costs were:

- Luminaire: 300-600 EUR
- Meter for individual luminaire: 100-200 EUR
- Junction box installation (single meter for full installation): 1000-2000 EUR

With smart controls, there would also be additional costs associated with the licensing of software and possibly other ancillary equipment.

Another point that was raised during the final written consultation was why no criterion for a minimum power factor had been proposed. The power factor is generally considered as the ratio of the real power consumed by a load (expressed in Watts and registered by the meter) to the apparent power of the circuit (expressed in Volt Amps).

The highest possible power factor is 1, indicating no loss of current or distortion of harmonics in the supplied "apparent" power. As losses and/or distortions in harmonics increase, the power factor decreases. Low power factors are problematic for electrical power suppliers and owners of road lighting installations could potentially face penalty charges for installing equipment with unacceptably low power factors.

Lower power factors also result in hidden environmental impacts since they increase losses in transmission lines, requiring more energy sources to be depleted to meet a given electricity demand. However, since these losses are not captured by increased consumption on client-side meters, it is important to specify a minimum acceptable power factor in GPP criteria.

The IEA 4E SSL Annex Tiers for outdoor lighting (street lighting luminaires, published in November 2016, already sets a minimum requirement of a power factor ≥0.90 for all LED road lighting.

The power factor is one aspect that is optionally reported on in the LightingFacts database and an analysis of over 7000 luminaires approved between 2009 and 2017 revealed that:

- 3620 of 7783 luminaires (46.5%) reported a power factor.
- 16 of those 3620 luminaires (0.4%) had a power factor <0.90.

- 421 of those 3620 luminaires (11.6%) had a power factor of 0.90 < x < 0.95.
- 3183 of those 3620 luminaires (88.0%) had a power factor of ≥0.95.

To avoid the risk of procurers ending up with luminaires that have unacceptably low power factors, and thereby facing the risk of penalty charges from electrical power suppliers, it is proposed to have a minimum technical specification for power factor.

6.4.3. Criteria proposals for metering and power factor

Core criteria	Comprehensive criteria
TS5 - Metering	
(Applicable to all tenders where no dedicated meter is yet in place for the lighting installation.) The procurer shall state any specific technical requirements for the metering system in the ITT. The tenderer shall provide details of the proposed metering equipment and any ancillary equipment required in order to monitor electrical consumption at the lighting installation level for the same lighting installation that is the subject matter of the ITT. **Verification:** The tenderer shall provide the technical specifications of the metering and measurement system and provide clear instructions on how to operate and maintain this system. A calibration certificate compliant with Measuring Instruments Directive 2004/22/EC shall be provided for each control zone.	***(Applicable to all tenders where no dedicated meter is yet in place for the lighting installation.)*** The procurer shall state any specific technical requirements for the metering system in the ITT. The tenderer shall provide details of the proposed metering equipment and any ancillary equipment required in order to monitor electrical consumption at the lighting installation level for the same lighting installation that is the subject matter of the ITT. The metering device must be capable of logging data on a 24-hour basis that can later be manually or remotely downloaded. **Verification:** The tenderer shall provide the technical specifications of the metering and measurement system and provide clear instructions on how to operate and maintain this system. A calibration certificate compliant with Measuring Instruments Directive 2004/22/EC shall be provided for each control zone.
TS6 – Power factor	
(Applicable when LED luminaires are being procured.) The power factor for the luminaire to be installed shall be ≥0.90. **Verification:** The tenderer shall provide a declaration of compliance with the criterion for the lighting equipment they intend to supply, supported by a declaration from the manufacturer and results from tests carried out in accordance with IEC 61000-3-2.	***(Applicable when LED luminaires are being procured.)*** The power factor for the luminaire to be installed shall be ≥0.95. **Verification:** The tenderer shall provide a declaration of compliance with the criterion for the lighting equipment they intend to supply, supported by a declaration from the manufacturer and results from tests carried out in accordance with IEC 61000-3-2.

6.5. Contract performance clauses relating to energy efficiency

6.5.1. Background research and supporting rationale

A CPC was proposed to ensure the correct functioning of any specified controls (e.g. timers, daylight controls, CLO drivers etc.) that relate to routine operation and dimming of the installation. The correct operation of these controls will have a direct impact on energy consumption (i.e. PDI and AECI values).

The contractor is obliged to provide the originally installed lighting equipment as specified in the design used in the successful tender except in cases where equivalent or better performing equipment can be provided at no extra cost to the procurer. The need for this CPC is to prevent the contractor from substituting the originally specified lighting equipment for cheaper (and inferior) products. However, if cheaper products are available on the market that are of equivalent or superior performance, then this CPC also allows for this mutually beneficial situation to be embraced, so long as it is clearly communicated to the procurer and that adequate supporting evidence is provided of the performance of the alternative lighting equipment.

A comprehensive level CPC (CPC6) has been proposed, which only applies to contracts where a re-design or a new design has been carried out. The CPC requires that a road area selected by the procurer, free of obstructions such as trees, bus-stops and parked vehicles and as free as possible from interference from other background light sources such as advertising boards and buildings, is tested for actual lighting levels and compared with the actual power consumption of the relevant luminaires. Due to the requirements for testing, CPC6 would tend to be suitable only for M-class roads.

The aim of CPC6 is to ensure that the appropriate level of illuminance/luminance is achieved on the road (not too high and not too low). Where the same contract has set energy consumption requirements (e.g. AECI) the monitoring of power consumption must be measured. The two measurements (light level and power consumption) are the only way to verify if an installation is actually resecting the claims (e.g. PDI and AECI) of the design in the winning tender.

6.5.2. Stakeholder discussion

For verification of the in-situ PDI value, the measurement grid and calculated illuminance values should be provided by the designer and they can be verified by an illuminance meter (+/- 10 %). Nonetheless, it was pointed out that such measurements are complicated due to uneven road surfaces, which requires a self-levelling photometer and increased measurement time. Taking measurements from a point 10 cm above the road surface was not recommended due to interference by reflected light from other sources.

Stakeholders had strong opinions about post-completion monitoring of energy efficiency performance. It was emphasised that although it was very useful and obliges the contractor to comply, this would introduce additional costs and should only be used in contracts that cover larger installations. One ball-park figure that was mentioned was 4000 EUR per project. The extra time, effort and cost associated with CPC6 may be considered as excessive in smaller projects. Even in larger projects, the nature of the road area to be lit may be so affected by background light (cars, windows, adverts etc.) and other interference (balconies, trees, parked vehicles etc.) that obtaining a realistic measurement that can be compared to the original design would not be possible or practical.

The option to measure illuminance instead of luminance was supported because it is possible that the reflectance of the real road differs significantly from the assumed reflectivity used in photometric calculations.

When considering onsite verification of light levels and energy consumption, the work of CEN TC 169 regarding verification steps should be considered and acceptable tolerances should be considered in terms of Annexes E and F to EN 13201-4.

One key question that arose with the comprehensive level CPC was "*what happens in cases of non-compliance*"? Ultimately this should be defined by the procurer and be clearly stated in the ITT. Options would be either to remedy the works at no additional cost or the application of financial penalties in proportion to the discrepancy between claimed energy efficiency and photometric performance. There is also the option to provide bonuses in the case of superior performance.

6.5.3. Criteria proposals

<table>
<tr><th>Core criteria</th><th>Comprehensive criteria</th></tr>
<tr><td colspan="2">CPC4: Commissioning and correct operation of lighting controls</td></tr>
<tr><td colspan="2">(Applies to TS2 and TS3.)
(Same for core and comprehensive criteria.)
The successful tenderer (contractor) shall ensure that new or renovated lighting systems and controls are working properly.
Any daylight linked controls shall be calibrated to ensure that they switch off the lighting when daylight is adequate.
Any traffic sensors shall be tested to confirm that they detect vehicles, bicycles and pedestrians, as appropriate.
Any time switches, CLO drivers and dimming controls shall be shown to be able to meet any relevant specifications defined by the procuring authority in the ITT.
If after the commissioning of the system, the lighting controls do not appear to meet the relevant requirements above, the contractor shall be liable to adjust and/or recalibrate the controls at no additional cost to the procuring authority.
The contractor shall deliver a report detailing how the relevant adjustments and calibrations have been carried out and how the settings can be used.
Note: For large utilities the new or renovated installation may simply have to be compatible with the existing control systems used for the wider lighting network. In this situation, this CPC would also refer to the compatibility of the controls with the existing control system.</td></tr>
<tr><td colspan="2">CPC5: Provision of originally specified lighting equipment</td></tr>
<tr><td colspan="2">(Applies to TS1-6 and AC1-2.)
(Same for core and comprehensive criteria.)
The contractor shall ensure that the lighting equipment (including light sources, luminaires and lighting controls) is installed as specified in the original tender.
If the contractor changes the lighting equipment from that specified in the original tender, explanations must be provided in writing for this change and any replacement equipment must match or exceed the technical specifications of the original lighting equipment (e.g. luminaire efficacy, dimming functionality, R_{ULO} etc.).
In either case, the contractor shall deliver a schedule of the actually installed lighting equipment, together with manufacturer invoices or delivery notes in an appendix.
If alternative lighting equipment is installed, test results and reports for luminous efficacy from the manufacturer(s) of any new light sources and luminaires shall be provided,</td></tr>
</table>

along with relevant documentation stating the performance of any new lighting controls.	
CPC6: Compliance of actual energy efficiency and lighting levels with design claims	
	(Only recommended for large installations with a significant amount of installed power in non-urban environments.) Where relevant, a suitable non-urban road sub-area shall be selected by the procurer where the luminaire positioning is in line with the PDI photometry study for in-situ photometric measurements (according to EN 13032-2) and energy consumption measurements (according to EN 13201-5) during an agreed period of one week. The selected sub-area must be free of significant interference to lighting from trees, bus stops or parked vehicles and from background light levels caused by advertising boards or buildings. For M-class roads with luminance requirements, it shall be acceptable to provide illuminance data instead, if concerns about the effect of real road surface reflectivity deviating significantly from design assumptions are justifiable. The parameters influencing the uncertainty in illuminance measurements mentioned in Annex F to EN 13201-4 should be considered. It is advisable to use automated illuminance measurement systems and to agree on the illuminance and data point tolerances before the project (±10 % is suggested). During the same one-week period peak power [W] and energy consumption [kWh] shall be measured and/or calculated for the relevant light points. The in-situ measured values of PDI and AECI shall be ±10 % of the design AECI value and ± 15 % of the design PDI value. Note: The consequences of non-compliance with the design values for PDI and/or AECI should be defined in the ITT. Options could include: • Remedial works to be undertaken at no additional cost to the procurer. • Financial penalties in proportion to the degree of non-compliance (perhaps related to foreseeable additional electricity costs over a defined period caused by the poorer performing installation). In cases where non-compliance is disputed, the contractor may repeat the measurements on the same sub-area or, if it can be argued that the sub-area was not suitable for measurement, select another sub-area. The procurer shall not be liable for the cost burden of any additional measurements. If the performance is actually better than the design predictions, financial bonuses may apply if the procurer chooses to define them in the ITT.

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.

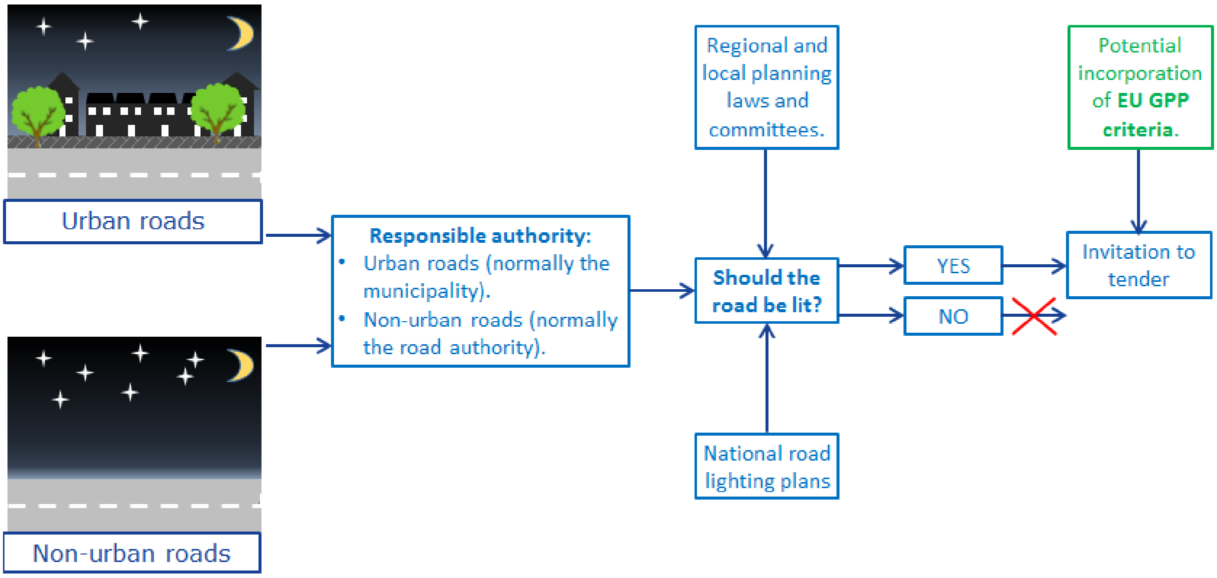

Figure 13. Role of EU GPP criteria in planning process for road lighting installations

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.

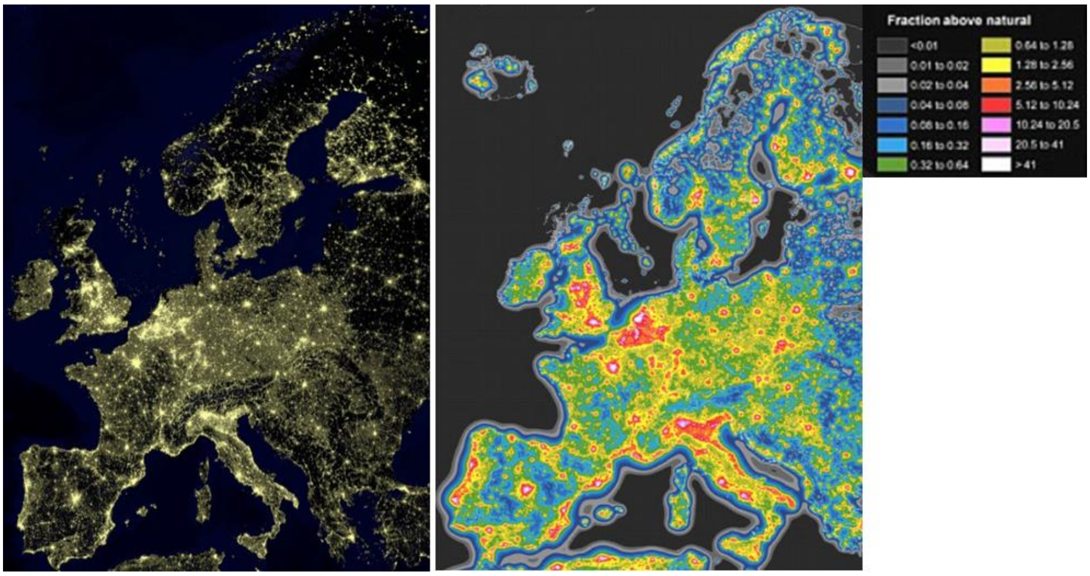

Figure 14. Light pollution in Europe: "Earthlights 2002" published by NASA (left) and a map of skyglow from Falchi et al., 2016 based on VIIRS DNB data from the Suomi NPP satellite (right).

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.

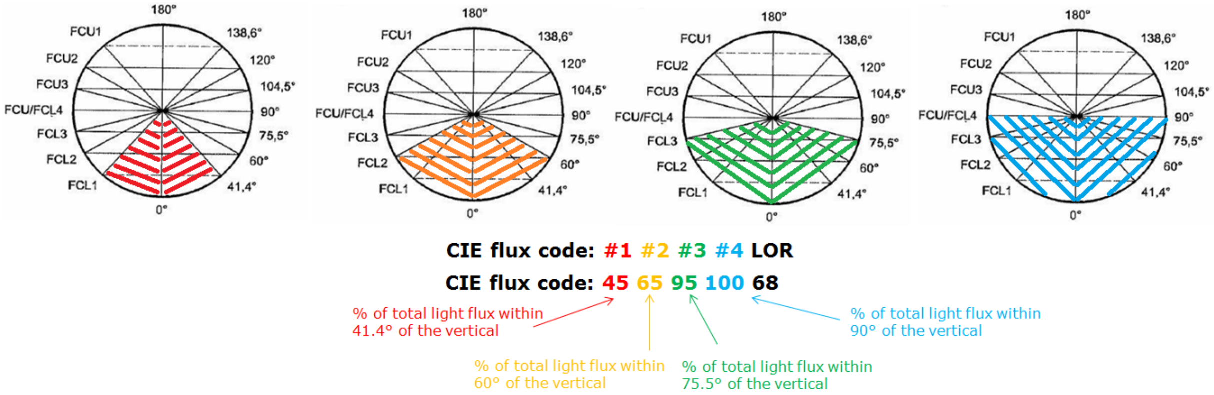

Figure 15. Illustration of illuminated zones applicable to CEN flux codes.

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.

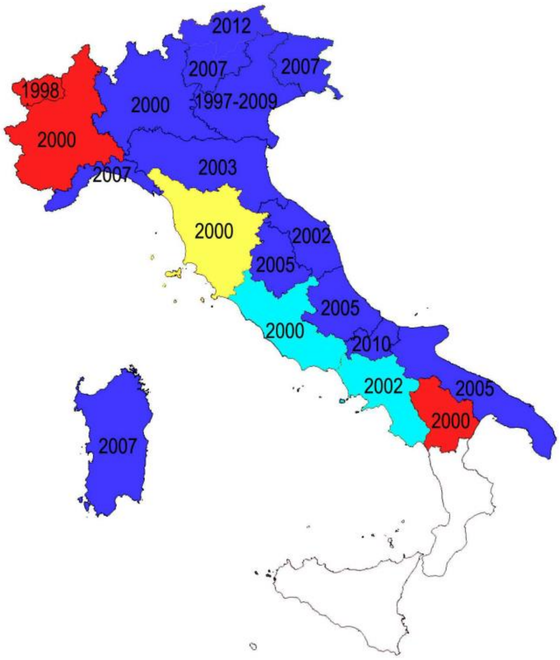

Figure 16 . Regions in Italy where 0% R_{ULO} is required (depicted in blue).

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

<table>
<tr><th>Core criteria</th><th>Comprehensive criteria</th></tr>
<tr><td colspan="2">TS7 Ratio of Upward Light Output (R_{ULO}) and obtrusive light</td></tr>
<tr><td>

(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.

</td><td>

(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.

</td></tr>
</table>

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.

<u>Blue rich light</u>

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.

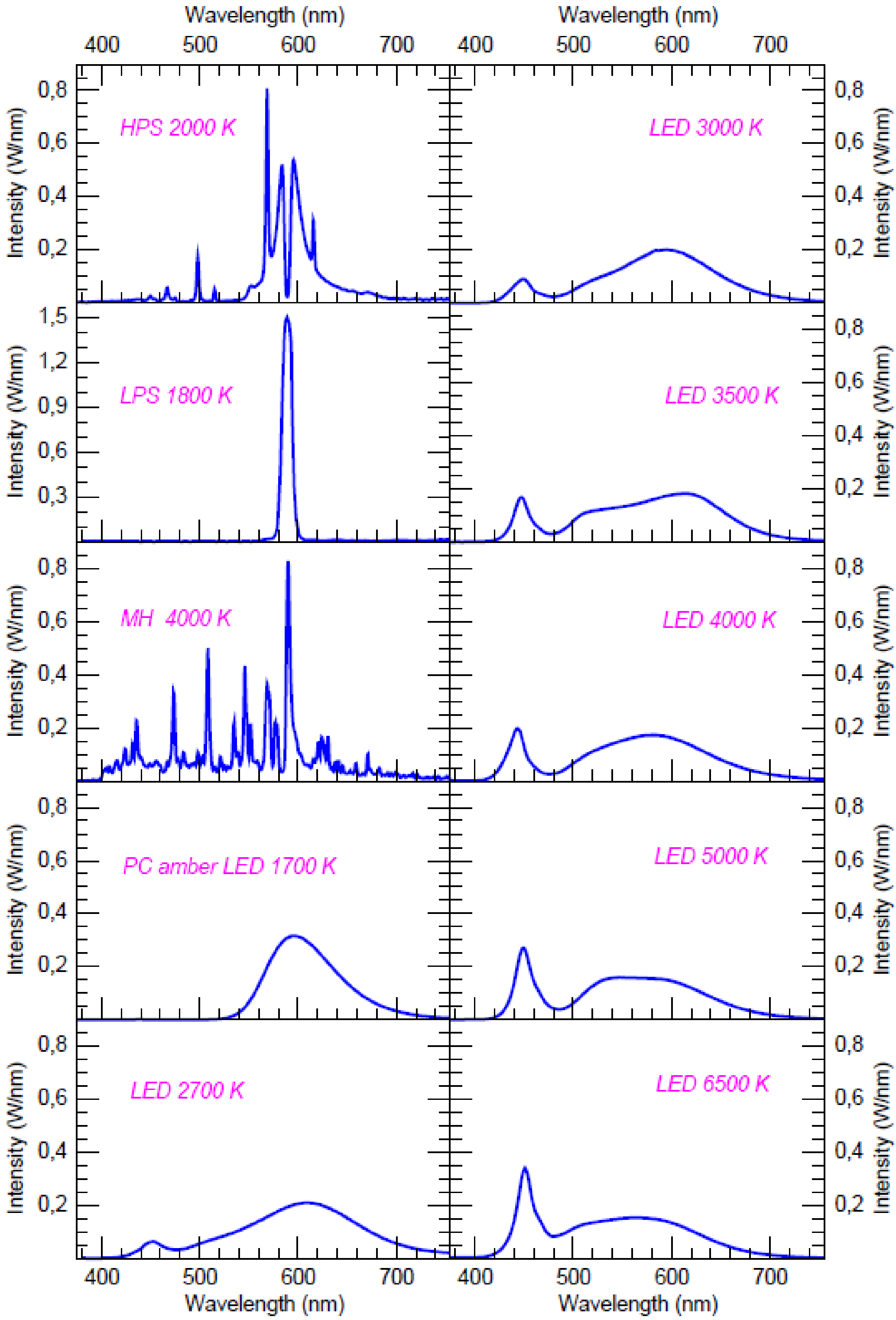

Figure 17. Spectral Power Distributions (SPDs) of different light sources commonly used in road lighting (DOE, 2017b). *PC stands for Phosphor Converted.

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.

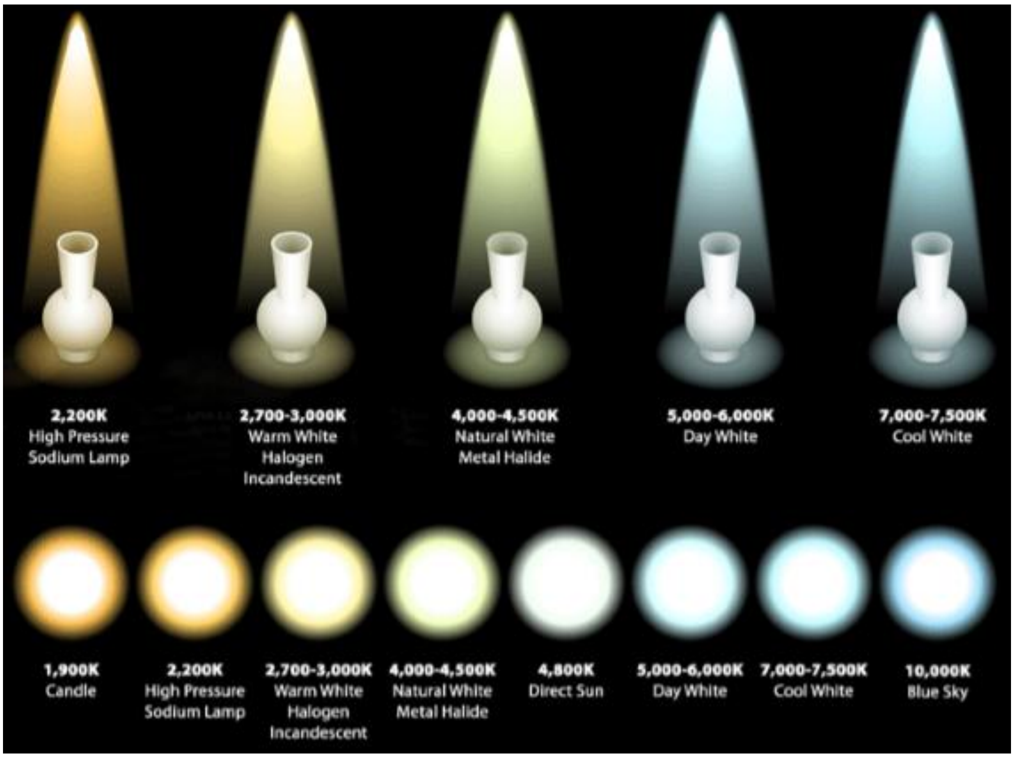

Figure 18. Illustration of different correlated colour temperatures (CCTs).

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.

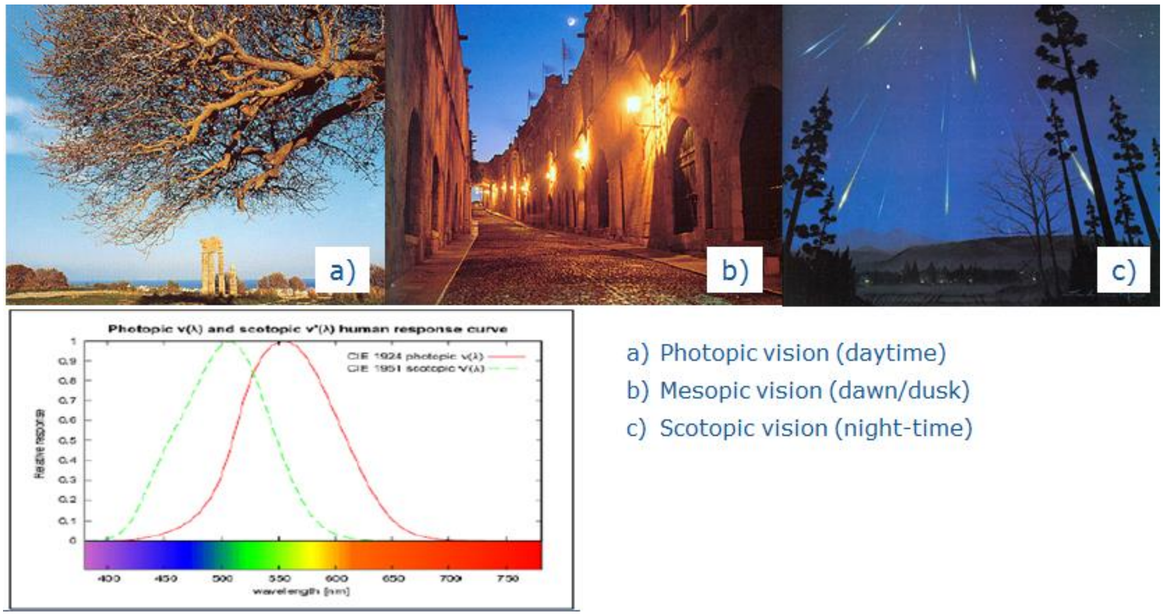

Figure 19. Illustration of the differences in photopic, mesopic and scotopic vision (a-c) and in the response of human photoreceptors in photopic and scotopic environments (Source: presentation titled "Lighting fundamentals").

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'.

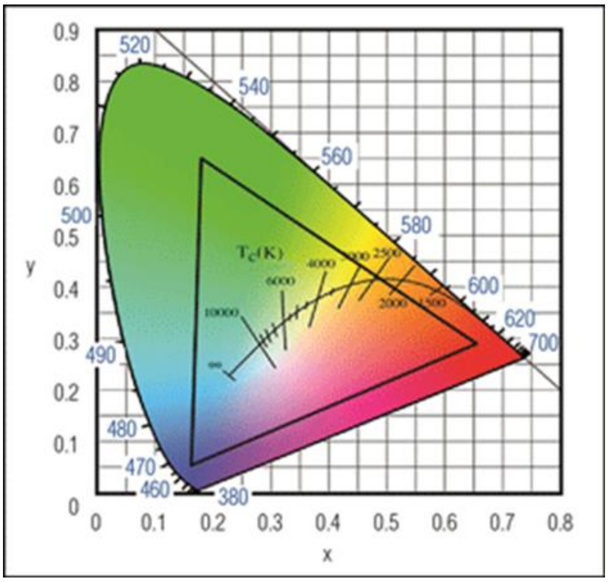

Figure 20. The CIE 1931 x,y chromaticity space showing the colour temperature locus and CCT lines: the lower the CCT, the more red light (Image sourced from this webpage).

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.

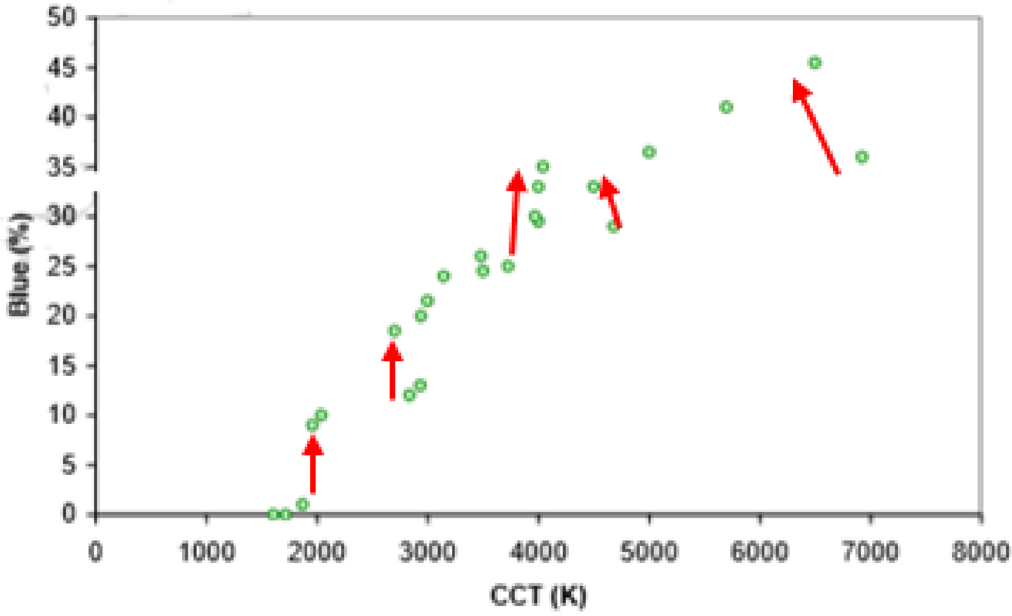

Figure 21. Correlation plot of blue light spectral power output versus CCT for different light sources.

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).

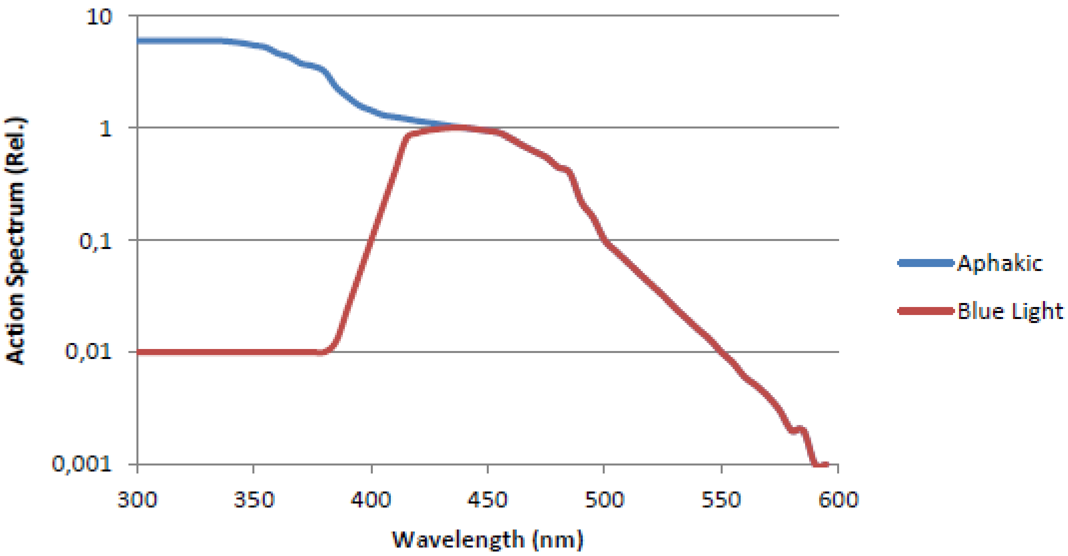

Figure 22. Blue light spectra compared to action spectra for aphakic eyes (from ICNIRP).

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.

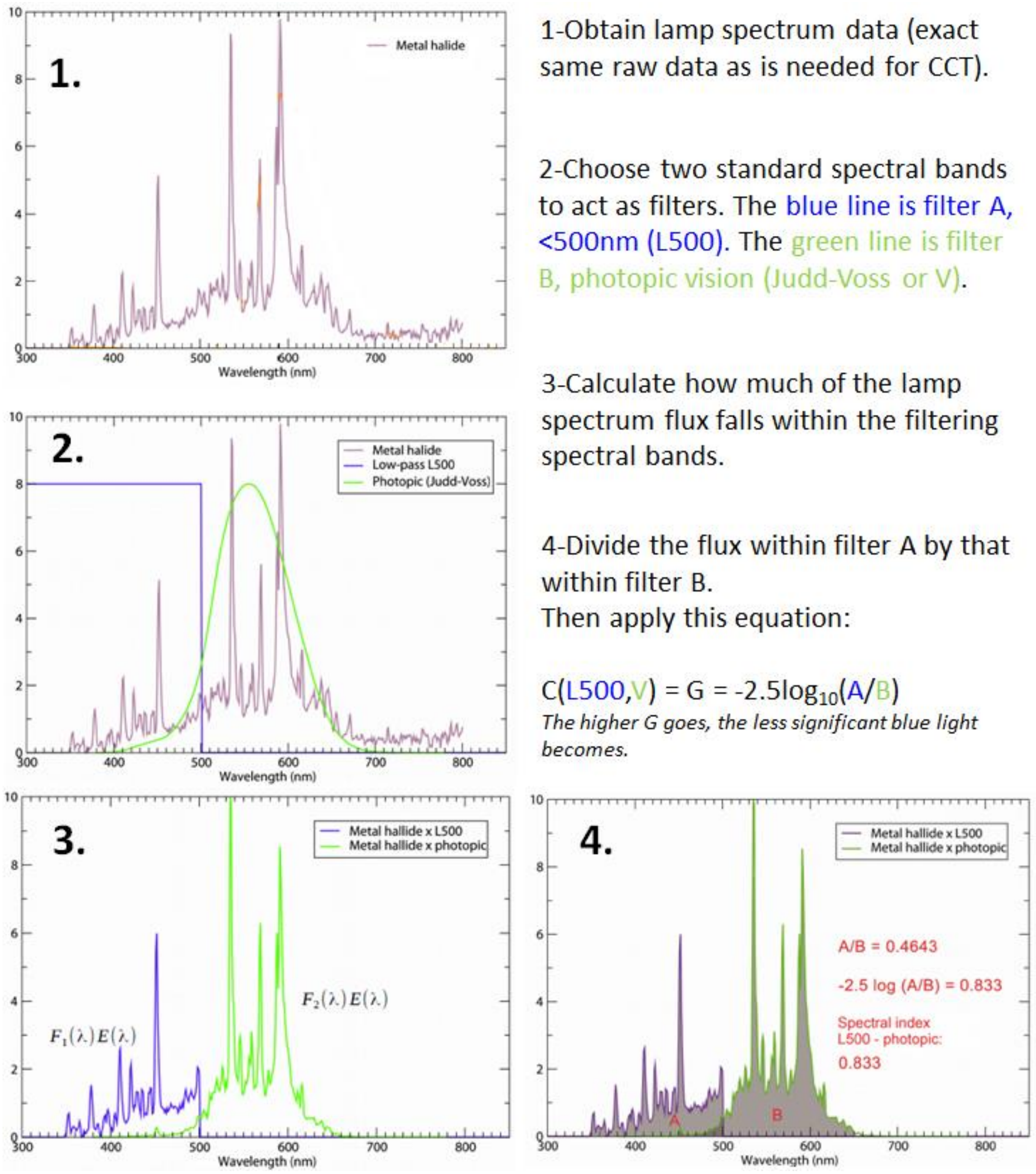

Figure 23. Example of how the spectral index C(L500,V), or G index, works.

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.

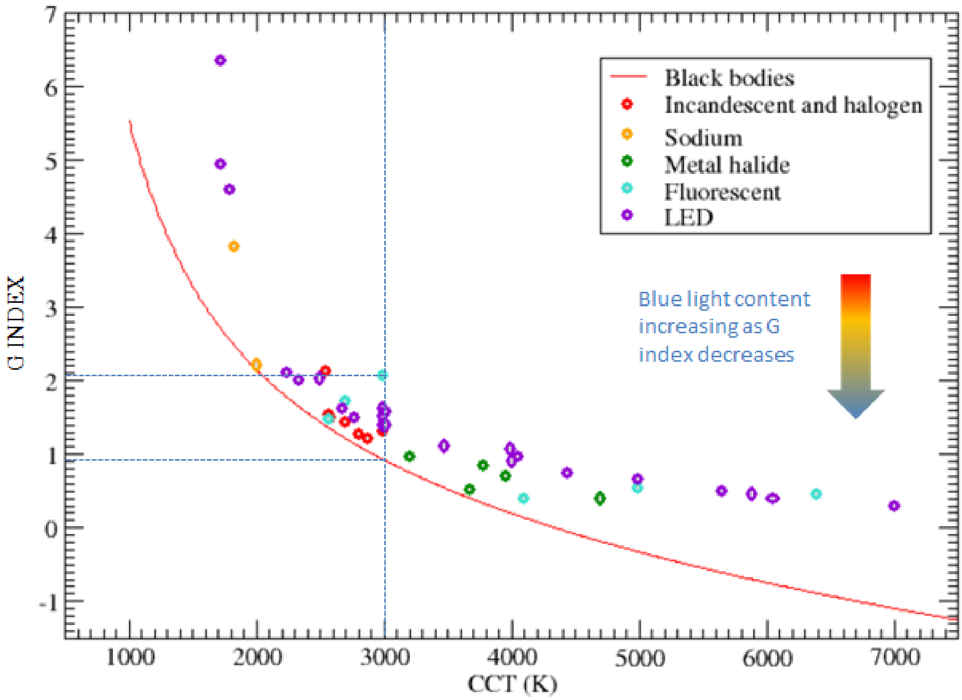

Figure 24. Correlation between CCT and G-index values for different lamps (specific comparison at 3000K highlighted).

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

<table>
<tr><th>Core criteria</th><th>Comprehensive criteria</th></tr>
<tr><td colspan="2">TS8 Annoyance</td></tr>
<tr><td colspan="2">(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).</td></tr>
<tr><td colspan="2">TS9: Ecological light pollution and star visibility</td></tr>
<tr><td>(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</td><td>(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</td></tr>
</table>

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

8. Lifetime

A lighting installation may perform well from an energy efficiency perspective and may deliver the desired quantities and qualities of light after installation but this is irrelevant if the installation is not able to maintain such performance for very long. Problems with the reliability and durability of lighting installations will have direct economic impacts as well as less direct environmental impacts.

All the criteria in this section are in one way or another related to guaranteeing a minimum useful lifetime of the lighting equipment that is procured. Longer life products that can be repaired or even upgraded to extend their useful life are an important part of European efforts to shift towards a circular economy.

8.1. Provision of instructions

8.1.1. Background research and supporting rationale

As lamps will probably have to be replaced or repaired at least once during the luminaire lifetime, it is important that the procurer has sufficient knowledge and information in order to carry out replacement and repair operations in a correct and timely manner.

When controls are provided with the system, the procurer, or the relevant operator, has to know exactly how to operate and calibrate them. Periodic recalibration of controls may be necessary as part of maintenance strategies. Besides extending the useful lifetime of the lighting equipment, correct maintenance and repair will also ensure that real-life energy consumption (AECI) can be maintained within the original design window.

8.1.2. Stakeholder discussion

In the proposals in TR 1.0, it was recommended to define a Contract Performance Clause (CPC) requiring the provision of instructions for key aspects related to the lifetime (disassembly of luminaire, replacement of light sources and minimum specifications for replacement light sources) and operation (of lighting controls, including timer or daylight level linked switches) of luminaires.

Stakeholders generally acknowledged the importance of adequate instructions but highlighted the fact that when the contract relates to only one part of a larger lighting network, the requirements for lighting controls will probably already be defined by procurers in technical specifications so that they fit in with the pre-existing centralised control scheme. In any case, it is still useful to have instructions at the level of the individual luminaire in case of the need for in-situ repair or adjustment.

8.1.3. Criteria proposals for provision of instructions

Core criteria	Comprehensive criteria
TS10 Provision of instructions	
(Applicable when the equipment and/or controls in the particular lighting installation requested in the ITT are different from the normal equipment installed elsewhere on the wider lighting network operated by the procurer.) *(Same for core and comprehensive criteria.)* The tenderer shall provide the following information with the installation of new or renovated lighting systems: • disassembly instructions for luminaires; • instructions on how to replace light sources (where applicable), and which lamps can be used in the luminaires without decreasing the energy efficiency; • instructions on how to operate and maintain lighting controls; • for daylight linked controls, instructions on how to recalibrate and adjust them; and • for time switches, instructions on how to adjust the switch-off times, and advice on how best to do this to meet visual needs without excessive increase in energy consumption. **Verification:** The tenderer shall provide a declaration of compliance with this criterion, supported by examples of written instructions that will be provided to the contracting authority should the tender be successful.	

8.2. Waste recovery

8.2.1. Background research and supporting rationale

Most procurement contracts in EU countries will relate to the renovation or relamping of existing lighting installations. This will result in the generation or waste lamps, ballasts, luminaires and other auxiliary controls. The disposal of waste electronic and electrical equipment (WEEE) has historically been a problem and a loss of potential valuable raw materials which are present in small amounts in each individual component or product.

Large scale organised collection of WEEE will maximise opportunities to recover valuable raw materials and is one of the main drivers behind the WEEE Directive (2012/19/EU). Under the Directive, Member States are obliged to create systems and infrastructure for the collection and recycling of WEEE.

The calculation of WEEE recovery rates is complex because first it is necessary to estimate the number/tonnage of WEEE products on the market and model the expected number of those products which will reach their End-of-Life in any given year. For this purpose, the Commission has provided calculator tools for each Member State that are prepopulated with numbers based on market data and consumption patterns specific to that Member State (EC, 2017).

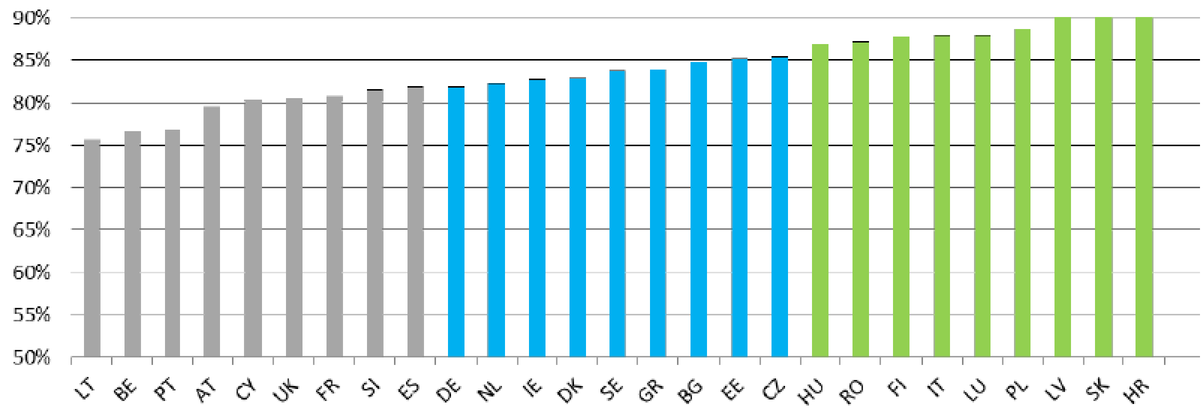

Figure 25. WEEE collection rate in different Member States in 2014 (Source: BIPRO, 2017).

Although collection rates of WEEE appeared to be generally on target for being at least 85% in 2019, it is important to ensure that tenderers know where to take the WEEE and commit to doing so if awarded the contract.

Lighting equipment is one of the 13 main categories of WEEE that are defined for WEEE statistics. Although collection rates are generally very high for this category, the main concern with lighting equipment is the potential presence of mercury in gas discharge lamps, which could require separation from other WEEE streams and special processing due to the volatility of mercury under ambient conditions.

8.2.2. Stakeholder discussion

In TR 1.0, CPCs were proposed for the contractor to commit to collecting, sorting and disposing of waste lamps, luminaires and lighting controls for recycling and, where relevant, to facilities accepting WEEE (Waste Electrical and Electronic Equipment). The comprehensive level CPC introduced the additional requirement to produce a bill of materials for a number of specified metals in the waste stream.

Stakeholders were generally of the opinion that a commitment to respecting the requirements of the WEEE Directive was sufficient and that requirements relating to bills of materials would represent additional costs and be of doubtful value when it comes to renovation at least 10-20 years in the future. Furthermore, it was pointed out that the specific information requested in the initially proposed comprehensive level CPC in terms of the quantities of the specific metals listed did not reflect current practice. How requirements for this CPC apply to different situations need to be clarified, i.e. (i) disposal of waste from a renovation project during the initial execution of the contract and (ii) design for recyclability for a potential future disposal of the new lighting equipment installed during the execution of the contract. Regardless, the scope of the CPC should be clarified (e.g. luminaires, light sources, control equipment, cabinets etc.).

One stakeholder added that the future recyclability of lighting equipment may be hampered by the presence of hazardous materials such as mercury. It could be justified that EU GPP could set criteria for mercury free lamps to be used on the basis that it may enhance the future recyclability of the waste lamp. LED lighting is mercury free and although High Pressure Mercury lamps have effectively been phased out by Regulation (EC) 245/2009 since 2015, it is still possible for many other different HID-based lamps still on the EU market to contain mercury (IMERC, 2015).

A mixed response from stakeholders was received about the potential ban on mercury-containing lamps. It was recognised that this would essentially ban the procurement of new HID-type lamps in any ITT containing this criterion as a technical specification. However, at the same time, procurement of new lamps is now dominated by LED lamps that would already comply. The benefit of using mercury-free lamps at the End-of-Life should be supported by labelling of the lamps as Hg-free.

8.2.3. Criteria proposals for waste recovery

<table>
<tr><th>Core criteria</th><th>Comprehensive criteria</th></tr>
<tr><td colspan="2">TS11 Waste recovery</td></tr>
<tr><td colspan="2">(Same for core and comprehensive criteria.)

The tenderer shall implement appropriate environmental measures to reduce and recover the waste produced during the installation of a new or renovated lighting system.

All waste lamps and luminaires and lighting controls shall be separated and sent for recovery in accordance with the WEEE directive[1]. Any other waste materials that are expected to be generated and that can be recycled shall be collected and delivered to appropriate facilities.

Verification:

The tenderer shall provide details of the waste handling procedures in place and identify suitable sites to which WEEE and other recyclable materials can be taken to for separation, recycling and heat recovery, as appropriate.</td></tr>
<tr><td colspan="2">CPC7 Commitment to waste recovery and transport to suitable sites</td></tr>
<tr><td colspan="2">(Applies to TS11.)

(Same for core and comprehensive criteria.)

The contractor shall provide a schedule of the waste collected during the project. In addition, the contractor shall provide details of any sorting that has been applied prior to transport to suitable sites identified in the original tender or to other suitable sites where waste can be sorted, processed, recycled and, if relevant, subject to heat recovery.

Delivery invoices shall be submitted as proof of delivery.</td></tr>
</table>

[1] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) recast (OJ L 197, 24.7.2012, p.38).

8.3. Product lifetime

8.3.1. Background research and supporting rationale

Apart from the potential to improve energy efficiency, one of the main advantages of LED lighting is the significantly longer lifetime of the light source compared to most other road lighting lamp technologies. Operation times of 100000 hours, equivalent to 25 years operation of road lighting, may be claimed.

Extension of the lifetime of luminaires and its components reduces the overall environmental impacts caused by shorter lifespans, raw material extraction and manufacturing processes. It also partly justifies the higher initial investment in more efficient road lighting installations. An extension of the warranty period would be an addition to the requirements on lifetime and would decrease the frequency of premature failures.

All lamp technologies suffer a decrease in lumen output for a given power consumption (i.e. a decrease in luminous efficacy) with time. This has been referred to as the factor of lamp lumen maintenance (F_{LLM}) and can be combined with potential losses of light output caused by dirt collecting on the luminaire (F_{LM}).

However, the lifetime of LED lighting is not so simple to guarantee. There are many different components that may contribute to the failure of an LED component, such as the driver, overheating, poor electrical connections etc. The reliability of a particular LED-based luminaire should be considered as the sum of all the failure rates of the individual critical failure mechanisms.

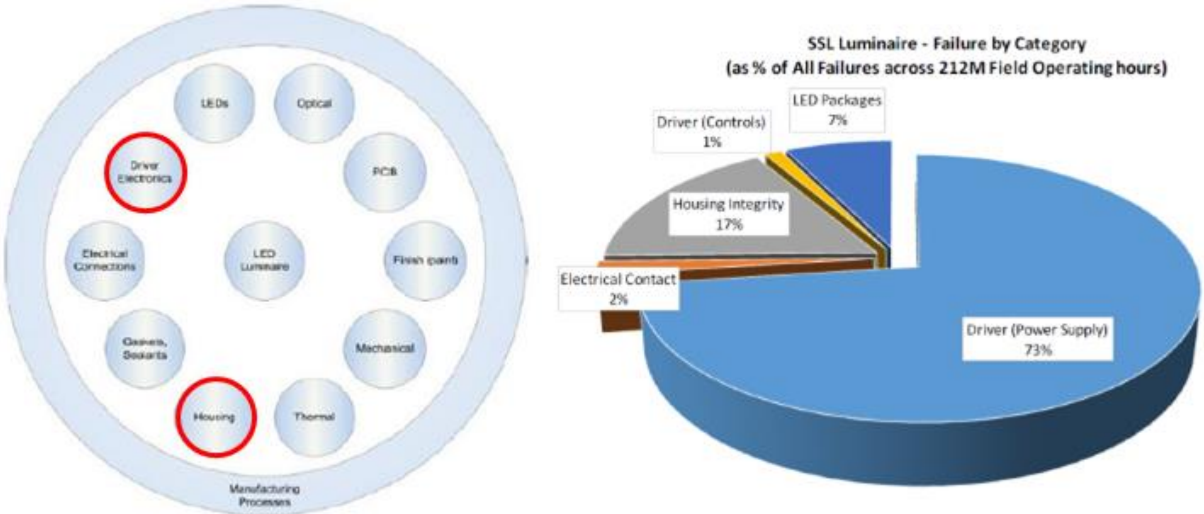

Figure 26. Examples of potential causes of LED failure (left) and statistics about the most common causes of failure (right). Source: LSRSC, 2014.

The relevant parameters relating to LED luminaire life times are Cz and LxBy are both defined in EIC 62717 and equivalent to the Lamp Survival Factor and Lamp Lumen Maintenance Factors for traditional HID lamps respectively. The former terms can be explained as follows:

- LxBy relates to gradual reductions in lumen output where x is the % of original lumen output still maintained after a defined operating time and y is the % of units that no longer meet the x % of original lumen output at that same time. For example, L70B50 at 50000 hours means that overall lumen output is at least 70% of the original output and less than 50% of the fixtures are <70%. It is common practice to term the "rated life" of an LED light source as the point when its luminous efficacy reaches 70% of the original efficacy.

- Cz relates to abrupt failures at the end of rated life. Abrupt failures happen with no set pattern in time. Consequently, linking to the LxBy value above, a Cz value of C10 at 50000 hours would mean 10% of the LED modules suffer abrupt failure during the rated life – and that the failure rate is effectively 0.2% per 1000 hours operation.

Due to the long lifetimes involved and the rapid development of LED lighting technology, there is not a sufficient evidence base of long term test data to verify lifetime claims. Even if there was, it would be relatively obsolete since the technology would have evolved significantly in the meantime.

In the US, the Illuminating Engineering Society of North America (IESNA) has an approved method (TM-21-11) taking LM-80 data and making useful LED lifetime projections. According to what has been reported in the stakeholder meeting a European standard is under elaboration and will be based on this same aspect.

8.3.2. Stakeholder discussion

An initial proposal in TR 1.0 was made for lumen maintenance to be L92B50 at 16000 hours (core) and both L92B50 at 16000 hours and L80B50 at 50000 hours (comprehensive).

Most stakeholders were agreed about the importance of the criterion, especially to those responsible for maintenance of the lighting installation and especially in harsh environments with large temperature fluctuations. However, there was a split opinion about whether maintenance factor specifications should extend beyond 6000 or 16000 hours. Those against longer term maintenance factors cited the current uncertainty in Europe regarding the extrapolation of laboratory data for LED light sources to longer lifetime expectancy claims. However, since then "*IEC 63013:2017 LED packages - Long-term luminous and radiant flux maintenance projection*" has been officially published.

Stakeholders in favour of longer term lifetime projections being included in criteria generally felt that the ambition level should be raised. It was pointed out that luminaires that meet L92B50 at 16000 hours would also tend to meet L80B50 at 50000 hours – so there is no great distinction between the original proposals for core and comprehensive levels. One stakeholder proposed to increase the comprehensive requirement to L80B10 and L80C08 at 50000h. Lighting Europe reported that they were considering the application of LxBy values for 100000 hours (i.e. 20 years operation) and such an approach may be interesting for comprehensive level criteria. Some stakeholders also pointed out that, from the procurers perspective, it is the Lx component of LxBy that is important and not the By part. This was also in line with a recent white paper published by LightingEurope (titled "*Evaluating performance of LED based luminaires*"). Consequently, it was proposed that GPP criteria should only focus on Lx.

Regarding standard methods for assessing LxBy and LxCz in the laboratory, one stakeholder opined that IEC 62722 should be used instead of a combination of IESNA LM80 and TM21. If abrupt failure is to be specifically addressed in lifetime criteria (i.e. LxCz values) then it would be worth referring to IEC 62861:2017, which will include optical materials, interconnectors, electronic subassemblies, cooling systems and construction materials used in LED light sources or luminaires. Another option is to simply have a criterion on the maximum acceptable failure rate for control gear (since this is the most common cause of failure as shown in Figure 26 above). However, any specific requirements for abrupt failure rates will always be questionable since they are based on predictions with a certain amount of statistical uncertainty and are not always published by manufacturers.

The truth is that long term performance can be estimated but never known for certain. For this reason, the idea of requesting extended warranties for LED light sources was raised. Mixed opinions from stakeholders were evident. While some stakeholders were against the idea of extended warranties, others felt that an example of 32000 hours operation (i.e. 8 years) would be a reasonable request and that reputable manufacturers would be more likely to commit to extended warranties. It was claimed that warranties of 3-5 years were already common practice and warranties up to 10 years could reasonably be requested but would likely have a cost impact for the procurer. However, longer warranties need to be backed up with clear CPCs otherwise they may simply represent a meaningless commitment.

8.3.3. Criteria proposals for product lifetime and warranty

Core criteria	Comprehensive criteria
TS12 – LED lamp product lifetime, spare parts and warranty	
(The thresholds defined here are applicable to LED-based light sources, lamps and luminaires.) Any LED-based light sources shall have a rated life at 25°C of: • L96 at 6 000 hours, • L70 at 50 000 hours (projected), • C0 at 3 000 hours or C10 at 6 000 hours, • C50 at 50 000 hours (projected). The repair or provision of relevant replacement parts of LED modules suffering abrupt failure shall be covered by a warranty for a period of 5 years from the date of installation. **Verification:** Test data regarding the maintained lumen output of the light sources shall be provided by an International Laboratory Accreditation Cooperation-accredited laboratory that meets IES LM-80* for actual data and IES TM-21* for projected data. The tenderer shall provide a copy of the minimum 5-year warranty to be signed if the tender is successful. The contractor shall provide a copy of the warranty that will apply if the tender is successful and provide the necessary contact details (phone and email as a minimum) for dealing with any related queries or potential claims. For clarity, the warranty shall, as a	***(The thresholds defined here are applicable to LED-based light sources, lamps and luminaires.)*** Any LED-based light sources shall have a rated life at 25°C of: • L96 at 6 000 hours, • L70 at 100 000 hours (projected), • L0C0 at 3 000 hours or C10 at 6 000 hours, • C50 at 100 000 hours (projected). The repair or provision of relevant replacement parts of LED modules suffering abrupt failure shall be covered by a warranty for a period of 7 years from the date of installation. **Verification:** Test data regarding the maintained lumen output of the light sources shall be provided by an International Laboratory Accreditation Cooperation-accredited laboratory that meets IES LM-80* for actual data and IES TM-21* for projected data. The tenderer shall provide a copy of the minimum 7-year warranty to be signed if the tender is successful. The contractor shall provide a copy of the warranty that will apply if the tender is successful and provide the necessary contact details (phone and email as a minimum) for dealing with any related queries or potential claims. For clarity, the warranty shall, as a

minimum, cover the repair or replacement costs of faulty LED module parts within a reasonable timeframe after notification of the fault (to be defined by the procurer in the ITT), either directly or via other nominated agents. Replacement parts should be the same as the originals, but if this is not possible, equivalent spare parts that perform the same function to the same or to a higher performance level may be used. The warranty shall not cover the following: a) faulty operation due to vandalism, accidents or other extreme weather events; b) lamps or luminaires that have been working for a significant time under abnormal conditions (e.g. used with the wrong line voltage), insofar as this can be proven by the contractor. **To be updated to LM-84 and TM 28 when these versions are published.*	minimum, cover the repair or replacement costs of faulty LED module parts within a reasonable timeframe after notification of the fault (to be defined by the procurer in the ITT), either directly or via other nominated agents. Replacement parts should be the same as the originals, but if this is not possible, equivalent spare parts that perform the same function to the same or to a higher performance level may be used. The warranty shall not cover the following: a) faulty operation due to vandalism, accidents or other extreme weather events; b) lamps or luminaires that have been working for a significant time under abnormal conditions (e.g. used with the wrong line voltage), insofar as this can be proven by the contractor. **To be updated to LM-84 and TM 28 when these versions are published.*

AC3 Extended Warranty

(Applies to TS12.)

(Same for core and comprehensive criteria.)

A maximum of X points shall be awarded to tenderers that are willing to provide initial warranties that go beyond the minimum warranty periods stated in TS12 and whose cost is already included in the bid price. Points shall be awarded in proportion to how long the warranty exceeds the minimum requirements, as follows:

- Minimum + 1 year: 0.2X points
- Minimum + 2 years: 0.4X points
- Minimum + 3 years: 0.6X points
- Minimum + 4 years: 0.8X points
- Minimum + 5 years or more: X points

Tenderers may also optionally provide quotations for extended warranties that are not included in the bid price, although points shall not be awarded for this. In such cases, no payment for any extended warranty will be required until the final year of the initial warranty, after which the procurer will make annual payments to the successful tenderer at the beginning of each year of the extended warranty.

Furthermore, the procurer will have the option to initiate or reject the offer of an extended warranty right up until the final year of the initial warranty; the costs of the extended warranty will be those initially proposed, plus inflation.

8.4. Reparability

8.4.1. Background research and supporting rationale

Reparability is one of the key principles that products need to embrace to ensure the transition to a circular economy. In general, products that can be repaired will retain their residual value for the second-hand market and are set up to have extended product lives.

For road lighting, reparability is of particular value to the manufacturer when the products are under warranty in cases where repair due to a simple fault could prevent the need to replace the entire product. Reparability is also of value to the procuring authority if the installation is managed by an in-house maintenance team.

8.4.2. Stakeholder discussion

Stakeholders felt that reparability was an important issue and stated that it was already being considered in mid to high tier products. It was considered important that the LED module and ballast are designed so that they can be replaced independently. A series of 4 reparability classes for LED luminaires established by Synergrid (specification C4/11-3) was described as follows:

- Class 1-LED module and auxiliaries can be removed and replaced in-situ at the luminaire mounting height;
- Class 2 – Auxiliaries can be removed and replaced in situ at the luminaire mounting height;
- Class 3 – luminaire has to demounted before removal and replacement of the LED module or auxiliaries;
- Class 4 – The luminaire is sealed and must be discarded in the case of failure of the LED module or any internal auxiliaries.

Another important aspect to consider in GPP criteria was that of "*upgradeability*" for LED light sources in existing luminaires. Upgrade could simply mean more energy efficient components, a lower energy consumption for a given photometric output or improved control and functionality. Upgradeable luminaires may offer significant economic and material savings when compared to the complete replacement of luminaires.

During the final written consultation, the publication of a white paper by LightingEurope which focuses on the "*serviceability*" of luminaires in the context of the circular economy was mentioned. The paper described the following relevant activities:

- Repair and preventative maintenance of hardware components or software (e.g. replacing a broken LED module or updating driver software to remove a bug).
- Replacement of hardware or software to improve performance (e.g. mounting a more efficient LED module).
- Replacement of hardware or software to meet different specifications (e.g. mounting a new LED module with different light output and/or colour).
- Replacement of hardware or software, or adding new hardware, to add new functionality (e.g. mounting a lamp with remote connectivity or updating software to accept inputs from a new sensor).

While the paper recognises the benefits of products that are designed in such a way as to maximise their serviceability, it claims that it is too early to consider any regulatory approach. Instead, an information scheme at the level of the luminaire should first be developed that could be ratified at the CEN/CENELEC level. An initial proposal was to split different components into those which are simply "*replaceable*" and those which are "*plug and play*". This latter would be much simpler to replace. Other important terms mooted were "*connectivity*" and "*programmability*".

8.4.3. Criteria proposals for reparability

Core criteria	Comprehensive criteria
TS13 Reparability	
(Same for core and comprehensive criteria.) The tenderer shall make sure that it is feasible and practical for a professional to access components (e.g. light source, lamp, LED module, driver) after the luminaire has been put into service. Components must be identifiable, accessible and removable without damaging the component or the luminaire. Replacement of components shall be able to be performed on site (i.e. at luminaire mounting height), without tools (i.e. plug and play) or with one of the following types of screwdriver: - standard, Pozidriv, Phillips, Torx, Allen key or combination wrench. **Verification:** The tenderer shall provide a technical manual, which shall include an exploded diagram of the luminaire illustrating the parts that can be accessed and replaced. The parts covered by service agreements under the warranty must also be indicated.	

8.5. Ingress Protection

8.5.1. Background research and supporting rationale

The lifetime of the luminaire itself, i.e. the housing, cabling and optics, is usually not an issue, but the output of good quality light depends on its adequate design and maintenance. Light quality is in particular affected by the amount of dirt and water getting inside the luminaire and should be reduced as much as possible. This can be assessed according to the IP rating system. According to CIE 154:2003, the IP rating (dust and moisture protection) has also a direct impact on the luminaire maintenance factors.

IP is a two digit code. The first digit indicates the level of protection that the enclosure provides against access to hazardous parts (e.g. electrical conductors, moving parts) and the ingress of solid foreign objects. The second digit indicates the protection of the equipment inside the enclosure against harmful ingress of water.

For all road lighting, it is necessary that no ingress of dust is allowed and protection against water is guaranteed. Benchmark values are provided in Ecodesign Regulation EC/245/2009:

- IP65 for road classes ME1 to ME6 and MEW1 to MEW6
- IP5x for road classes CE0 to CE5, S1 to S6, ES, EV and A

IP65 rating means "*No ingress of dust; complete protection against contact*" and "*Water projected by a nozzle against enclosure from any direction shall have no harmful effects*".

8.5.2. Stakeholder discussion

In TR 1.0, a technical specification was proposed for the ingress protection rating of luminaires in M or C class roads of 65 or 66 (depending on local conditions) and of 55 for luminaires used in P class roads.

Some stakeholders were against the imposition of minimum requirements for IP ratings for luminaires in GPP criteria. The main argument against this was that the correct application of IEC 60598-1 standard (specifically clause 9) is considered appropriate for deciding what IP rating is required. Any over specification of IP rating was claimed to simply add cost but no environmental benefits.

However, it was argued that a good IP rating is an essential component of ensuring a good product lifetime. A general requirement for IP 65 for all road lighting was proposed by one stakeholder. Another specific suggestion was to require IP66 for road classes M1 to M6 and IP55 for road classes C0 to C5, P1 to P6, ES, EV and A. Another stakeholder added that IP65 was the minimum requirement in Belgium.

8.5.3. Criteria proposals for Ingress Protection

Core criteria	**Comprehensive criteria**
TS14 Ingress Protection (IP) rating	
(Same for core and comprehensive criteria.) Luminaires for M- and C-class roads shall have an optical system with an ingress protection rating of IP65 or higher, depending on the local conditions. Luminaires for P-class roads shall be IP55 or higher, depending on the local conditions. **Verification:** The tenderer shall provide the technical specifications, demonstrating that this criterion has been met according to IEC 60598-1 clause 9.	

Note: The tests for the ingress of dust, solid objects and moisture specified in IEC 60598-1 are not all identical to the tests in IEC 60529 because of the technical characteristics of luminaires. An explanation of the IP numbering system is given in Annex J of the standard.

8.6. Failure rate of control gear

8.6.1. Background research and supporting rationale

The control gear is often a weak point for the luminaire life time. As discussed in the Preliminary report (section 3.4.1.2.2) high-quality drivers provide a service life of more than 50000 hours with a failure rate of 0.2% per 1000 hours. Low-performance devices come with a service life of 30000 hours and failure rates of 0.5% per 1000 hours. Therefore, the core criteria are set at the standard for high quality drivers while the comprehensive criteria go a step further.

8.6.2. Stakeholder discussion

In TR 1.0, minimum technical specifications were made for maximum acceptable failure rates of 0.2% per 1000h and a 5 year warranty (core level) and 0.1% per 1000 with a 7 year warranty (comprehensive level).

Stakeholders accepted that the failure rates were well chosen although lower failure rates associated with better quality control gear would result in increased costs. Reputable suppliers will already have failure rate test data from industry quality control testing. Stakeholders were not aware of any international standards for assessing failure rates for control gear. When prompted about possible requirements in GPP criteria for higher protection levels in control gear due to dielectric strengths, stakeholders felt that this would be difficult to verify and should not be specified as it was still under discussion in the IEC technical committee.

8.6.3. Criteria proposals for control gear failure rates

Core criteria	Comprehensive criteria
TS15 Failure rate of control gear	
The specified control gear failure rate shall be lower than 0.2 % per 1000 h and be covered by an 8-year warranty for control gear. **Verification:** The tenderer shall provide a declaration of compliance with the above failure rate for any control gear it intends to supply. The declaration shall be supported by relevant industry-standard testing procedures.	The specified control gear failure rate shall be lower than 0.1 % per 1 000 h and be covered by a 10-year warranty for control gear. **Verification:** The tenderer shall provide a declaration of compliance with the above failure rate for any control gear it intends to supply. The declaration shall be supported by relevant industry-standard testing procedures.

8.7. Labelling of LED luminaires

8.7.1. Background research and supporting rationale

This potential criterion is of direct relevance to LED road lighting in particular. If metering is not in place, a common situation according to stakeholder feedback, it is difficult to estimate the current electricity consumption of the lighting installation. When it comes to replacing lamps, it is extremely important to know the relevant input voltages. These issues are also relevant to traditional lamp technologies, as illustrated by the labelling scheme that provided in Finnish Transport Agency guidelines.

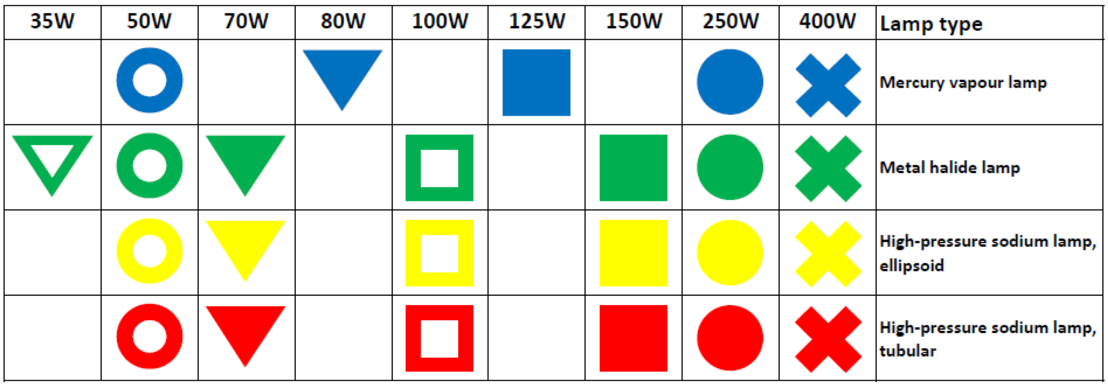

Figure 27. Example of labelling system recommended in Finland for traditional lamp technologies (FTA, 2016).

With traditional lamp technologies, labelling was to some extent simpler because the lamps were only supplied with certain standard power ratings (e.g. 35W, 50W, 100W, 250W etc.). However, with LED lamps, the rate of technological advance is so fast that there is not yet any industry standard power rating that can apply. This fact, coupled with the possibilities for dimming, make it extremely difficult to assess the actual energy performance of existing road lighting installations, which in turn makes it more difficult to accurately assess the potential for energy savings by retrofitting the installation with new and more efficient lamps.

An example of labelling requirements specifically for LED installations is provided in the Synergrid technical specification used in Belgium (Synergrid), which include the following:

- Wiring diagram.
- Manufacturer's name, code, serial number and date of manufacture.
- Type of lighting appliance.
- Nominal input voltage (or range).
- Nominal input current (or range).
- Total input power (or range).
- Light flux emitted at ambient temperature (25°C).
- LED current in mA.
- Colour temperature and colour rendering index.
- Indication of the dimming control technology (if applicable).
- Mercury free or mercury-containing

8.7.2. Stakeholder discussion

Some requests were made for an EU GPP criterion that requires a certain amount of key information to be available on the luminaire. The main reason for this is because LED technology is advancing so quickly, that it is important that procurers can remain aware of the actual equipment that they have installed and be well informed when the time comes to replace the existing LED lamps or luminaires. In theory, all of this information should be kept in records of the public authority, but these can be lost or incorrectly archived.

Traditional HID lamp technologies tend to come in one of 3 or 4 standard power ratings but LED lamps can have a much broader range of power ratings. Such a situation can make it impossible to accurately estimate the AECI of the lighting installation.

The most important information necessary was generally considered as: power rating; luminous flux; Upward Light Ratio (ULR); CIE flux codes and CCT. In later discussions, it was also proposed to include information about the G-Index. The added value of this information is that it could then be combined with the luminous flux to calculate the amount of blue light being injected into the environment from the lighting installation:

$$B = \frac{L}{683}\ x\ 10^{(-0.4G)}$$

Where: B is the power of blue light emission (in Watts), L is the luminous flux (in lumens) and G is the G-index (unitless).

No objections were received by stakeholders to including this information although no particularly preferable way of providing this information was described either. The main options are: stickers with QR codes; stickers with information printed on top or engravings onto metal plates.

8.7.3. Criteria proposals for labelling of LED luminaires

<table>
<tr><th>Core criteria</th><th>Comprehensive criteria</th></tr>
<tr><td colspan="2">TS16 Labelling of LED luminaires</td></tr>
<tr><td colspan="2">(Applicable when new LED luminaires are installed.)
(Same for core and comprehensive criteria.)
The luminaires proposed to be installed by the tenderer shall carry, as a minimum, the following technical information:
• manufacturer's name, code, serial number and date of manufacture;
• input power rating;
• luminous flux at 25°C;
• upward Light Ratio;
• CIE flux codes;
• correlated colour temperature (CCT);
• G-index;
• indication of the dimming control technology (if applicable).
The information should be included in the luminaire and, where possible, also in a part of the light pole that is accessible from ground level. The tenderer should specify how exactly this information will be displayed (e.g. on a label with a QR code, a label with written information or a metal plate with engravings).</td></tr>
</table>

Verification:
The tenderer shall provide a sample description of the label they propose to provide with their lighting equipment if their tender is successful.
CPC8 Labelling of LED luminaires
(Applies to TS16.)   *(Same for core and comprehensive criteria.)*   The contractor shall commit to providing labels for the luminaires they supply that contain at least the minimum information specified in TS16.

9. Traffic signals

Although not strictly the same subject matter, criteria for traffic signals are included together with the broader criteria-set for road lighting. The main reason for grouping traffic signals here is that there is no dedicated EU GPP product group for traffic signals (e.g. *EU GPP Traffic Management Systems*) and they are not included within the scope for "*EU GPP Road Design, Construction and Maintenance*".

9.1. Life Cycle Cost

9.1.1. Background research and supporting rationale

The existing EU GPP criteria for traffic signals focus exclusively on energy efficiency and set maximum operating wattages of 9 to 12W (core) or 7 to 9.5W (comprehensive depending on the diameter of the roundel, the colour of the light and whether the display was a full ball or just an arrow.

The criteria proposed in TR 1.0 (October 2016) were identical to the comprehensive ambition level set in the 2012 criteria for energy efficiency. The only additional aspect was that a minimum lamp lumen maintenance factor (L92B50 at 16000 hours) and a minimum lamp survival factor of L92C08 at 16000 hours were set.

In both the existing EU GPP criteria and the TR 1.0 proposal, there is a lack of data about the energy consumption of pedestrian signals – which will also be highly relevant to the contractual subject matter in the majority of road intersections.

Energy efficiency and lifetime data can be quite neatly combined with a life cycle cost framework over a defined period. Better energy efficiency results in lower electricity costs and better lifetime results in reduced maintenance costs. An added advantage of longer life is that there will be less disruption to traffic caused by traffic signal maintenance.

It is uncertain whether the energy efficiency criteria are ambitious enough and what range of performance is available on the market. The market front-runner performance appears to be of the order of just 1-2W (Siemens, 2016). This performance can only be achieved by replacing load resistors and switching elements with digital LED driver modules.

Due to the fact that front-runner performance could be 4-9 times better that the EU GPP requirements and doubts about how widely available front-runner products are and how much more expensive such technology is, it is considered most appropriate to propose a criterion for traffic signals based on life cycle cost.

Chicago case study (C4O Cities, 2011)

In 2011, the city of Chicago reported on an ambitious $32 million project, running from 2004-2014, to retrofit traffic signals with LED technology at 2900 intersections. The new LED traffic signals consume 85% less energy and save $2.55 million per year. It was unclear if the cost savings referred to all 2900 intersections up for replacement or only to the 1000 intersections that had been replaced at the time of the report. Regardless, the worst-case payback period was less than 13 years.

In terms of relative importance in Chicago, installed power for traffic signals was 6MW while road lighting was 70MW.

Graz case study (COMPETENCE)

Graz has around 260 traffic signal intersections and is promoting the replacement of traffic signals with LED technology whenever the existing lamp needs to be replaced. The assessment assumed an energy consumption of 75W for the traditional lamp and 10W for the replacement LED lamp. In terms of lifetime, the traditional lamps were replaced every 6 months as per a fixed maintenance schedule (an annual maintenance cost of

€960,000). The replacement schedule can be extended by a factor of 6 (i.e. up to 3 years instead of every 6 months) when using LED lamps.

At the time of publication (year unknown), LED lamps for traffic signals were 2-3 times higher than traditional lamps but it could be realistically expected that this would be paid back within 2 years simply by the longer lifetime.

In terms of relative importance in Graz, electricity consumption for traffic signals was 1.7 million kWh/yr while (ca. €220,000) road lighting was 8.5 million kWh/yr (ca. €1.1 million).

For comparison, the same document citing the Graz case study provided details of the 2001 retrofit of traffic signals in Stockholm in 2001 (530 intersections). A total additional LED-related investment of €3 million was paid back in 4-5 years thanks to annual savings in electricity (€471,000/yr) and maintenance (€243,000/yr).

Early US experience (RPN, 2009)

Even back in 2009, LED was the standard approach for any new traffic signal installations in the US. The replacement of traditional incandescent lamps with LED lamps results in energy savings of around 93%. In 2009 the reported difference in lamp costs was typically $3 for incandescent bulbs and $150 for LED bulbs – a factor of 50 difference!

Despite the major differences in capital costs, savings on electricity and maintenance are so high that payback periods of 0.5 to 3 years for retrofitting traffic signals with LEDs are the norm.

The energy saving potential of retrofitting an individual traffic signal will depend on the duty cycle (i.e. red-amber-green). The US study found that, in general, the retrofitting of red signals should be prioritised over green signals and that amber signals were of least potential energy savings.

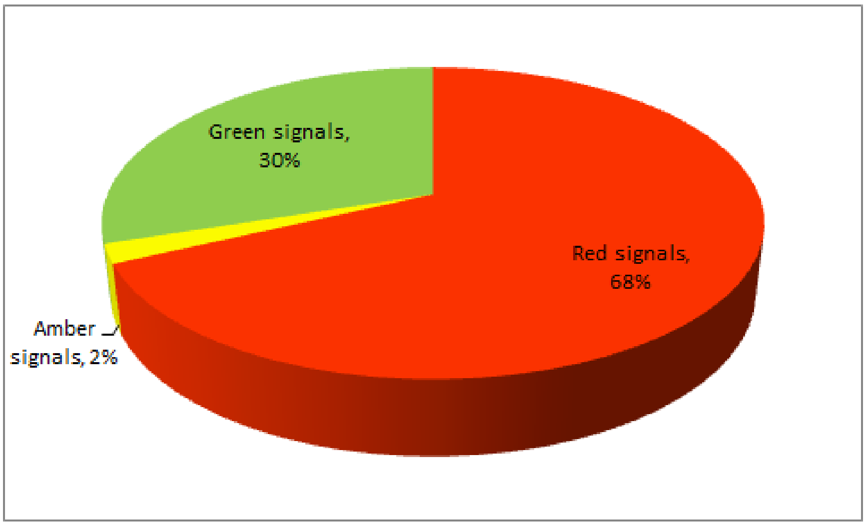

Figure 28. Energy saving potential for different lights in traffic signals (Source RPN, 2009)

The authors of the 2009 RPN guide also illustrated the specific savings that are possible for different traffic light fixtures.

Table 14. Energy and cost savings of incandescent vs. LED traffic signals

	Incandescent wattage (Annual energy consumption, kWh)	LED Wattage (Annual energy consumption, kWh)	Annual electricity savings per LED*
12 inch red ball (55% duty cycle)	150 (723)	10 (48)	$67.50
12 inch red ball (90% duty cycle)	150 (1183)	7 (55)	$112.80
12 inch green ball (45% duty cycle)	150 (591)	11 (43)	$54.80
12 inch green arrow (10% duty cycle)	150 (131)	7 (6)	$12.50
Stop hand display	67 (528)	8 (63)	$46.50
Walking figure display	67 (59)	8 (7)	$5.20

*assuming an electricity cost of $0.10/kWh

Specific examples of municipalities implementing the replacement of traffic signals were provided:

- Denver, CO (1996): Replacement of >20,500 traffic signals (150W incandescent with 14W LED or 69W incandescent with 8W LED) saving $276,000 per year in electricity and $154,000 per year in maintenance. Payback period was less than 4 years.
- Salt Lake City, UT (2001-2007): Replaced red and green bulbs with LEDs and reduced electricity consumption by 70% (almost 2 million kWh/yr) and electricity costs by $115,000/yr.
- Portland, OR (2001): Replaced 6900 red and 6400 green incandescent bulbs with LEDs at a cost of $2.2 million and reduced electricity consumption by 4.9 million kWh/yr, reduced electricity costs by $335,000/yr and reduced maintenance costs by $45,000.

Considering the notable increases in electricity costs in the last 10-15 years and the simultaneous decrease in the cost of LED lamps, it is clear that the financial benefits of investing in LED-based traffic signals has increased significantly and must today be the stand-out candidate in any ITT that considers lifetime costs. Today the main competition is likely to be between one LED-product and another LED-product.

There is clearly a lot of experience in calculating life cycle costs and payback periods for justifying investments in LED traffic signals although the precise details of how this is done are not well published and are likely to vary from one project to another and from one public authority to another. This could be due to factors such as the use of in-house or contracted maintenance staff and electricity tariffs.

9.1.2. Stakeholder discussion

Very little discussion took place about criteria relating to traffic signals. Some mixed comments were raised about the wattage requirements initially proposed in TR 1.0 with one stakeholder stating that the limits were already too ambitious and another stating that the ambition limits were acceptable.

Further doubts were raised about the 1W traffic signal front-running technology in terms of capital cost and the need for ancillary equipment that would rule out simple retrofits.

In general, support was expressed for lifetime criteria.

9.1.3. Criteria proposals for Life Cycle Cost

Core criteria	Comprehensive criteria
TS1 – Life Cycle Cost	
(Same for core and comprehensive criteria.) The life cycle cost shall be calculated based on the specifications set by the procurer, which should include: • the timeframe (e.g. 8 years); • an inventory of the traffic signals required (e.g. red ball signals, amber ball signals, green ball signals, green arrow signals, pedestrian stop signals and pedestrian go signals); • the average duty cycle of each traffic signal (e.g. red signal 55 %, amber signal 2 %, green signal 43 %); and • the electricity rate (e.g. EUR 0.12/kWh). The tenderer shall provide the following details in order to complete the life cycle cost assessment: • the period of time that bulbs are covered by warranty for abrupt failure; • the rated lifetime of the lamp (i.e. the time when lamp lumen output is expected to fall to 70 % of the original output); • the average power demand (kW) during the timeframe set by the procurer and converted into a total power consumption (kWh) over the same timeframe; • the purchase cost for lamps (both at the beginning and for any necessary replacement during the defined timeframe); • the purchase cost for any ancillaries; • the purchase cost for any poles, foundations and new electrical connections; and • the installation cost (hours of labour multiplied by labour rates, plus any costs for lifting equipment, etc.). ***Verification:*** The procurer shall provide the tenderers with a common spreadsheet-based life cycle cost calculator in which the information required from the procurer has already been entered. The tenderer shall submit a copy of the completed spreadsheet, together with a declaration confirming that these costs are valid at least for a defined period covering the original timescale planned for the execution of the contract after selection of the successful tenderer.	
AC1 Lowest Life Cycle Cost	
(Applies to TS1.) *(Same for core and comprehensive criteria.)* A maximum of X points shall be awarded to the tenderer whose proposal is shown to have the lowest life cycle cost. Points shall be awarded to other tenderers in proportion to how their life cycle cost compares to the lowest cost using the following formula: $$Points\ awarded\ to\ tender\ A = X\ x\ \frac{lowest\ LCC\ of\ all\ tenders}{LCC\ of\ tender\ A}$$ **Verification:** Once all tenders have been received, the procurer shall be able to determine which	

tender provides the lowest life cycle cost and use this to determine how many points should be applied to each tender.

9.2. Warranty

9.2.1. Background research and supporting rationale

The justification for a criterion relating to product warranty for traffic signals is broadly similar to the arguments presented for warranties for street lighting in section 9.3. The superior longevity of LED lamps and their lower incidence of abrupt failure when compared to incandescent lamps results in less frequent replacement cycles and maintenance interventions.

One notable difference between traffic signals and street lights is that the former are 24 hours per day switching through short duty cycles of the order of seconds while the latter tend to have one single and continuous duty cycle for 10-12 hours per day and then are switched off. As a result, lamps used in traffic signals need to be replaced more frequently than lamps based on the same technology when used in street lighting. This fact should also be reflected in shorter warranty periods for traffic signals.

Despite the superior longevity of LED-based lamps compared to incandescent lamps, there is a range of performance within LED technology alone. As illustrated in Figure 26 in section 8.3.1, a number of factors can contribute to a reduced lifetime of LED lamps. A sufficiently long warranty is an indirect way of ensuring that the contractor will take extra care to minimise the possible factors that could shorten lamp lifetime. Such factors include:

- overheating of electronics due to inadequate heat sinks/cooling mechanisms,
- the use of good quality LED chips,
- the use of durable capacitors and drivers that can accurately regulate currents within design specifications.

The need for a warranty going beyond the standard 2 year period is also necessary in order to back up claims and assumptions made in the life cycle cost assessment.

9.2.2. Stakeholder discussion

Since this is a new proposal, no previous stakeholder discussion has taken place about this criterion in particular for road lighting.

The main motivation for including such a criterion is that if it is relevant for road lighting it should be even more relevant for traffic signals, given the more acute potential safety impact.

9.2.3. Criteria proposals for traffic signal warranty

Core criteria	**Comprehensive criteria**
TS2 – Product lifetime, spare parts and warranty	
(The thresholds defined here are applicable to LED-based light sources, lamps and luminaires.) Any LED-based light sources shall have a rated life at 25°C of: • L96 at 6 000 hours,	*(The thresholds defined here are applicable to LED-based light sources, lamps and luminaires.)* Any LED-based light sources shall have a rated life at 25°C of: • L96 at 6 000 hours,

• L70 at 50 000 hours (projected), • L0C0 at 3 000 hours or C10 at 6 000 hours, • C50 at 50 000 hours (projected). The repair or provision of relevant replacement parts of LED modules suffering abrupt failure shall be covered by a warranty for a period of 5 years from the date of installation. **Verification:** Testing and verification shall be conducted by an International Laboratory Accreditation Cooperation-accredited laboratory that meets IES LM-80* for actual data and IES TM-21* for projected data. The tenderer shall provide a copy of the minimum 5-year warranty to be signed if the tender is successful. The contractor shall provide a copy of the warranty that will apply if the tender is successful and provide the necessary contact details (phone and email as a minimum) for dealing with any related queries or potential claims. For clarity, the warranty shall, as a minimum, cover the repair or replacement costs of faulty LED module parts within a reasonable timeframe after notification of the fault (to be defined by the procurer in the ITT), either directly or via other nominated agents. Replacement parts should be the same as the originals, but if this is not possible, equivalent spare parts that perform the same function to the same or to a higher performance level may be used. The warranty shall not cover the following: a) faulty operation due to vandalism, accidents or other extreme weather events; b) lamps or luminaires that have been working for a significant time under abnormal conditions (e.g. used with the wrong line voltage), insofar as this can be proven by the contractor. **To be updated to LM-84 and TM 28 when these versions are published.*	• L70 at 100 000 hours (projected), • L0C0 at 3 000 hours or C10 at 6 000 hours, • C50 at 100 000 hours (projected). The repair or provision of relevant replacement parts of LED modules suffering abrupt failure shall be covered by a warranty for a period of 7 years from the date of installation. **Verification:** Testing and verification shall be conducted by an International Laboratory Accreditation Cooperation-accredited laboratory that meets IES LM-80* for actual data and IES TM-21* for projected data. The tenderer shall provide a copy of the minimum 7-year to be signed if the tender is successful. The contractor shall provide a copy of the warranty that will apply if the tender is successful and provide the necessary contact details (phone and email as a minimum) for dealing with any related queries or potential claims. For clarity, the warranty shall, as a minimum, cover the repair or replacement costs of faulty LED module parts within a reasonable timeframe after notification of the fault (to be defined by the procurer in the ITT), either directly or via other nominated agents. Replacement parts should be the same as the originals, but if this is not possible, equivalent spare parts that perform the same function to the same or to a higher performance level may be used. The warranty shall not cover the following: a) faulty operation due to vandalism, accidents or other extreme weather events. b) lamps or luminaires that have been working for a significant time under abnormal conditions (e.g. used with the wrong line voltage), insofar as this can be proven by the contractor. **To be updated to LM-84 and TM 28 when these versions are published.*
AC2 Extended Warranty	

(Applies to TS2.)

(Same for core and comprehensive criteria.)

A maximum of X points shall be awarded to tenderers that are willing to provide initial warranties that go beyond the minimum warranty periods stated in TS2 and whose cost is already included in the bid price. Points shall be awarded in proportion to how long the warranty exceeds the minimum requirements, as follows:

- Minimum + 1 year: 0.2X points
- Minimum + 2 years: 0.4X points
- Minimum + 3 years: 0.6X points
- Minimum + 4 years: 0.8X points
- Minimum + 5 years or more: X points

Tenderers may also optionally provide quotations for extended warranties that are not included in the bid price, although points shall not be awarded for this. In such cases, no payment for any extended warranty will be required until the final year of the initial warranty, after which the procurer will make annual payments to the successful tenderer at the beginning of each year of the extended warranty.

Furthermore, the procurer will have the option to initiate or reject the offer of an extended warranty right up until the final year of the initial warranty; the costs of the extended warranty will be those initially proposed, plus inflation.

9.3. Dimming

9.3.1. Background research and supporting rationale

The background research for dimming of LED-based traffic signals is essentially the same as that presented in section 6.2.1.

9.3.2. Stakeholder discussion

Most of the relevant discussion took place during the 2nd AHWG meeting. Stakeholders emphasised the benefits of dimming: reduced energy consumption, reduced light pollution and reduced risk of overheating, with the latter aspect also reducing the risk of abrupt failure.

Unlike road lighting, the difference with traffic signals is that they must operate both during the day and the night. The maximum luminous flux from a traffic signal is based on it being sufficiently visible to road users during the day.

Somewhat ironically, traffic signals are easier to identify during the night because there is much less interfering background light. This led some stakeholders to propose that traffic signals should be able to be dimmed during the night-time without compromising the minimum visibility required.

Consequently, an award criterion is proposed to reward tenderers who are able to offer systems with dimming controls.

9.3.3. Criteria proposals for traffic signal warranty

Core criteria	**Comprehensive criteria**
AC3 – Dimming controls	
(Applicable to all calls for tender, unless it is clear that dimming controls would lead to a higher total cost of ownership. Procurers should clearly define the desired dimming performance in the ITT.) *(Same for core and comprehensive criteria.)* Points shall be awarded to tenderers that specify light sources and luminaires with fully functional dimming controls that are programmable to implement dimming during periods of low night-time road use intensity. **Verification:** The tenderer shall provide documentation from the manufacturer(s) of the light sources and luminaires that are proposed for use by the tenderer, showing that they are compatible with dimming controls. The documentation shall also provide a power curve of light output versus power consumption, state the maximum dimming possible and provide instructions about how to programme and re-programme the controls.	

References

AMA, 2016. American Medical Association. Report of the Council on Science and Public Health. Human and environmental effects of Light Emitting Diode (LED) community lighting.

ANSES, 2016. Assessment of the health risks associated with night work. https://www.anses.fr/en/system/files/AP2011SA0088EN.pdf.

Bailes HJ and Lucas RJ, 2013. Human melanopsin forms a pigment maximally sensitive to blue light) supporting activation of and signalling cascades. Proceedings of the Royal Society B: Biological Sciences. 280 (1759).

Benke KK and Benke KE, 2013. Uncertainty in Health Risks from Artificial Lighting due to Disruption of Circadian Rhythm and Melatonin Secretion: A Review. Human and Ecological Risk Assessment: An International Journal. 19(4): 916-929.

Biodiv, 2015. Les Cahiers de BIODIV'2050 n°6, 'Eclairage du 21ème siècle et biodiversité- Pour une meilleure prise en compte des externalités de l'éclairage extérieur sur notre environnement', 7/2015, available at : http://www.mission-economie-biodiversite.com/publication/eclairage-du-21eme-siecle-et-biodiversite

BIPRO, 2017. WEEE compliance promotion exercise. Final Report.

BSL, 2018. See: http://bsl.lacity.org/led-contractors-vendors.html

Chamorro E, Bonnin-Arias C, Pérez-Carrasco MJ, de Luna JM, Vázquez D, and Sánchez-Ramos C (2013). Effects of Light-emitting Diode Radiations on Human Retinal Pigment Epithelial Cells In Vitro. Photochemistry and Photobiology. 89: 468–473

COMPETENCE. Energy efficiency in streetlighting and transport infrastructure Available online at: http://www.eltis.org/sites/eltis/files/Competence_reference_material_urbandesign_en_6.pdf - last accessed January 2018.

C40 Cities, 2011. Case Study: LED traffic lights reduce energy use in Chicago by 85%. Available online at: http://www.c40.org/case_studies/led-traffic-lights-reduce-energy-use-in-chicago-by-85 - last accessed December 2017.

DECRETO 190/2015 de 25 de agosto, de desarrollo de la Ley 6/2001, de 31 de mayo, de ordenación ambiental del alumbrado para la protección del medio nocturno (CVE-DOGC-B-15237054-2015.

DOE (2015). Solid-State Lighting R&D plan. DOE/EE-1228. Last accessed online July 2017.

DOE (2016): "CALiPER Snapshot Report on Outdoor Area Lighting', available on https://energy.gov/eere/ssl/articles/new-caliper-snapshot-report-outdoor-area-lighting

DOE (2017), Street lighting and blue light – Frequently Asked Questions. Available at: https://www.energy.gov/sites/prod/files/2017/03/f34/Street%20Lighting%20and%20Blue%20Light%20FAQs.pdf - last accessed December 2017.

DOE, 2017b. An investigation of LED Street Lighting's Impact on Sky Glow. Available at: https://www.energy.gov/sites/prod/files/2017/05/f34/2017_led-impact-sky-glow.pdf - last accessed December 2017.

Duffy JF and Czeisler CA (2009). Effect of Light on Human Circadian Physiology. Sleep Med Clin. 4(2): 165-177.

EC, 2016. Buying green! A handbook on green public procurement, 3rd edition. ISBN 978-92-79-56848-0.

EC, 2017. Manual for the use of the WEEE calculation tool.

Eisenbeis, G., Artificial night lighting and insects: Attraction of insects to streetlamps in a rural setting in Germany. P.281-304 In Eds. Rich and Longcore, 2006. Ecological consequences of Artificial Night Lighting.

Falchi et al., 2011. Limiting the impact of light pollution on human health, environment and stellar visibility. Journal of Environmental Management, 92, p.2714-2722.

Falchi et al., 2016. The new world atlas of artificial night sky brightness. Science Advances, Vol. 2(6) e1600377.

Fotios, S and Gibbons R., 2018. Road lighting research for drivers and pedestrians: The basis of luminance and illuminance recommendations. Lighting Res. Technol., 50, p.154-186.

Frank, K., Effects of Artificial Night Lighting on Moths p.305-344 In Eds. Rich and Longcore, 2006. Ecological consequences of Artificial Night Lighting.

FTA, 2016. Finnish Transport Agency Guidelines. Quality requirements of road luminaires and lighting fixtures.

Galadi-Enriquez D., 2018. Beyond CCT: The spectral index system as a tool for the objective, quantitative characterization of lamps. Journal of Quantitative Spectroscopy & Radiative Transfer, 2016, 399-408.

Garcia-Saenz et al., 2018. Evaluating the Association between Artificial Light-at-Night Exposure and Breast and Prostrate Cancer Risk in Spain (MCC-Spain Study). Environmental Health Perspectives, 047011.

Glickman G, Levin R and Brainard GC, 2002. Ocular input for human melatonin regulation:relevance to breast cancer. Neuro Endocrinol Lett. Jul, 23 Suppl 2: 17-22.

Godley BF, Shamsi FA, Liang FQ, Jarrett SG, Davies S, and Boulton M (2005). Blue light induces mitochondrial DNA damage and free radical production in epithelial cells. J. Biol. Chem. 280, 21061–21066

Henderson et al., 2012. Measuring economic growth from outer space. American Economic Review, 102(2), p.994-1028.

IARC (2010). Monograph Volume 98: painting, firefighting, and shiftwork. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans.

ICNIRP, 2013. Health Phys. 105(1):74-96, Table 2.

ILE, 2002. Guidance notes for the reduction of light pollution. The Institution of Lighting Engineers, UK.

IMERC (2015). Interstate Mercury Education and Reduction Clearinghouse. Fact sheet: Mercury use in lighting. Last accessed in December 2017. Available at http://www.newmoa.org/prevention/mercury/imerc/factsheets/lighting_2015.pdf

James et al., 2017. Outdoor Light at Night and Breast Cancer Incidence in the Nurses' Health Study II. Environmental Health Perspectives, 087010.

Joo EY, Abbott SM, Reid KJ, Wu D, Kang J, Wilson J, and Zee PC (2017). Timing of light exposure and activity in adults with delayed sleep-wake phase disorder. Sleep Med. 32:259-265

Kang, S. G., Yoon, H. K., Cho, C. H., Kwon, S., Kang, J., Park, Y. M., ... & Lee, H. J. (2016). Decrease in fMRI brain activation during working memory performed after sleeping under 10 lux light. Scientific reports, 6, 36731.

Knop E., Zoller L., Ryser R., Gerpe C., Horler M. and Fontaine C., 2017. Artificial light at night as a new threat to pollination. Nature, 548, p.206-209.

Kuse Y, Ogawa K, Tsuruma K, Shimazawa M, and Hara H (2014). Damage of photoreceptor-derived cells in culture induced by light emitting diode-derived blue light, Sci Rep. 4: 5223.

La Sorte et al., 2017. Seasonal associations with urban light pollution for nocturnally migrating bird populations. Global Change Biology, DOI: 10.1111/gcb.13792

Los Angeles, 2013. See: https://www.forbes.com/sites/justingerdes/2013/01/25/los-angeles-saves-millions-with-led-street-light-deployment/#66b07d398d90

LSRSC, 2014. LED luminaire lifetime: recommendations for testing and reporting. Solid-state lighting product quality initiative, 3rd edition, September 2014, Next generation lighting industry alliance LED systems reliability consortium.

Lucas RJ, Peirson SN, Berson DM, Brown TM, Cooper HM, Czeisler CA, Figueiro M, Gamlin PD, Lockley SW, O'Hagan JB, Price LL, Provencio I, Skene DJ and Brainard GC (2014). Measuring and using light in the melanopsin age. Trends Neurosci. 37(1): 1-9.

Magee M, Marbas EM, Wright KP Jr, Rajaratnam SM and Broussard JL, 2016. Diagnosis, cause, and treatment approaches for delayed sleep-wake phase disorder. Sleep Med Clin. Sep; 11(3): 389-401. DOI: 10.1016/j.jsmc.2016.05.004.

Mattis J and Sehgal A (2016). Circadian Rhythms, Sleep, and Disorders of Aging. Trends in Endocrinology & Metabolism 27(4): 192-203.

NEMA (2015). Energy savings with Fluorescent and LED dimming. National Electrical Manufacturers Association. Accessed online July 2017.

Portland, 2015. See: https://1190kex.iheart.com/articles/portland-local-news-123543/led-streetlight-conversion-saves-portland-thousands-13791851/#ixzz3s3aSKNiE

Rajkhowa R., 2012. Light pollution and impact of light pollution. International Journal of Science and Research (IJSR), 3(10), p.861-867.

RAS, Royal Astronomical Society webpage: http://www.ras.org.uk/events-and-meetings/123 last accessed October 2017.

Rodriguez et al., 2017. Seabird mortality induced by land-based artificial lights. Conservation Biology, In press, DOI: 10.1111/cobi.12900.

Roehlecke C, Schaller A, Knels L, and Funk RH (2009) The influence of sublethal blue light exposure on human RPE cells. Mol.Vis. 15, 1929–1938

RPN, 2009. Responsible Purchasing Network Guide to LED Exit Signs Street Lights and Traffic Signals. Accessed online: http://www.everglow.us/pdf/rpn-led-purchasing-guide.pdf

Sanders and Scott, 2008. Review of luminaire maintenance factors, Mott MacDonald.

SCHEER, 2017. SCHEER, 2017. Scientific Committee on Health, Environmental and Emerging Risks. Preliminary opinion on Risks to human health of Light Emitting Diodes.

Schomerus C and Korf HW (2005). Mechanisms regulating melatonin synthesis in the mammalian pineal organ. Ann N Y Acad Sci. 1057: 372-383

Siemens (2016). Press release, available online at: https://www.siemens.com/press/en/pressrelease/?press=/en/pressrelease/2016/mobility/pr2016040225moen.htm - last accessed December 2017.

Silsby SL, 2013. HPS to LED Conversion – A City of Phoenix Experience.

Silva et al., 2017. Light pollution affects nesting behaviour of loggerhead turtles and predation risk of nests and hatchlings. J Photochem Photobiol B, Biol. 173, p.240-249.

Simoes et al., 2017. Influence of artificial lights on the orientation of hatchlings of Eretmochelys imbricate in Pernambuco, Brazil. Zoologia, June, DOI: 10.3897/zoologia.34.e13727

Swanson GA and Carlson CA, 2012. Cost-benefit analysis of energy efficient technologies available for use in roadway lighting. Final Report.

Synergrid. Technical specification 005. C4/11-3 specification s for luminaires equipped with LED technology.

Synergrid-b. Technical specification 005. Public lighting equipment. C4/11-2: Prescriptions for luminaires. Photometric requirements.

Takahashi JS (2017). Transcriptional architecture of the mammalian circadian clock. Nat 36 Rev Genet. 2017 Mar;18(3):164-179

Van Tichelen P., Geerken T., Jansen, B. Vanden Bosch M., van Hoof V., Vanhooydonck L., Vercalsteren A.,2007. EuP study lot 9, Ecodesign for public street lighting, Final report, 2007. VITO. Available from http://www.eup4light.net

Wang XS, Armstrong ME, Cairns BJ, Key TJ and Travis RC (2011). Shift work and chronic disease: the epidemiological evidence. Occup Med (Lond) 61(2): 78-89.

List of abbreviations and definitions

AC – Award Criteria
AECI – Annual Energy Consumption Indicator
AHWG – Ad Hoc Working Group
ALARA – As Low As Reasonably Achievable
CCT – Correlated Colour Temperature
CFL – Compact Fluorescent Lamp
CLO – Constant Light Output
CPO – Virtual Power Output
CPC – Contract Performance Clause
CRI – Colour Rendering Index
EIR – Edge Illumination Ratio
ENEC+ - European Norms Electrical Certification
HID – High Intensity Discharge
HPM – High Pressure Mercury
HPS – High Pressure Sodium
IP – Ingress Protection
IPEA – Parameterized Energy Index for Luminaires
IPEI – Parameterized Energy Index for Lighting Systems
ITT – Invitation To Tender
LCA – Life Cycle Assessment
LCC – Life Cycle Cost
LED – Light Emitting Diode
LPS – Low Pressure Sodium
LLMF/F_{LLM} – Lamp Lumen Maintenance Factor
LMF/F_{LM} – Luminaire Maintenance Factor
LSF/F_{LS} – Lamp Survival Factor
MH – Metal Halide
PDI – Power Density Index
RW – Road Width
SC – Selection Criteria
TR – Technical Report
TS – Technical Specification
ULOR/R_{ULO} – Upward Light Output Ratio / Ratio of Upward Light Output

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Annexes

Annex I: Calculating PDI.

The PDI value, in $W/(lx.m^2)$ essentially tells us how much power is consumed to provide one lux average illuminance (lx) over one square metre. Generally speaking, the lower the PDI value, the better the lighting system energy efficiency. It is relative to the installed illumination and therefore does not take into any desired light level and consequently, whether or not the installation is over-lit.

The PDI value is technology neutral and should include power consumption from all components of a luminaire with light source installed. For this reason, there is no need to set overlapping requirements for individual types of lamps and ballasts.

Calculating PDI[W/(lx.m²)] or [W/lm]

The Power Density Indicator is calculated according to EN 13201-5:2016 as follows:

$$PDI = D_P = \frac{P}{\sum_{i=1}^{n}(E_i \, x \, A_i)}$$

Where P is the system power, Ei is the average maintained horizontal illuminance of sub-area A. and n is the number of sub-areas. Any one particular sub-area may have illuminance classes defined as luminance requirements, L,m (e.g. M-class road sections) or illuminance, E,m or illuminance requirements E,hs (e.g. C or P class road sections). The following conversion formulas for switching from luminance and illuminance are provided in EN 13201-5:2016:

- *Illuminance (E,m) = Luminance (L̄,m) / 0.07 (where 0.07 is a general "rule of thumb" coefficient for a reference asphalt surface, in $cd/(m^2.lx$. For greater accuracy, in-situ measurements of the asphalt road surface reflectivity should be taken (especially if not asphalt!) and results generated via a specialised lighting program).*
- *Illuminance (E,m) = Hemispherical illuminance (E,hs) / 0.65*

It should be noted that 1 W/(lx.m²), i.e. the unit of PDI, is equivalent to 1 W/lm which is the reciprocal value of the installation efficacy in lm/W. The PDI indicator does not take into account dimming and/or over-lighting.

As indicated above, it is important to be aware of the target area to be lit, A, and this in turn requires knowledge about the road profile. It is important to be aware of the road profile and the target area to be lit when calculating the PDI.

Road profile

The road profile describes the layout of the road sections to be lit, lighting points, any adjacent pedestrian areas intended to be lit and any vegetated areas or central reservations not intended to be lit, see Figure 29 below.

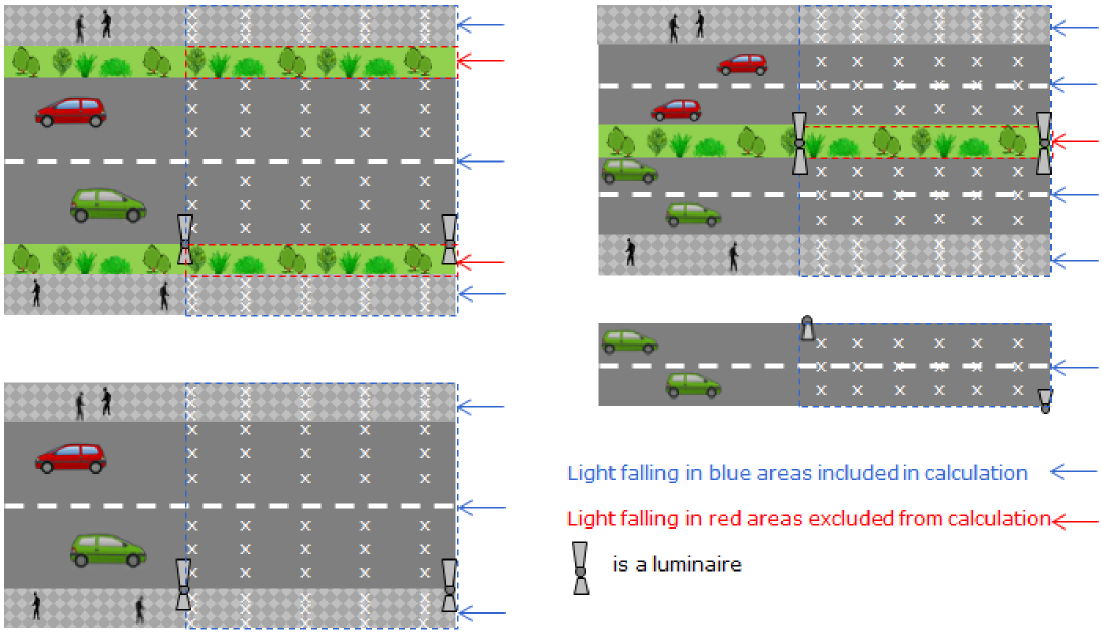


Figure 29. Examples of different possible road profiles and the associated areas to be included in any PDI calculations (adapted from EN 13201-5)

The results for PDI and AECI will be influenced by light output that is essentially "*spilled*" onto non-target areas. Consequently, a clear understanding of the road profile is important to ensure that different designs are comparable. In certain circumstances, where there is a degree of freedom about the placement of luminaires, the road profile will need to be considered in detail to deliver the optimum energy efficiency without creating problems due to glare or a lack of uniformity. Note that road classes M1-M6 have Edge Illumination Ratio (EIR) and if the carriageway of a road is not surrounded by other areas, the surrounding areas used for calculating EIR are not included in the calculation of power density indicator. As a consequence this can lower the PDI.

<u>Example calculations with real data – (i) road only (Synergrid-b)</u>

The following example is for a road where the ***<u>target average maintained luminance is 1.00 cd/m²</u>***. To minimise the potential for over-lighting, the target luminance also must not be exceeded by more than 25% (i.e. luminance must be between 1.00 and 1.25 cd/m² - the lower within this range the better). The EN 13201-5:2016 standard is less stringent in this respect, allowing average luminance to be exceeded by up to 50%.

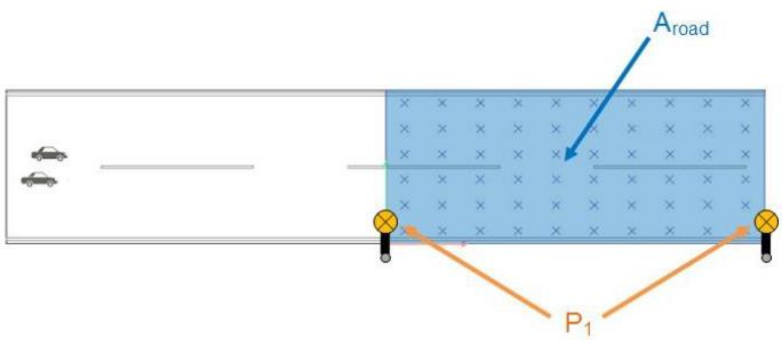


Figure 30. Target area for the calculation of PDI in one road sub-area (Source: Synergrid-b).

To calculate PDI, it is necessary to use suitable lighting calculation software and the photometric file of the light source and luminaire. A real example of the main data needed to calculate PDI include:

- Road width = 7m
- Distance between light poles = 36m
- Sub area, A_{road} = 252m^2
- Height of luminaires = 8m
- Power consumption of the two luminaires (P1) = 115 W (HPS lamp 110W on electronic ballast)
- Luminous flux of the lamp = 10000 lm
- Maintenance factor = 0.92 (IP66, glass cover)

From these data, the average maintained illuminance on A_{road} can be calculated to be 14.4 lx (including the maintenance factor). Once the illuminance is known, the PDI can be calculated as follows:

$$PDI = D_P = \frac{P_1}{E_{road}\ x\ A_{road}} = \frac{115W}{14.4lx\ x\ 252m^2} = 0.032\ W.lx^{-1}.m^{-2}$$

A final check is required to see if the average maintained luminance level is adequate, so it is necessary to convert illuminance into luminance:

$$Illuminance\ (lx)\ x\ surface\ reflectivity\ coeff. = Luminance\ (cd.m^{-2})$$
$$= 14.4lx\ x\ 0.0722cd.lx^{-1}.m^{-2} = 1.04cd.m^{-2}$$

The final luminance result was indeed compliant with the example (i.e. between 1.00 and 1.25 cd.m^{-2}) and the PDI was calculated as 0.032 W.m^{-2}.lx^{-1}.

It is important to understand that the surface reflectivity coefficient is not a fixed number but will vary depending on the colour and texture of the road surface. Even for a given road surface, the actual reflectivity varies as a function of the wavelength of light.

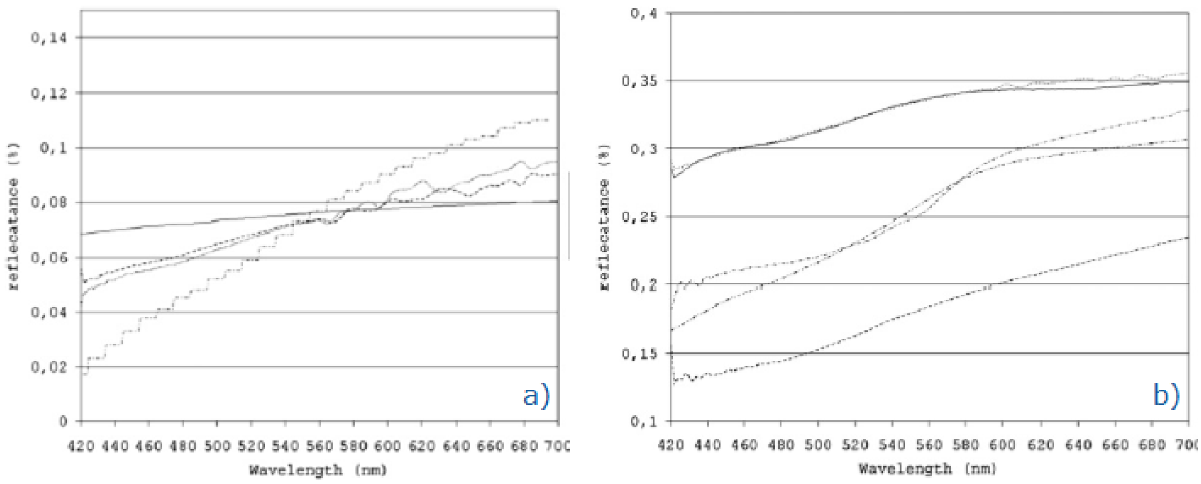


Figure 31. Light reflectance as a function of wavelength on a) asphalt surfaces and b) concrete surfaces (adapted from Falchi et al., 2011, original data sources can be found therein).

From the graphs above it is clear that light at longer wavelengths is reflected more. This is especially important in M-class roads when trying to calculate the installed power that is necessary to achieve a given luminance on the road. The higher the proportion of longer wavelength light emitted in the visual range, the lower the installed power should need to be. Other important aspects are the much higher reflectivity of concrete in general (x3 to x5) compared to asphalt and the fact that there is a significant range of variation amongst different concretes (more significant) and amongst different asphalts (less significant).

Example calculations with real data – (ii) road with sidewalk

In cases where the road profile requires different lighting levels for at least 2 different areas, the calculation of PDI is more complex and another example (again from the Synergrid technical specification document) is provided below:

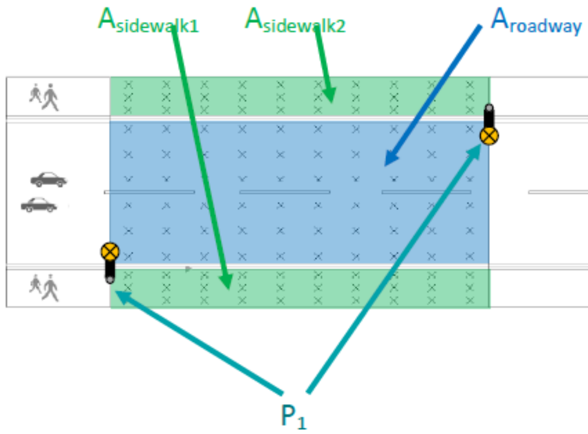


Figure 32. Target areas for calculation of PDI where two lighting classes are required in one sub-area (Source: Synergrid-b).

The following details can be used in lighting software to calculate the average maintained illuminance on the road and on the sidewalks:

- Width of roadway = 7m
- Width of the sidewalk = 2m (on each side)
- Distance between the light poles = 25m
- Sub area A_{road} = 175m^2
- Sub area $A_{sidewalk1}$ = 50m^2
- Sub area $A_{sidewalk2}$ = 50m^2
- Power rating of luminaire P1 = 103W (90 W MHHP with electronic ballast)
- Maintenance factor = 0.87 (MHHP lamp, IP 66, glass cover)
- Luminous flux = 10500 lm
- Height of the luminaire = 8m

This results in an average maintained illuminance on road of 17.4lx (including the maintenance factor and on the sidewalks of 12.2lx (again including the maintenance factor).

The clearest explanation of the PDI calculation is by following the "absolute method" described in the Synergrid specification. It is necessary to read of the percentages of light output from the luminaire that fall on each of the target areas, as illustrated in Figure 33.

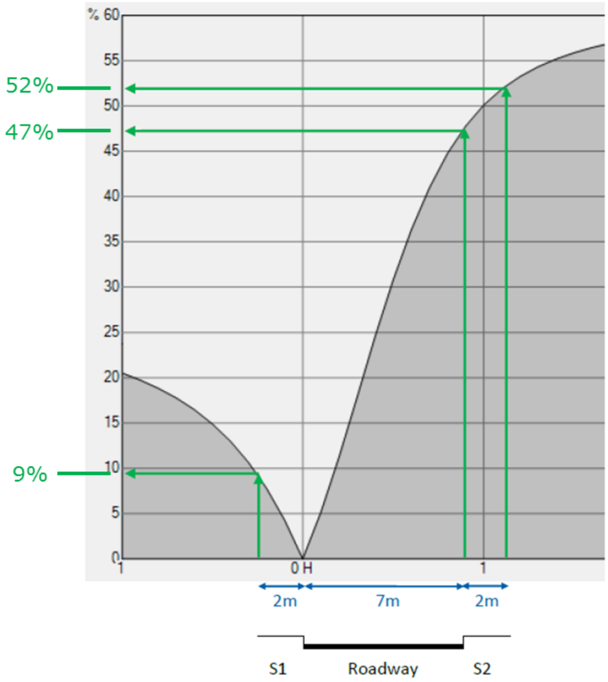


Figure 33. Reading of the "utilance" of luminous flux from luminaire (Source: Synergrid).

The extrapolation of data reveals that 9% of the luminous flux lands on sidewalk 1, 47% lands on the road and 5% (i.e. 52% - 47%) lands on sidewalk 2 – resulting in an overall utilance of 61%, or 0.61.

For the calculation of PDI to be true, it is also necessary to account for the energy that is spent on light that does not reach the target areas. So percentage of power used to illuminate the road is essentially 77% of the 103W (i.e. 47%/61% x100), on sidewalk 1 it is 14.8% of the 103W (i.e. 9%/61% x 100) and on sidewalk 2 is it 8.2% of the 103W (i.e. 5%/61% x100). This two sidewalk values can be combined (i.e. taking 23% of the power) since, due to the staggered layout of lighting points shown in Figure 32, they will receive the same total luminous flux overall.

So the PDI calculations now become:

$$PDI = D_{Proadway} = \frac{0.77\ x\ 103W}{17.4lx\ x\ 175m^2} = 0.026\ Wm^{-2}lx^{-1}$$

And

$$PDI = D_{Psidewalk1+2} = \frac{0.23\ x\ 103W}{(12.2lx\ x\ 50m^2) + (12.2lx\ x\ 50m^2)} = 0.0194\ Wm^{-2}lx^{-1}$$

For ease of comparison with different designs, the PDI for the road, sidewalk 1 and sidewalk 2 can also be aggregated into a single value so long as the average (and maximum) maintained luminance/illuminance levels are specified equally and are complied with by all designs.

Limitations of PDI

Although the PDI is a useful measure of the energy efficiency of the installation, it is not so easy to understand for procurers, who will be most interested in the electricity bill. As the term suggests, PDI, is only an indicator of energy efficiency and not a direct measure of energy consumption.

Because PDI is relative to the installed illumination, it does not take into account over-lighting. For example, it is possible for a road to have a very low PDI value even when in reality the lighting levels on the road, and thus the energy consumption, could be much higher than they needed to be. This is why it is necessary to have some check that luminance or illuminance levels do not exceed targets by more than a certain amount (e.g. 25%). The PDI can potentially be weighted to factor in constant light output (CLO) and dimming scenarios by adjusting the system power value but how this number is arrived at is not so transparent in the standard PDI calculation.

PDI should not be used as a stand-alone requirement for energy efficiency. In order to avoid potential perverse outcomes, it is very important that the procurer specifies the average and maximum maintained lighting levels required for each sub-area of the road.

Annex II: Reference PDI and AECI table.

Table 15. PDI reference values and their translation into AECI "base values" as a function of road width

		Year	Ambition level and road width (to be lit)											
			Core ≤5m	Comp ≤5m	Core 5-6m	Comp 5-6m	Core 6-7m	Comp 6-7m	Core 7-8m	Comp 7-8m	Core 8-9m	Comp 8-9m	Core ≥9m	Comp ≥9m
PDI reference values $W.lx^{-1}.m^{-2}$ =1 / (lum. eff.x MF x utilance)		2018-19	0.023	0.018	0.020	0.016	0.018	0.015	0.016	0.013	0.014	0.012	0.014	0.012
		2020-21	0.021	0.016	0.018	0.015	0.015	0.013	0.014	0.011	0.012	0.011	0.012	0.011
		2022-23	0.018	0.014	0.016	0.013	0.014	0.012	0.012	0.010	0.011	0.010	0.011	0.010
AECI 'base values' $kWh.m^{-2}.yr^{-1}.lx^{-1}$ (Basically PDI x 0.001kW/W x 4015h/y and x 1.00 (core) or 0.73 (comp.) dimming factor)		2018-19	0.094	0.053	0.081	0.048	0.071	0.044	0.063	0.038	0.057	0.035	0.057	0.035
		2020-21	0.083	0.047	0.071	0.042	0.062	0.039	0.055	0.033	0.050	0.031	0.050	0.031
		2022-23	0.074	0.042	0.063	0.038	0.055	0.035	0.049	0.030	0.044	0.028	0.044	0.028
Actual AECI reference values which are simply the AECI base values above multiplied by the illuminance (lux). **C0 or C1 levels must be able to meet to AECI based on 20lux (e.g. via improved dimming).* *Note that for M-class roads, the luminance needs to be specified, which will be influenced by the surface reflectivity of the road (luminance = Illuminance x reflectivity).*	C0*, C1*, C2 (avg. 20 lux)	2018-19	1.874	1.057	1.607	0.961	1.406	0.881	1.250	0.755	1.125	0.705	1.125	0.705
		2020-21	1.654	0.935	1.418	0.850	1.240	0.779	1.103	0.668	0.992	0.623	0.992	0.623
		2022-23	1.470	0.833	1.260	0.757	1.103	0.694	0.980	0.595	0.882	0.555	0.882	0.555
	C3 / P1 (avg. 15 lux)	2018-19	1.406	0.793	1.205	0.721	1.054	0.661	0.937	0.566	0.843	0.529	0.843	0.529
		2020-21	1.240	0.701	1.063	0.637	0.930	0.584	0.827	0.501	0.744	0.467	0.744	0.467
		2022-23	1.103	0.625	0.945	0.568	0.827	0.520	0.735	0.446	0.662	0.416	0.662	0.416
	C4 / P2 (avg. 10 lux)	2018-19	0.937	0.529	0.803	0.480	0.703	0.440	0.625	0.378	0.562	0.352	0.562	0.352
		2020-21	0.827	0.467	0.709	0.425	0.620	0.389	0.551	0.334	0.496	0.312	0.496	0.312
		2022-23	0.735	0.416	0.630	0.379	0.551	0.347	0.490	0.297	0.441	0.278	0.441	0.278
	C5 / P3 (avg. 7.5 lux)	2018-19	0.703	0.396	0.602	0.360	0.527	0.330	0.469	0.283	0.422	0.264	0.422	0.264
		2020-21	0.620	0.351	0.532	0.319	0.465	0.292	0.413	0.250	0.372	0.234	0.372	0.234
		2022-23	0.551	0.312	0.473	0.284	0.413	0.260	0.368	0.223	0.331	0.208	0.331	0.208
	P4 (avg. 5 lux)	2018-19	0.469	0.264	0.402	0.240	0.351	0.220	0.312	0.189	0.281	0.176	0.281	0.176
		2020-21	0.413	0.234	0.354	0.212	0.310	0.195	0.276	0.167	0.248	0.156	0.248	0.156
		2022-23	0.368	0.208	0.315	0.189	0.276	0.173	0.245	0.149	0.221	0.139	0.221	0.139
	P5 (avg. 3 lux)	2018-19	0.281	0.159	0.241	0.144	0.211	0.132	0.187	0.113	0.169	0.106	0.169	0.106
		2020-21	0.248	0.140	0.213	0.127	0.186	0.117	0.165	0.100	0.149	0.093	0.149	0.093
		2022-23	0.221	0.125	0.189	0.114	0.165	0.104	0.147	0.089	0.132	0.083	0.132	0.083
	P6 (avg. 2 lux)	2018-19	0.187	0.106	0.161	0.096	0.141	0.088	0.125	0.076	0.112	0.070	0.112	0.070
		2020-21	0.165	0.093	0.142	0.085	0.124	0.078	0.110	0.067	0.099	0.062	0.099	0.062
		2022-23	0.147	0.083	0.126	0.076	0.110	0.069	0.098	0.059	0.088	0.056	0.088	0.056

The differences in PDI values for different years are based on a tiered increase in luminaire efficacy that is expected to be delivered by the LED industry or 17 lm/W every two years between the periods 2018 and 2023. The starting luminaire efficacies are 120 lm/W (core) and 130 lm/W (comp.) in 2018.

For all PDI reference values a maintenance factor (MF) of 0.85 is assumed. The utilance values vary as a function of road width and criterion ambition level as follows: Core/Comp: ≤5m wide (U=0.42/0.5); 5-6m wide (U=0.49/0.55); 6-7m wide (U=0.56/0.6); 7-8m wide (U=0.63/0.7); 8-9m wide (U=0.7/0.75); ≥9m wide (U=0.7/0.75).

Annex III. Examples of PDI specs in IT and BE

Italian approach to PDI requirements

One stakeholder provided details about the approach to PDI in Italy, where the term "IPEI" (defined as the Parameterized Energy Index for Lighting Systems) has been designed to give a broad evaluation of lighting installation energy efficiency in a comparable manner. IPEI is related to the ratio between PDI (or Dp) and a fixed reference value (PDI_{ref} or Dp,r) that is defined for each road lighting class as per the definitions in EN 13201 (i.e. M-class, C-class and P-class roads).

Table 16. IPEI (reference PDI values) for different Italian road classes

Road class	PDI (IPEI) (W/lux.m^2) Road lighting	Area lighting, roundabout, parking lot	Pedestrian area, bike lane
M1	0.035		
M2	0.037		
M3	0.040		
M4	0.042		
M5	0.043		
M6	0.044		
C0		0.03	0.039
C1		0.032	0.042
C2		0.034	0.044
C3 (P1)		0.037	0.048
C4 (P2)		0.039	0.051
C5 (P3)		0.041	0.053
P4		0.043	0.056
P5		0.045	0.059
P6		0.047	0.061
P7		0.049	0.064

The reference PDI_{ref} is less demanding for classes with lower luminance/illuminance requirements - which is justified since these will use lower wattage lamps that may have lower inherent luminaire efficacies. Denominated road types are: '*road lighting (M classes)*', '*area lighting, roundabout, parking (C&P classes)*' and '*pedestrian or bike lane' (P classes)*'. Depending on the IPEI ratio energy efficiency labels are given to lighting installations (G to A5+). The IPEI labels serves as a benchmark in public tenders in Italy.

Belgian approach to PDI requirements

One stakeholder made reference to a Belgian standard (Synergrid C4/11-2, 2016 version) that defines the minimum energy efficiency requirements (PDI and AECI) for M class roads and that these requirements have indeed been linked to road width as shown in the table below.

Table 17. Maximum PDI values permitted for Belgian M-class and C-class roads

Lighting class	Road width 4m	5m	6m	7m	8m	9m	10m	11m
M2	0.035	0.035	0.035	0.03	0.025	0.02	0.02	0.02
M3	0.05	0.045	0.04	0.035	0.03	0.03	0.03	0.03
M4	0.05	0.045	0.04	0.035				
M5	0.05	0.045	0.04	0.035				
C2	0.06	0.05	0.04	0.03	0.03	0.03	0.03	
C3	0.065	0.055	0.045	0.035	0.035	0.035	0.035	
C4	0.07	0.06	0.05	0.04	0.04	0.04	0.04	

The data in Table 17 reveal that as the road width decreases, the maximum permitted PDI value increases. This is consistent with the general idea that it is more difficult to efficiently light narrower roads due to light spilling over the target area (i.e. the "utilance" factor decreases).

The PDI requirements also become more relaxed as the lighting level required decreases (i.e. moving from M2 to M5 or C2 to C4) because these will require lower wattage lamps that may result in inherently lower luminaire efficacies. While this reasoning holds true for HID type lamps, it is not really the case for LED-based lamps, whose efficacies are much less dependent on operating power.

The Belgian requirement is very pragmatic but is only applicable in regions where there is a common approach to classifying the required lighting levels for roads. Since this is not common across the EU, it is not recommended to refer to road classes at all in the criteria but instead to the average maintained luminance or illuminance level specified by the procurer.

Annex IV. Examples of Life Cycle Costing

Life cycle costing (LCC) is a hugely relevant topic for road lighting. The dominant life cycle cost for traditional High Intensity Discharge (HID) technologies has always been electricity consumption during the use phase. LED technologies are more efficient but, although their cost has rapidly decreased during the last five years, they are also more expensive to buy than HID. When considering a shift from HID to LED, public authorities need to be able to make the best objective decision for them from an economic perspective. Conversion of a road lighting installation from HID to LED typically requires a high capital outlay greater than a public authority's annual road lighting budget. Consequently, demonstrating lower LCCs may actually be a pre-requisite for obtaining financing to convert to a LED installation.

A number of LCC comparisons have been carried out in US cities and towns, where LED uptake for road lighting installations began. Some are briefly described below.

- The City of Portland invested \$18.5 million in replacing 45 000 HPS light points with LED with 50 % lower energy consumption — leading to savings of \$1.5 million per year in reduced energy and maintenance costs. That equates to a payback period of eight years when discount rates are factored in (Portland, 2015).
- The City of Los Angeles invested \$57 million in replacing 140 000 HPS light points with LED with 63 % lower energy consumption (Los Angeles, 2013). The energy savings were initially expected to be around 40 %, but advances in LED technology ahead of the project resulted in greater savings. The study also noted rapidly falling unit costs (e.g. between March and September 2012, the cost fell from \$495 to \$309). Annual savings of \$2.5 million in maintenance costs alone are expected, due to the lower failure rate of LED (0.2 % for LED versus 10 % for HPS). Together with \$7.5 million savings in electricity costs, the total annual savings of \$10 million should result in a payback period of five to six years. However, the study urged caution in procuring LED solutions, when it was found that only 84 of 244 LED units met the quality specifications set out by the Bureau of Street Lighting website (BSL, 2018).
- Charlotte County considered the costs in 2016 of changing their 2 145 light points from HPS to LED lighting. Their existing maintenance costs were assumed to be between \$28 and \$55 per light point, depending on the type. The power cost of an HPS light was around \$12/month and a LED light assumed to be \$6/month (a 50 % reduction). Current energy and maintenance costs (for HPS) are \$310 000 and \$80 000 respectively. The costs they quoted for different types of luminaire were as follows: cobra head (HPS \$345, LED \$780) and decorative head (HPS \$1 200, LED \$1 800). It was assumed that an HPS lamp would be replaced every 5 years, the LED power module (\$150) would be replaced every 5 years as well, and the LED optical module (\$750) would need to be replaced every 20 years. They concluded that costs for HPS and LED were similar over a 20-year period, but that falling LED costs would soon make it the more economical option.
- In Minnesota (City of Chanhassen) in 2012, simple payback periods of 8-12 years were estimated for converting from HID to LED lighting (Swanson and Carlson, 2012). Lifetimes of 6 years (21 000 hours) and 22 years (78 000 hours) were estimated for HID and LED lamps respectively (based on 3 550 hours' operation per year). The authors found that the pricing for LED luminaire purchase varied significantly depending on the efficacy required, the size of the order and the

length of the supply chain. For batches of 500 luminaires, the prices ranged from \$250 to \$1 325 per LED luminaire. A new HPS lamp was estimated to cost \$11 and a new pole \$800. To install a new HPS lamp or a new LED luminaire was estimated to cost \$110 and the installation of a new pole \$1 500. A 60 % saving in energy consumption was assumed for LED and total service costs of LED over 22 years were estimated at \$220. Different discount rates of 2 %, 4 % and 8 % were applied, an electricity rate of \$0.046/kWh was assumed and three different leasing rates were considered. In almost all cases, the LED option was cheaper than the HID option from an LCC perspective. The higher the discount rate, the less attractive the LED option.

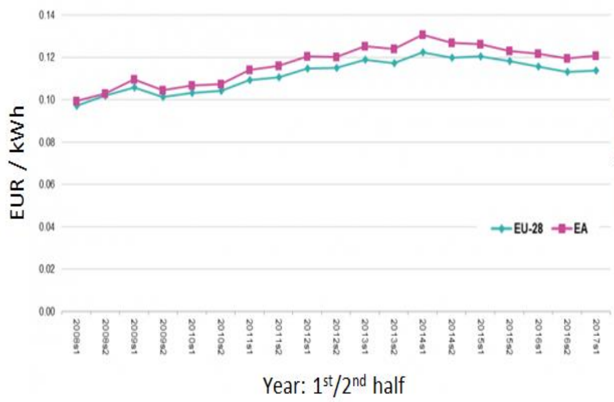
- In Phoenix, the conversion of almost 95 000 HPS light points to LED was considered in 2013 (Silsby, 2013). Over a period of 10 years, they considered HPS and LED with the following characteristics: energy cost per light per year (HPS \$72.36, LED \$32.88); fixture cost (HPS \$250, LED \$475); fixture installation (HPS \$29, LED \$29); and lamp life (HPS 20 000 hours, LED 50 000 hours). In conclusion, they found that LED was around 20 % cheaper over a period of 10 years. Applied to the City of Phoenix, this equated to around \$5 million per year once the whole system was converted. For a \$1 million investment in LED, a 9-year simple payback period was calculated.

Using the LCC calculator from the Swedish National Agency for Public Procurement, a number of scenarios are calculated to demonstrate the influence of different variables on LCC of any particular design solution. The tool requires the following input parameters from the procurer and the supplier:

Table 18. Input parameters required for calculating LCC with the Swedish tool (note that 1 SEK is roughly equal to 0.1 EUR)

Data from procurer	Data from supplier	
Usage time (years)	Investment costs	Number of luminaires and price per luminaire (SEK/luminaire).
Discount rate (%)		Material and labour cost per luminaire installation (SEK/luminaire).
Electricity price (SEK/kWh)		Number of poles and foundations and price per pole and foundation
Annual electricity price change (%/year)		Material and labour cost per pole installation and foundation (SEK/pole or foundation).
Operating time (hours per year)		Cost of any external control devices and start up
Operating hours at full power, at level 1 (dimming) and level 2 (more dimming), all in hours/year	Operating costs	Power consumption at full power, at power level 1 and at power level 2 (in Watts)
	Maintenance costs	Light source replacement capital cost (SEK/piece)
		Light source replacement labour cost (SEK/piece)
		Light source replacement intervals (hours)
		Electrical ballast / control driver replacement capital cost (SEK/piece)
		Electrical ballast / control driver replacement labour cost (SEK/piece)
		Electrical ballast /control driver replacement interval (hours)
		Luminaire lifespan (years)
		Pole lifespan (years)
Note that the maintenance costs in the right hand column may be able to be defined by the procurer if they also manage the lighting installation and have competent and qualified staff.		Inspection cost (SEK/piece)
		Inspection interval (year)
		Surveillance cost (SEK/piece)
		Surveillance interval (year)

It is recommended that any LCC study cover a period of at least 20 years, possibly longer. Given the very low economic growth and inflation during the last 10 years in Europe, it is recommended to use a low discount rate of 1-2%. With regards to possible increases in electricity prices during the period of the LCC, Eurostat data was consulted as shown below.



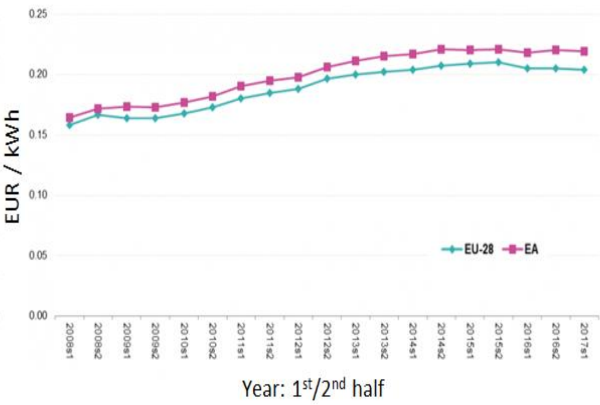


Figure 34. Electricity price increases for non-household customers (left) and household customers (right). Source: Eurostat.

The data in Figure 34 reveal that the average annual increase in electricity during the period 2008-2017 was 2% for non-household rates and 2.5% for household rates. It should be noted that non-household rates were considered as those customers consuming 500-2000 MWh/year. For the purposes of road lighting, the non-household rate of 0.12 EUR/kWh shall be used together with a presumed 2% annual increase in electricity price.

Another aspect to consider is whether the luminaires should be cleaned periodically or not. With traditional HID light sources, cleaning is typically carried out every 5 years, at the same time as lamps needed to be replaced. However, with LED lamps it may be that replacement only needs to occur every 10, 15 or 20 years. This raises the question of whether or not cleaning, as a standalone maintenance operation, should be carried out. For the purposes of these LCC calculations, it is assumed that needs for cleaning are greatly reduced by the use of 0.0% upward light output luminaires and so cleaning interventions are not considered.

Example scenario 1: New installation (HPS versus LED over 30 years).

The following example assumes a new installation and compares the LCC of using light sources that are either: HPS, cheaper LED (LED-1) or more expensive LED (LED-2). A total of seven different options were included: 1 for HPS (no dimming), 3 for lower quality LED (3 dimming scenarios) and 3 for higher quality LED (3 dimming scenarios). When considering dimming scenarios, 1 level dimming was when 50% of the time, light output was dimmed to 50% and 2 level dimming was when 25% of the time, light output was dimmed to 50% and 25% of the time, light output was dimmed to 10%. An electricity cost of €0.12/kWh was assumed as well as an annual increase in electricity cost of 2% and a discount rate of 1%. The installation operates for 4000 h/yr. The other main input cost elements were as described below.

Table 19. Input costs and assumptions for the 7 different scenarios new installation costing over a 30 year period

	Option 1 HPS no dimming	Option 2 LED-1 no dimming	Option 3 LED-1 1 level dimming	Option 4 LED-1 2 level dimming	Option 5 LED-2 no dimming	Option 6 LED-2 1 level dimming	Option 7 LED-2 2 level dimming
No. luminaires	500 units	500 units	500 units	500 units	500 units	500 units	500 units
Price per luminaire*	€280	€500	€500	€500	€800	€800	€800
Labour cost per luminaire	€89	€89	€89	€89	€89	€89	€89
No. poles and foundations	500 units	500 units	500 units	500 units	500 units	500 units	500 units
Price per pole and foundation	€3240	€3240	€3240	€3240	€3240	€3240	€3240
Labour cost per pole and foundation	€1215	€1215	€1215	€1215	€1215	€1215	€1215
Cost of external control device/system	€0	€0	€0	€0	€0	€0	€0
Luminaire power consumption (50% of time)	150 W	100 W	100 W	100 W	80 W	80 W	80 W
Reduced power level 1 (25% of time)	150 W	100 W	50 W	50 W	80 W	40 W	40 W
Reduced power level 2 (25% of time)	150 W	100 W	50 W	10 W	80 W	40 W	8 W
Light source replacement price	€9	€200	€200	€200	€300	€300	€300
Light source replacement labour cost	€89	€89	€89	€89	€89	€89	€89
Light source replacement interval	20000 h	50000 h	50000 h	50000 h	100000 h	100000 h	100000 h
Ballast/driver replacement price	€160	€160	€160	€160	€160	€160	€160
Ballast/driver replacement labour cost	€89	€89	€89	€89	€89	€89	€89
Ballast/driver replacement interval	80000 h	50000 h	50000 h	50000 h	100000 h	100000 h	100000 h
Luminaire lifespan	30 yrs	30 yrs	30 yrs	30 yrs	30 yrs	30 yrs	30 yrs
Pole lifespan	30 yrs	30 yrs	30 yrs	30 yrs	30 yrs	30 yrs	30 yrs

**includes light source and ballast/control drivers*

The output of the LCC is illustrated below in Figure 35.

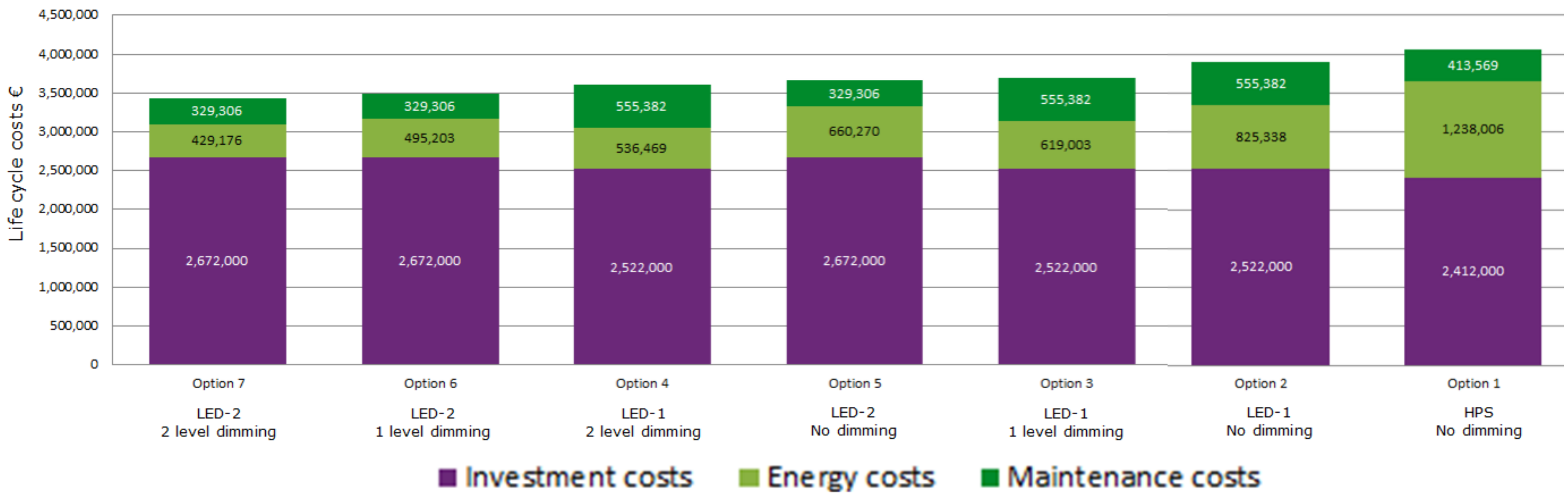


Figure 35. Graphical presentation of LCC results for the 7 options described in Table 19.

The data presented in Figure 35 show some very interesting conclusions. Due to the fact that the installation is new, investment costs dominate the overall LCC for all options. Even though investment costs are slightly cheaper for the HPS luminaires and that significant maintenance cost reductions were possible due to the low cost of HPS light sources, this was not sufficient to compensate for the need to change these light sources more frequently and the fact that LED-1 and LED-2 offer power consumption reductions of 33% and 47%.

Comparing HPS, LED-1 and LED-2 for the no dimming scenarios (i.e. options 1, 2 and 5), the following conclusions can be drawn:

- The investment costs increased by €110,000 going from HPS → LED-1 and by a further €150,000 going from LED-1 → LED-2.
- The energy costs decreased by €410,000 going from HPS → LED-1 and by a further €165,000 going from LED-1 → LED-2.
- The maintenance costs increased by €140,000 going from HPS → LED-1 but then decreased by €225,000 going from LED-1 → LED-2. In this case, the longer lifetime (100,000h) of the LED-2 light source more than compensated for its higher replacement cost compared to the other light sources.

The effect of dimming (i.e. comparing options 2, 3 and 4 or comparing options 5, 6 and 7) had clear and directly proportional benefits on the fraction of LCC relating to energy costs. Dimming by 50% for 50% of the time (i.e. curfew) reduced energy costs by 25%. Going further (i.e. dimming to 50% for 25% of the time and to 10% for 25% of the time) resulted in energy cost reductions of 35%. It is extremely important to highlight that equally significant savings can also be achieved simply by procuring more energy efficient luminaires in the first place in order to achieve a given light level or even more simple, by considering if a lower light level would be acceptable in the first place even during peak hours.

Example scenario 2: Existing installation (HPS replacement versus LED luminaire retrofit over a period of 10, 20 or 30years).

A much more common scenario in Europe will be where an existing lighting installation needs to be refurbished. The public authority will basically have two choices: (i) simply replace the HPS lamps with new HPS lamps or (ii) retrofit the existing poles with LED luminaires. The main issues with the second option are that it has a significantly higher capital outlay and that not all LED luminaires are equal. Consequently, the aim of this analysis is explore the effect of different types of LED luminaire (that get progressively more expensive, but more durable and more energy efficient at the same time) and also the effect of the choice of life cycle period. The input data used is given below (again the electricity cost was €0.12/kWh, the electricity annual price increase was 2% and the discount rate was 1%).

Table 20. Input costs and assumptions for the 5 different scenarios for an existing installation over a 10, 20 or 30 year period

	Current facility	Retrofit LED-1 no dimming	Retrofit LED-1 With dimming	Retrofit LED-2 With dimming	Retrofit LED-3 With dimming
No. luminaires	500 units	500 units	500 units	500 units	500 units
Price per luminaire	€9**	€500	€500	€750	€1000
Labour cost per luminaire	€89	€89	€89	€89	€89
No. poles and foundations	500 units	500 units	500 units	500 units	500 units
Price per pole and foundation	€0	€0	€0	€0	€0
Labour cost per pole and foundation	€0	€0	€0	€0	€0
Cost of external control device/system	€0	€0	€0	€0	€0
Luminaire power consumption (50% of time)	150 W	100 W	100 W	80 W	65 W
Reduced power level 1 (25% of time)	150 W	100 W	50 W	40 W	32.5 W
Reduced power level 2 (25% of time)	150 W	100 W	50 W	40 W	32.5 W
Light source replacement price	€9	€200	€200	€350	€500
Light source replacement labour cost	€89	€89	€89	€89	€89
Light source replacement interval	20000 h	50000 h	50000 h	100000 h	100000 h
Ballast/driver replacement price	€160	€160	€160	€200	€250
Ballast/driver replacement labour cost	€89	€89	€89	€89	€89
Ballast/driver replacement interval	80000 h	50000 h	50000 h	100000 h	100000 h
Luminaire lifespan	30 yrs	30 yrs	30 yrs	30 yrs	30 yrs
Pole lifespan	30 yrs	30 yrs	30 yrs	30 yrs	30 yrs

**includes light source and ballast/control drivers*

***to account for 1st replacement of HPS lamp instead of retrofitting*

****dimming was assumed to be to 50% of normal lighting during 50% of the operational hours (i.e. curfew)*

Figure 36. Comparison of LCC for different retrofitting options and periods

The data presented in Figure 36 are particularly interesting because they highlight the importance of the period that the LCC covers on the final result. When assessing costs over 10 years only, simple replacement of HPS lamps was the most economical option despite the fact that energy costs were double or triple those or some other options. There is a real possibility that public authorities will choose to wait until the LED road lighting market matures (and costs decrease even further) before deciding on massive refurbishment programmes. Another major influence on such decisions will be whether or not government subsidies or other financial incentives are available for LED-retrofitting.

When looking at the LCC over 30 years, simple relamping was the least economical option although it must be added that the key benefits for LED-retrofitting was the ability to dim light output.

When looking over a period of 20 year, simple relamping was the 3rd most economical option, only being beaten by the cheaper LED options where dimming was carried out.

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