Hera Luce
Ufficio Ingegneria e Sviluppo

MEMORANDUM
Light Pollution by Road Lighting

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An holistic approach to light pollution

We light our outdoor nighttime environment to meet certain societal goals, such as increasing safety and security, enhancing economic development, as well as highlighting historic areas or landmarks of towns. Our society has become a 24-hour society, and nighttime lighting has become a necessity to facilitate using our roadways and downtown areas.

Light pollution is what we could call a side effect of anthropogenic light propagation into the nocturnal environment. The first studies began in 1970s and were focused on its impact on the starry sky; nowadays light pollution has widened its meaning by including effects as sky glow, light trespass, over-illumination and glare - but also by including adverse effects on wildlife and human health.

Recently Italian GPP criteria has proposed the following definition[1]:

"Light Pollution is the sum of all adverse impacts of artificial light on the environment due to any part of the light from a light 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) can cause overt adverse effects on human beings and environment".

Measuring light pollution can be tricky – Recital 9 of the EU Commission Regulation n° 245/2009 references (in a disparaging way) that: *"In the absence of internationally agreed scientific methods for measuring its environmental impact, the significance of the so-called «light pollution» could not be assessed"*. This is the reason why Italian GPP is endowed with rational and equitable light pollution criteria, due to scientific literature and a practical approach. Moreover, including lights that *"can cause* ***overt*** *adverse effects"* it is possible to avoid confusion between terms such as "obtrusive light", "light trespass", "skyglow", etc. by encompassing the full spectrum of (manifest and scientifically proven) problems caused by light pollution.

The competing interests between whether or not to regulate artificial lighting are based on the benefits associated with artificial lighting: For many the perceived needs for light at night could balance the problems that it may cause. But we should be aware that light pollution is not just concerned with the loss of the night sky, but is a complex and emerging problem including ecological and environmental harm.

On the other side, there is no "easy way" to limiting light pollution and some proposed criteria, such as "no flux over 90°" or "CCT less than 3000K" are too simplistic, in most cases ineffectual

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[1] See also Regulation n°245/2009, Annex II(e) and (f)

(i.e. inside city limits) and they could be seen as unnecessary limiting constraints for luminaires market.

An assessment of road lighting effects on human beings has already been provided with our Memorandum "Circadian effects of road lighting".

In this paper we will assess artificial light skyglow and equitable light pollution criteria (for both preserving dark sky sites and allowing amenity lighting where necessary).

Atmospheric scattering and skyglow

Sky glow occurs from both natural and human-made sources. The natural component of sky glow has five sources: sunlight reflected off the moon and earth, faint air glow in the upper atmosphere, sunlight reflected off interplanetary dust, starlight scattered in the atmosphere, and background light from faint, unresolved stars and nebulae. Artificial light that is either emitted directly upward by luminaires or reflected from the ground (or other surfaces) is scattered by dust and gas molecules in the atmosphere, producing a luminous background: it has the effect of reducing one's ability to view the stars.

RAYLEIGH AND MIE SCATTERING

In the Earth's atmosphere, absorption and scattering is caused by molecules and aerosol (particles such as fine dust or water droplets). The combined effects of absorption and scattering is called "extinction" and is generally expressed in km^{-1}. Thus, the extinction ε provides information on how much radiation is left after a certain propagation distance. This amount is often expressed as a transmission factor T, (in the limit of not too high values of ε) defined by:

$$T = \exp(-\varepsilon R)$$

where R is the length of the propagation path (distance) in km. Although transmission is often used in engineering applications, it should be kept in mind that its value depends on R, whereas extinction is a property of the atmosphere itself.

The theory of scattering encompasses three domains that are distinguished on the basis of the dimensionless size parameter x:

$$x = \frac{\pi D}{\lambda}$$

where D is the diameter of the scatterer and λ is the wavelength.

If $x << 1$, Rayleigh scattering applies, if $x >> 1$, geometrical optics apply and for the domain where $x \approx 1$, Mie scattering applies.

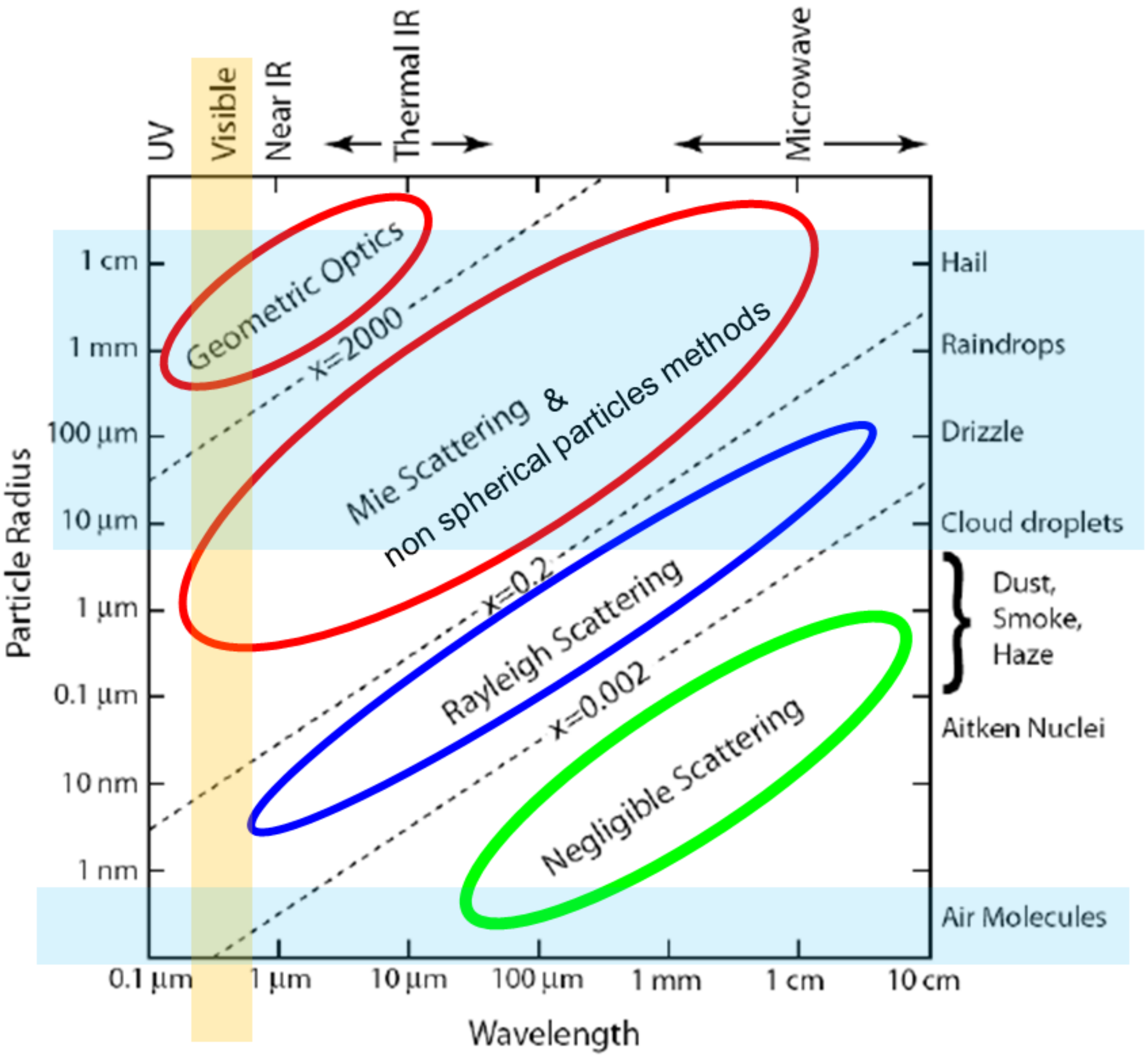

Figure 1. Single scattering relationships by spherical scatterer.

Since we are interested in light pollution caused by road lighting, λ is on the order of 0.5 µm: As we can see in Figure 1 (where only single scattering and spherical scatterer were taken into account – multiple scattering and scattering by non-spherical objects are too complex to be plotted), the scattering by air molecules is described by Rayleigh scattering, scattering by aerosols, drizzle, cloud droplets, haze is described by Mie scattering and scattering by raindrops, hail and snow flakes is described by geometrical optics (i.e. rainbow effect).

The three scattering theories are related: Rayleigh scattering and geometrical optics are limiting cases of the more complex Mie theory.

While Mie scattering and geometrical optics depend on particles amount, shape, dimension and on radiation relative orientation and wavelength, Rayleigh scattering depend only on particle amount and radiation wavelength.

The directional dependence of Mie scattering is shown in Figure 2 – while Rayleigh scattering is relatively diffuse.

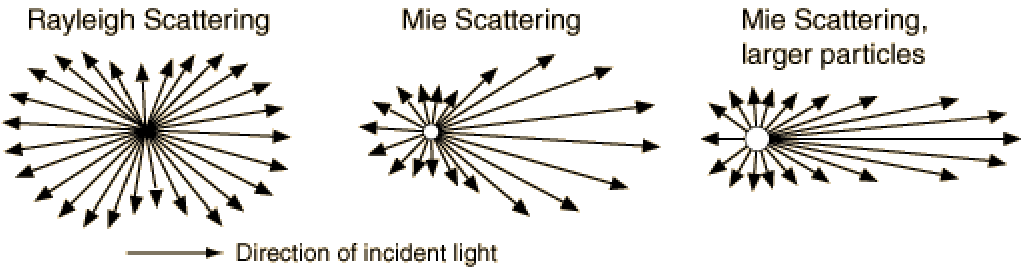

Figure 2. Directionality of scattering in the atmosphere.

Rayleigh pattern is symmetrical, with stronger scattering in forward and backward directions: In the case of road lighting, one might thus state that only 50% of the Rayleigh scattering could contribute to potential light pollution and even less for Mie scattering with higher angle irradiance.

Because the effect of light pollution is not a local phenomenon (the scattered light will generally travel a certain distance through the atmosphere until observer), a certain percentage of the light is lost due to extinction effects: For lower angle irradiance Mie scattering can produce higher propagation distance, while Rayleigh diffuse scattering generally increase atmosphere's extinction value.

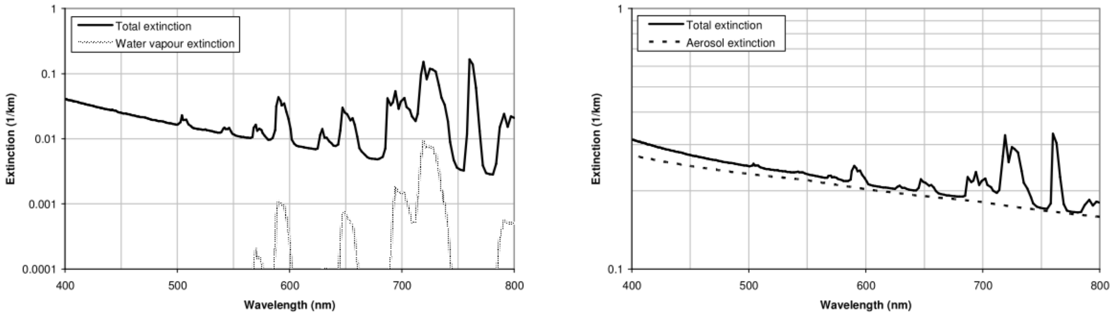

Figure 3. Extinction of the Earth's atmosphere. Left panel: molecular effects. Right panel: molecular + aerosol effects.

The left panel in Figure 3 shows the transmission due to molecules only: The smooth increase in extinction from longer to shorter wavelengths represents the increasing efficiency of the Rayleigh scattering. The "peaks" at longer wavelength represent molecular absorptions by water vapour and CO_2. The absorption bands at 580, 650, 690 and 730 nm are due to water vapour and will become more pronounced when the relative humidity in the atmosphere increases. The right panel of Figure 3 shows the extinction due to molecules and aerosols. The aerosols (dashed line) do not give rise to absorption peaks, but cause a smooth increase of the extinction towards shorter wavelengths.

All factors combined (black line in the right panel), the “minimal” extinction of the Earth’s atmosphere is found for 550÷700 nm interval. This implies that the light pollution due to street lamps emitting in this mid-interval (i.e. HPS lamps) will relatively efficiently propagate through the atmosphere.

The directionally and wavelength dependence of the Rayleigh scattering are given by:

$$I_R(\theta) \propto \lambda^{-4}(1 + \cos^2\theta)$$

From this, it follows that monochromatic blue light is more efficiently scattered than red light when referring to air molecules action (raised to the wavelength 4th power).

Many authors had used this relationship to demonstrate that LED (which is more bluish compared to HPS technology) could cause an increase of the light pollution and they underpinned this by comparing the Rayleigh scatter index of various light sources.

For what we have evaluated so far, this conclusion is too simplistic, because:

1) our atmosphere is not only made by air molecules, but also by pollution, dust, fog, haze (unfortunately it is not always a sunny day) – and sometimes it rains (or worse);
2) LED light is not a monochromatic blue light, but it has a wide continuous spectrum (from blue to red).

When considering point 1) it is possible to say that Mie scattering (or at least a combination of Ryleigh and Mie scattering) could better fit the actual behavior of atmosphere. Unfortunately, the directionality and the wavelength dependence of Mie scattering are not easily expressed in a proportionality relation.

With small approximations, it is possible to state that Mie scattering is proportional with an inverse power law wavelength-dependend function, where the exponent (called “Ångström Coefficient” or AC) is depending on the size of particle radius: AC = 4 is the highest value that represents Rayleigh scattering with small molecules and AC = 0.1 (or less) is the lowest value that represent geometric optics (when wavelength has a negligible contribution).

Moreover, the larger the particles the greater the directionality of light scattered in the atmosphere.

Under these conditions, it easy to understand why Rayleigh model could be assumed as the worst case ever[2], while real atmosphere generally is a mixture of molecules and aerosol and that this mixture has a less strong wavelength dependency[3].

Summing all up: Rayleigh scattering, due to air molecules, exhibits strong wavelength dependence, anisotropism and higher extinction values; Mie scattering, due to aerosols, exhibits weak wavelength dependence, higher directionality and lower extinction values.

When considering point 2) it is possible to assess HPS and LED lamps scattering by comparing the scattering probability under different conditions, considering that – as a first estimate – HPS can be approximated as a monochromatic "orange" light source (with a 550÷650 nm peak) and LED can be seen as composed by two monochromatic light sources, one "blue" (with a 425÷475 nm peak) and one "orange" (again with a 550÷650 nm peak); neutral white LED (4000K) is composed of about 25% monochromatic blue and 75% monochromatic orange light, while warm (3000K) white LED is composed of about 15% monochromatic blue and 85% monochromatic orange light.

The graph of scattering probability is shown in Figure 4: on the abscissa axis, are the wavelengths of colliding light; on the ordinate, are the scattering probabilities. Depending on particle radius, we have different curves, which range from air molecules (the lowest one) to raindrops (the highest one).

Using this graph, we could assess the approximated scattering probabilities for each kind of light source mentioned above under two different conditions: extreme clean air (with Rayleigh scattering and AC = 4) and polluted/marine air (with Mie scattering and AC = 0.7).

		EXTREME CLEAN AIR (only air molecules – Rayleigh scattering)	POLLUTED/MARINE AIR (air molecules and aerosol – Mie scattering)
Scattering Probability	HPS lamp	0,70	6,30
	Warm white LED	0,7 x 0,85 + 2,0 x 0,15 = 0,90	6,3 x 0,85 + 7,5 x 0,15 = 6,48
	Neutral white LED	0,7 x 0,75 + 2,0 x 0,25 = 1,03	6,3 x 0,75 + 7,5 x 0,25 = 6,60
	Blue LED	2,00	7,50

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[2] IDA. Visibility, environmental, and astromical issues associated with blue-rich white outdoor lighting. Report May 4, 2010. International dark-sky association.

[3] Garstang, RH. Model for artifical night-sky illumination. Publications of the Astronomical Society of the Pacific 1986 n° 98, 364-375.

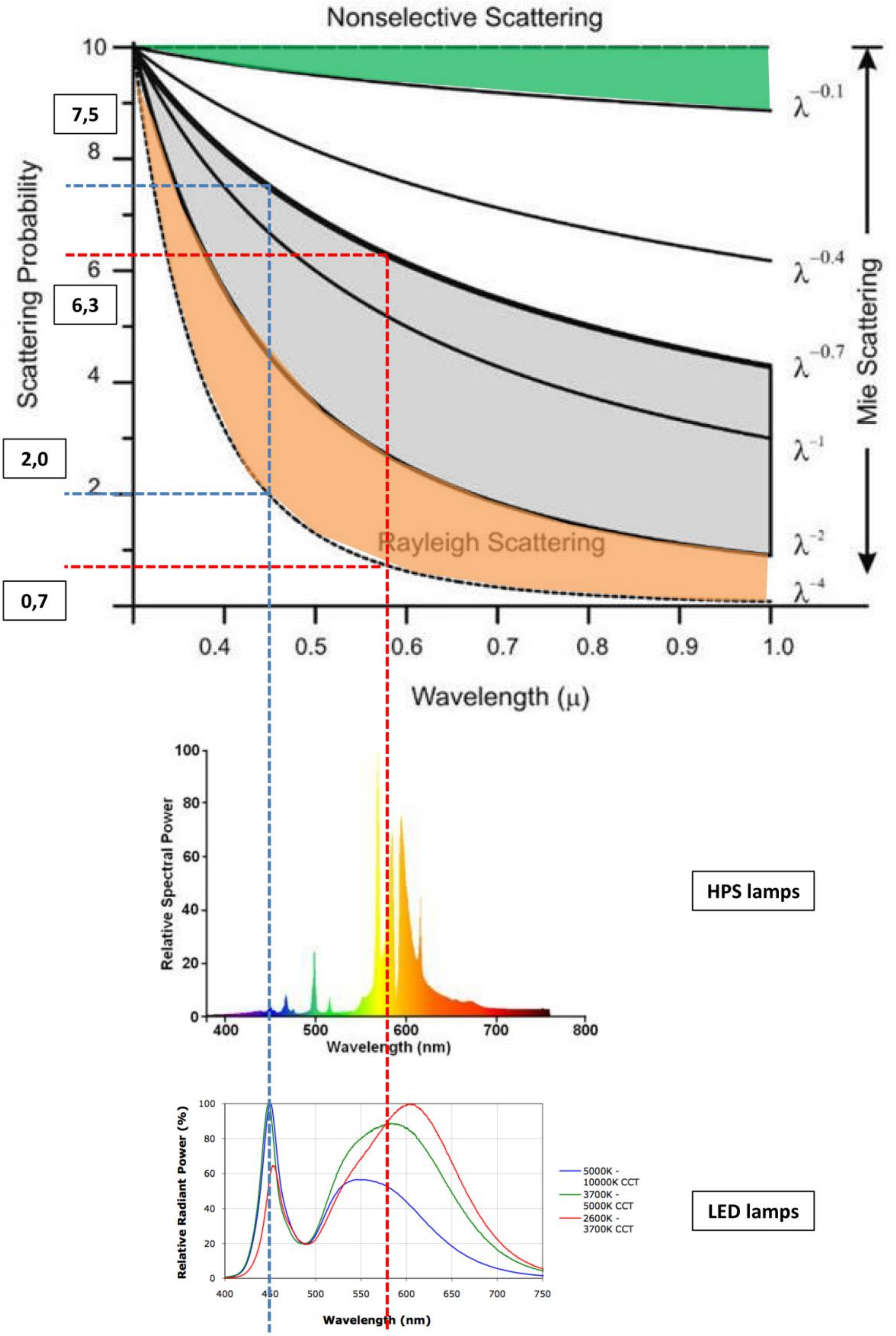

Figure 4. Scattering probability under different atmospheric conditions and particles size with references to blue and red light wavelengths.

If we consider the relative deltas using HPS scattering probability as the base value, we can appreciate how low are the differences between neutral white LED and warm white LED – even under the worst case ever (Rayleigh scattering). In fact, in terms of visibility and light hindrance, we expect that changes in the amount of scattered light of more than at least 30% will lead to significant results.

		EXTREME CLEAN AIR (only air molecules – Rayleigh scattering)	POLLUTED/MARINE AIR (air molecules and aerosol – Mie scattering)
HPS relative scattering	HPS lamp	0%	0%
	Warm white LED	+29%	+3%
	Neutral white LED	+47% (+18% to WW LED)	+5% (+2% to WW LED)
	Blue LED	+186%	+19%

For environments with a lower meteorological conditions, scattering probability become less depended from wavelength and therefore any kind of commercial white light source are undoubtedly equally polluting. Moreover correlated color temperature (CCT) or color rendering index (CRI) is not appropriate for characterizing the potential impacts of a light source on light pollution because CRI and CCT metrics could be not directly correlated with lamps spectra.

SURFACES AND GROUND REFLECTION

Until now we have only considered the direct rays that are emitted by luminaires, but ground and surface reflected rays could be different from their original source.

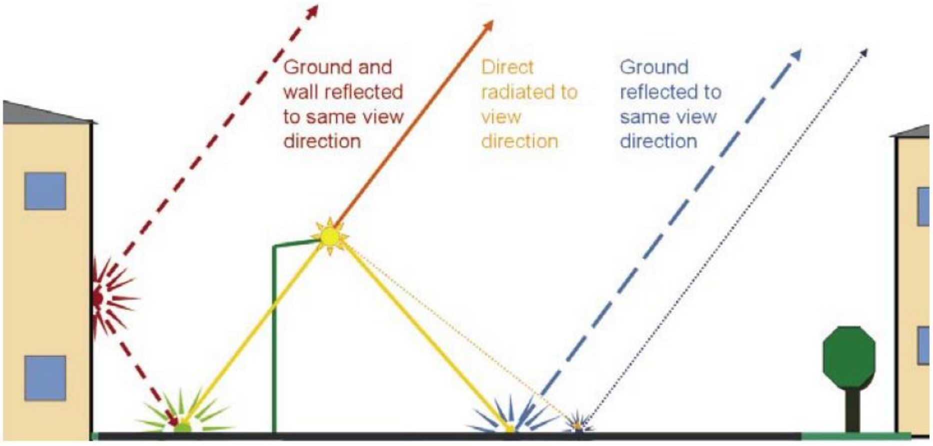

Figure 5. Direct and surface reflected rays in a typical urban road.

Surface reflections usually increase away from normal incidence and all surfaces become highly reflective close to grazing angle. The scattering off surfaces does effectively the reverse, having a cosine distribution peaking at normal incidence and falling to zero grazing incidence.

This effectively follows the projection of a surface area into the view direction. The combination as a function of incidence angle is called the bi-reflection distribution function (BRDF).

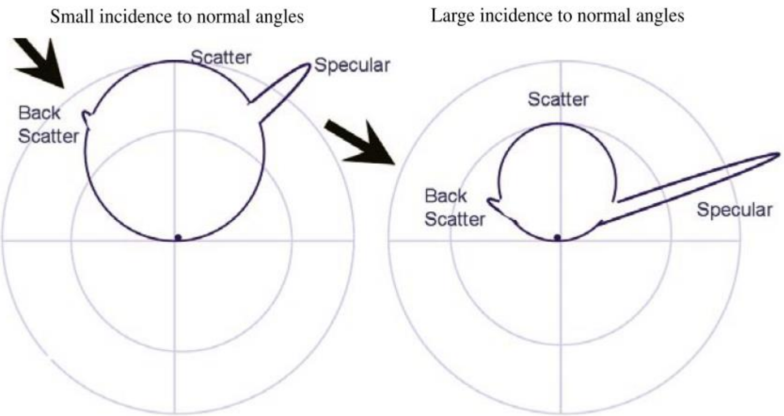

Figure 6. Bi-directional Reflectance Distribution Function. Showing dependence of scatter on cosine of incidence and cosine of view projection angle, and specular reflection near 1-cosine dependence on incidence angle (near Lambertian), increasing towards grazing.

To visualize the differences between different surfaces' reflection, we could consider a mirrored surface and a red stucco surface. The mirror reflects all of the components of light almost equally and the reflected specular light follows a trajectory having the same angle from the normal as the incident light. The red stucco surface, however, does not reflect all wavelengths because it absorbs most of the blue and green components, and reflects the red light. Also, the diffuse light that is reflected from the rough surface is scattered in all directions.

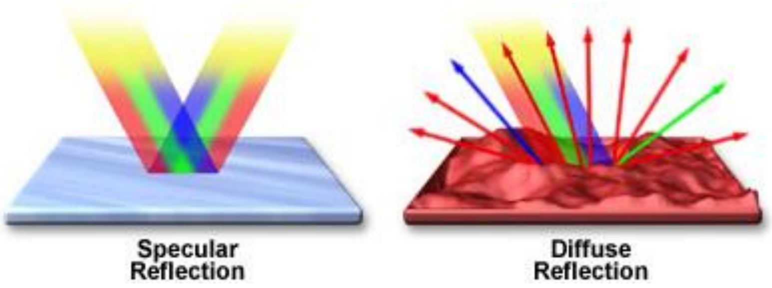

Figure 7. Light reflection on mirrored and red stucco surfaces.

The presence of buildings around luminaires can cause a screening effect (mainly at shallow angles) which may change spectrum, direction and intensity of incident light. We can assume a stronger effect near town center, where the presence and density of tall buildings can block most of incident light and where reflected light create a prominent steep angle flux; in this case it is possible to identify town center as a single luminous source (even if researches do not always agree on city emission functions[4,5,6,7]) with its own spectrum and where sky brightness produced by the emission over 30° exceeds that produced by the emission between the horizontal and 30° for every single luminaire[8]. Moreover, from results of modelling sky luminance of the city of Padova[9], it can be inferred that the sky luminance inside a city could be produced more by the sources in the surrounding land than by the city itself.

Ground reflection affects both urban and rural area. At close distance, scatter is dominated by ground reflection, while at longer distance it becomes dominated by low angle light from above the horizon[10].

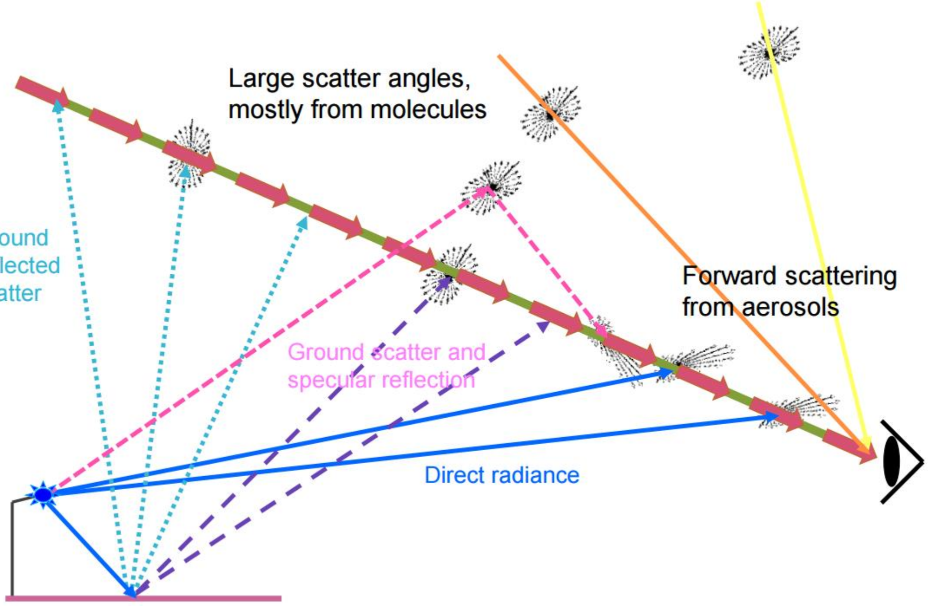

Figure 8. Contribution of direct and ground radiance to atmosphere scattering, considering the line of sight (steep angle scatter is due mostly by air molecues and Ryleigh scattering; shallow angle scatter is due mostly by aerosols and Mie scattering) .

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[4] Garstang RH. Model for Artificial Night-Sky Illumination. Publ Astron Soc Pac 98:364-375, 1986.

[5] Falchi F, Cinzano P. Measuring and Modelling Light Pollution. Mem Soc Astron Ital 71: 139, 2000.

[6] Soardo P, Lacomussi P, Rossi G, Fellin L. Compatibility of road lighting with star visibility. Lighting Research and Technology, 40, 307-322, 2008.

[7] Luginbuhl CB, Duriscoe DM, Moore CW, Richman A, Lockwood GW, Davis DR. From the Ground Up II: Sky Glow and Near-Ground Artificial Light Propagation in Flagstaff, Arizona. Publications of the Astronomical Society of Pacific, Volume 121, Issue 876, pp. 204-212, 2009.

[8] Cinzano P, Diaz Castro FJ. The artificial sky luminance and the emission angles of the upward light flux. Memorie della Società Astronomia Italiana, Vol. 71, p.251, 2000.

[9] Cinzano P. Measuring and Modelling Light Pollution, ed. P. Cinzano, Mem. Soc. Astron. Ita., in press, 1999.

[10] Baddiley CA. Model to Show the Differences in Skyglow from Types of Luminaires Designs. Starlight. La Palma, Canary Islands, 2007.

Usually, in street lighting design, ground reflectance is considered independently of the wavelength and with a typical value of $Q_0 = 0,07$ (based on asphalt reflectance). But, for the most of road pavements, the relative reflectances are higher for the long wavelength region: Due to the higher content in the long wavelength region HPS lamps are usually more effective than MH (or other white lamps) in terms of light reflected from the pavements[11].

Again, it is possible to assess HPS and LED lamps ground reflected scattering by comparing the scattering probability under different conditions, considering that – as a first estimate – HPS can be approximated as a monochromatic “orange” light source and LED can be seen as composed by two monochromatic light sources, one “blue” and one “orange”.

The graph of spectral reflectance of asphalt and concrete is shown in Figure 9: on the abscissa axis, are the wavelengths of colliding light; on the ordinate, is the reflectance. Using this graph, we could assess the approximated reflection for each kind of light source mentioned above.

	Asphalt Reflection (absolute)	Asphalt Reflection (HPS relative)
HPS lamp	0,080	0%
Warm white LED	0,074	-8%
Neutral white LED	0,070	-13%
Blue LED	0,040	-50%

If we couple the table above with previous results, we can assess the relative scattering due to ground reflection (that is the prevailing effect at close distance from the observer).

		EXTREME CLEAN AIR (only air molecules – Rayleigh scattering)	POLLUTED/MARINE AIR (air molecules and aerosol – Mie scattering)
HPS relative scattering	HPS lamp	0%	0%
	Warm white LED	+21%	-5%
	Neutral white LED	+34% (+13% to WW LED)	-8% (-3% to WW LED)
	Blue LED	+136%	-31%

While it is not possible to evaluate spectrum change because of complexity given by the large amount of variables underneath, we can also consider a plausible “red shift” of reflected light by asphalt pavements. Additionally, if we consider concrete pavements, differences may be even more pronounced.

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[11] Ekrias A, Ylinen A, Eloholma M, Halonen L. Effects of pavement lightness and colour on road lighting performance. CIE Expert Symposium on road surface photometric characteristics, Torino Italy 9-10 July, 2008.

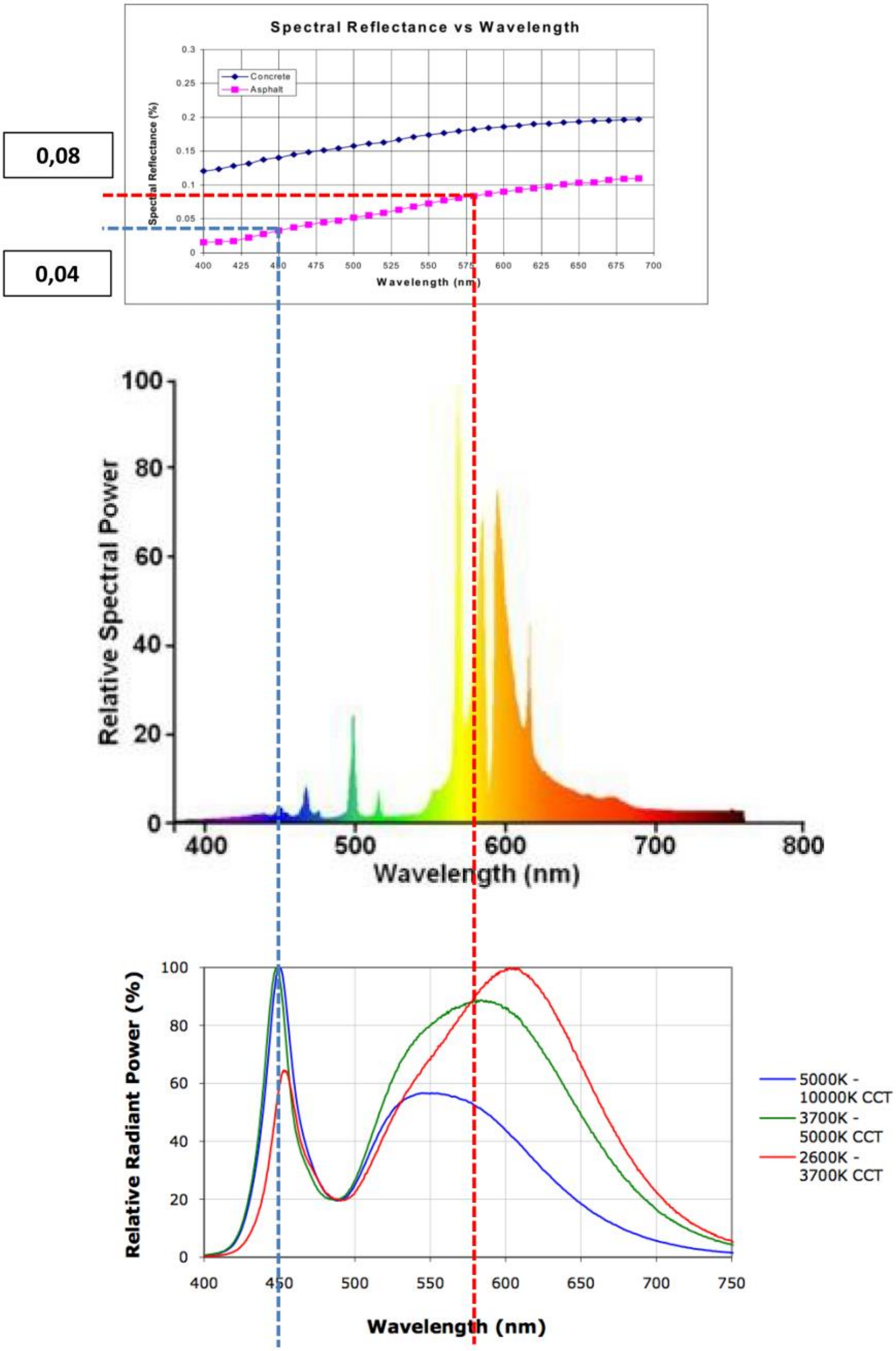

Figure 9. Scattering probability under different atmospheric conditions and particles size with references to blue and red light wavelengths.

Aside from asphalt and concrete pavements, we could consider grass as the third most significant horizontal surface. Obviously there are thousands of different grass type and species with different spectral reflectance, but taking as example the graph in Figure 10, it is possible to affirm that in this case "green" spectrum (around 550 nm) play a major role in ground reflection.

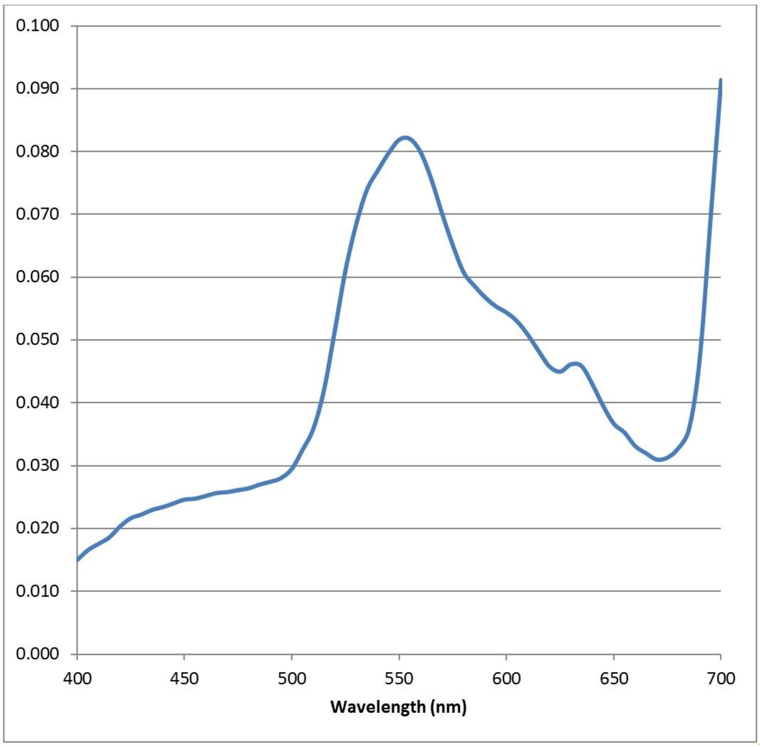

Figure 10. *Poa pratensis* spectral reflectance distribution.

Even in this case, HPS lamps are more effective than LED lamps.

Finally, for environments with a lower meteorological conditions, we know that scattering probability become less depended from wavelength and water, ice or snow covering ground could result in a more linear spectral reflectance. Again, in this cases, any kind of commercial white light source are undoubtedly equally polluting.

PHOTOPIC, MESOPIC AND SCOTOPIC VISION

The terms photopic, mesopic and scotopic vision refer to three ranges of human vision adaptation level, which differ in anatomical response, spectrum and their effect on visual acuity[12].

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[12] The Illuminating Engineering Society of North America (IES) has incorporated these effects into its lighting recommendations for low light levels, found in the IES Handbook (10th Ed.) and in TM-12-12, Spectral Effects of lighting on Visual Performance at Mesopic Lighting Levels.

To better understand these terms we could refer to properties of light-sensitive cells on the retina:

- the cones cover most of the retina, but their greatest concentration is at the fovea, the center back of the eye, giving us fine visual acuity when we look directly at something. They are less dense away from the fovea, giving us less precise peripheral vision. There are three kinds of cones: long-wavelength, medium-wavelength and short-wavelength cones (formerly call the red, green and blue cones, respectively). In combination they are responsible for giving us color vision. The cones are most active in medium and high light levels. As the general environmental brightness drops, the cones become less effective and it becomes difficult for us to discern fine details and colors;
- the rods are primarily responsible for giving us peripheral vision and providing information about contrast and movement. There are no rods at the fovea of the eye, but they cover the rest of the retina in greater concentration than the cones. The rods become overwhelmed with high light levels, but at low light levels, they are more active than the cones are.

Unfortunately, photoreceptors alone are insufficient to explain night vision, because rods and cones ought to translate the light they receive into electrical, and then chemical, signals and then bipolar, horizontal, amacrine, and ganglion cells have to interpret this information before wrapping all up and sending signals to brain.

The part of the retina of which the photoreceptors pertain to a single optic nerve fiber are called “receptive field”. But in a broader way the definition includes a description of the substructure, of how you have to stimulate an area to make the cell respond: Receptive fields have been mapped for all levels of the visual system from photoreceptors, to retinal ganglion cells, to lateral geniculate nucleus cells, to visual cortex cells, to extra-striate cortical cells. A major difference between photopic and scotopic vision concerns inhibition and convergence that inherit receptive fields and could not be explained only in terms of photoreceptors.

The three ranges of adaption level could be summarized in the following way:

1) **Photopic**: This term generally covers adaptation levels of 3 cd/m^2 and higher (where “adaptation level” is the overall brightness of your environment that your eyes have adjusted to and that is mostly determined by the luminance of the surface we happen to be looking at[13]). The combined peak sensitivity of the cones is at 555 nm, in the yellow-green part of the visible spectrum (see yellow curve in Figure 11): The lumen, the basic metric of visible light, is defined by photopic luminosity function;

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[13] Moon, P., and D. E. Spencer. The Specification of Foveal Adaptation. J. Optical Society of America 33(8):444-456, 1943.

2) **Mesopic**: This term refers to a range of human vision with both rods and cones active. There is no hard-line transition at either end, but for most intents and purposes the mesopic range is generally considered to be from 3 cd/m^2 down to 0.005 cd/m^2;
3) **Scotopic**: This term corresponds to an adaptation level below 0.005 cd/m^2. The peak sensitivity of the rods is at 507 nm, in the blue-green part of the visible spectrum (see blue curve in Figure 11). While there may be some (very little) cone activity at 0.005 cd/m^2, once the light level drops below 0.001 cd/m^2, only the rods are active. At this point, the ability to discern colors as well as fine details is gone (since there are no rods at the fovea and the cones are not receiving enough light to be stimulated).

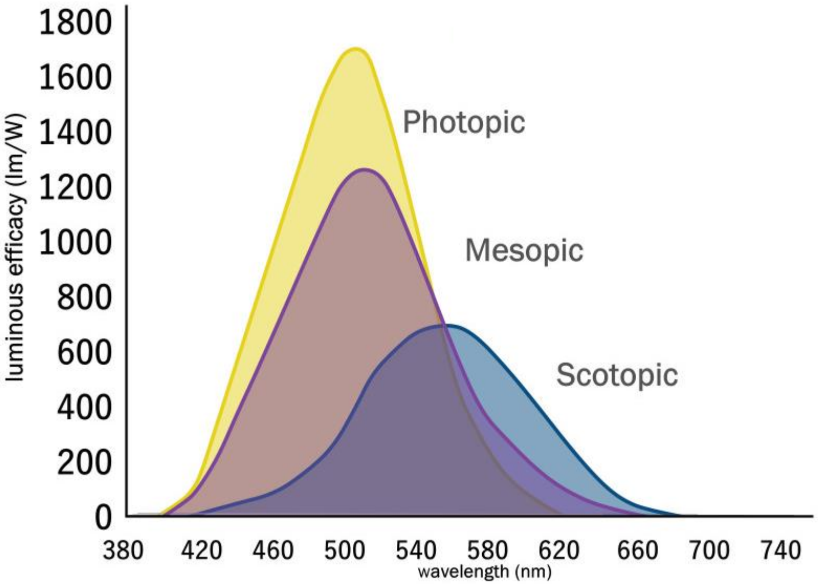


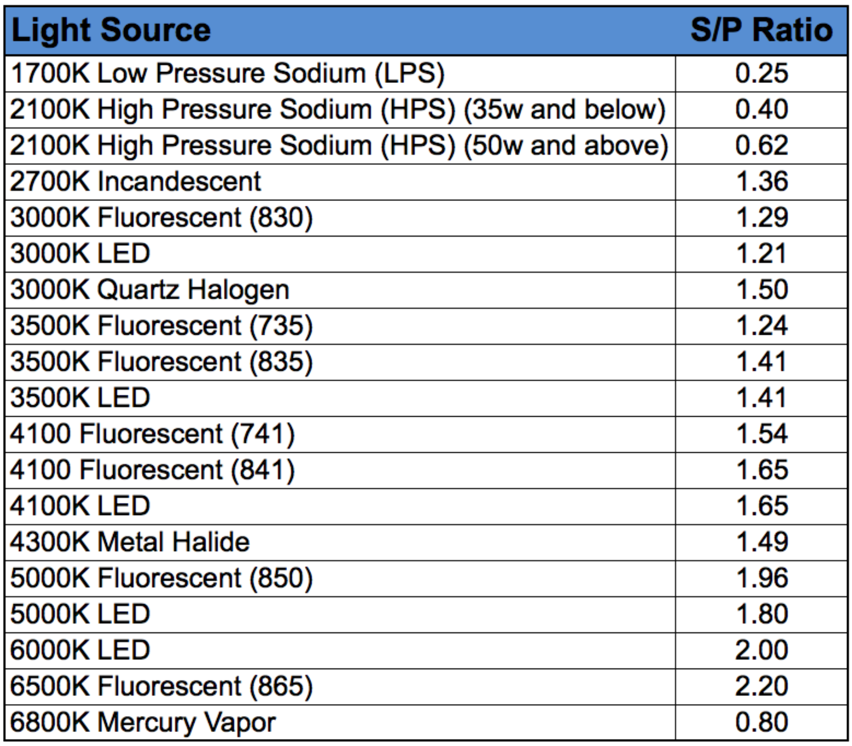
Figure 11. Photopic and scotopic sensivity curve (mesopic curve lies between photopic and scotopic curve).

Because of this difference in spectral sensitivity, the luminance, defined by the photopic luminosity function, is not always a good measure of visibility at low light levels: If we assume an average 30% lambertian reflectance of environment, luminance of 3 cd/m^2 would result from illuminance of approximately 30 lux while luminance of 0.005 cd/m^2 would result from illuminance of about 0.05 lux; if we assume an average 10% lambertian reflectance of environment (i.e. road surfaces with dark surrounding environment), luminance of 3 cd/m2 would result from illuminance of approximately 90 lux while luminance of 0.005 cd/m2 would result from illuminance of about 0.15 lux.

In urban environments, there is enough ambient light at night to prevent real scotopic vision and the peak of visual sensitivity is generally in the mesopic range. We should also consider that brightly lit areas (such as shopping streets) could near photopic vision, while full moonlight can reach up to 1 lux, leaving scotopic vision confined to unlit areas during moonless days. The lower the light level, the greater shift away from the photopic sensitivity curve to scotopic sensitivity curve.

Because photopic and scotopic luminous efficiency functions are different, they will yield different values for the scotopic and photopic lumens for the same light source. The ratio of these two values is the scotopic-to-photopic (S/P) ratio. This is the ratio of the luminous output of a light source evaluated according to the CIE scotopic spectral luminous efficiency function, *V'(λ)*, to the luminous output evaluated according to the CIE photopic spectral luminous efficiency function, *V(λ)*. The sources with higher ratio would appear brighter than low S/P ratio sources with the same lumens under mesopic conditions.

Typical S/P ratios of commercially available light sources used in outdoor lighting applications are conveniently listed in Figure 12.

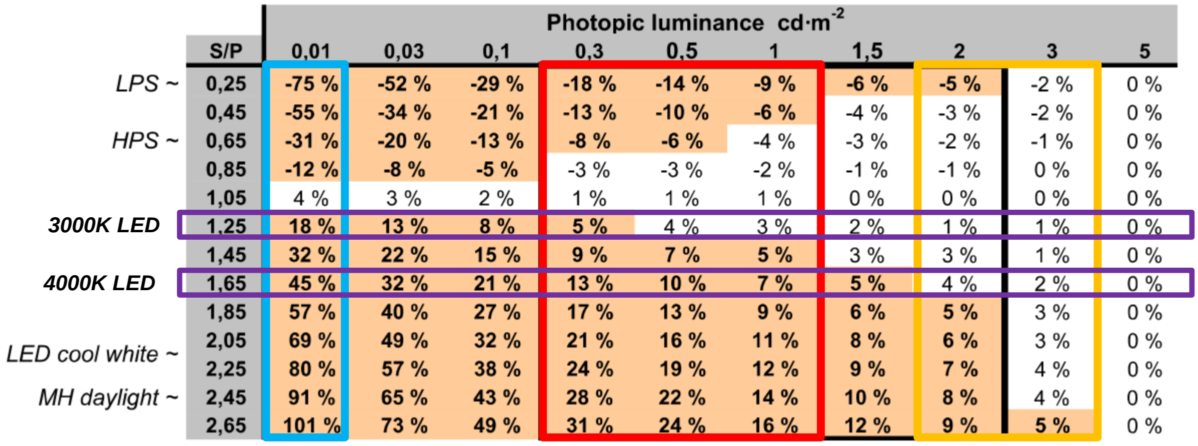


Light Source	S/P Ratio
1700K Low Pressure Sodium (LPS)	0.25
2100K High Pressure Sodium (HPS) (35w and below)	0.40
2100K High Pressure Sodium (HPS) (50w and above)	0.62
2700K Incandescent	1.36
3000K Fluorescent (830)	1.29
3000K LED	1.21
3000K Quartz Halogen	1.50
3500K Fluorescent (735)	1.24
3500K Fluorescent (835)	1.41
3500K LED	1.41
4100 Fluorescent (741)	1.54
4100 Fluorescent (841)	1.65
4100K LED	1.65
4300K Metal Halide	1.49
5000K Fluorescent (850)	1.96
5000K LED	1.80
6000K LED	2.00
6500K Fluorescent (865)	2.20
6800K Mercury Vapor	0.80

Figure 12. Typical S/P ratio for commercial light sources.

Some publications on mesopic lighting have indicated that the S/P ratio of a lamp can be estimated from its correlated color temperature (CCT), but this is incorrect except for incandescent lamps (which have little practical application to mesopic lighting): again, CCT metrics could be not directly correlated with lamps features.

The use of mesopic dimensioning changes the luminous output and consequently the luminous efficacy orders of lamps, as seen in Figure 13:



		Photopic luminance cd·m^{-2}									
	S/P	0,01	0,03	0,1	0,3	0,5	1	1,5	2	3	5
LPS ~	0,25	-75 %	-52 %	-29 %	-18 %	-14 %	-9 %	-6 %	-5 %	-2 %	0 %
	0,45	-55 %	-34 %	-21 %	-13 %	-10 %	-6 %	-4 %	-3 %	-2 %	0 %
HPS ~	0,65	-31 %	-20 %	-13 %	-8 %	-6 %	-4 %	-3 %	-2 %	-1 %	0 %
	0,85	-12 %	-8 %	-5 %	-3 %	-3 %	-2 %	-1 %	-1 %	0 %	0 %
	1,05	4 %	3 %	2 %	1 %	1 %	1 %	0 %	0 %	0 %	0 %
3000K LED	1,25	18 %	13 %	8 %	5 %	4 %	3 %	2 %	1 %	1 %	0 %
	1,45	32 %	22 %	15 %	9 %	7 %	5 %	3 %	3 %	1 %	0 %
4000K LED	1,65	45 %	32 %	21 %	13 %	10 %	7 %	5 %	4 %	2 %	0 %
	1,85	57 %	40 %	27 %	17 %	13 %	9 %	6 %	5 %	3 %	0 %
	2,05	69 %	49 %	32 %	21 %	16 %	11 %	8 %	6 %	3 %	0 %
LED cool white ~	2,25	80 %	57 %	38 %	24 %	19 %	12 %	9 %	7 %	4 %	0 %
MH daylight ~	2,45	91 %	65 %	43 %	28 %	22 %	14 %	10 %	8 %	4 %	0 %
	2,65	101 %	73 %	49 %	31 %	24 %	16 %	12 %	9 %	5 %	0 %

Figure 13. Differences between mesopic and photopic luminance (%) calculated with CIE 191:2010 recommended mesopic system.

For example, at a photopic luminance of 1 cd/m^2, the use of the CIE 191:2010 system results in a change between +5% and +10% for lamps with S/P-ratios between 1,5 and 2,0; at 0,3 cd/m^2 the change is between about +10 % and +20 %. Mesopic metric could give the manufacturers foundations on which to develop light sources that are optimized for low light level applications. This will result in better energy-efficiency and visual effectiveness in outdoor lighting conditions.

For our purposes, we will just focus on the relatively higher skyglow (or at least the perceived sky brightness) produced under the same photopic luminance by different light sources. Using Figure 13 table, we could define three different adaption levels:

1) brightly lit areas (such as commercial districts) – highlighted in orange in Figure 13;
2) urban lit areas (under UNI 13201 specifications) and their surroundings – highlighted in red in Figure 13;
3) unlit areas with no near artificial sources around – highlighted in blue in Figure 13.

When comparing 3000K LED sources with 4000K LED sources, we could appreciate a major difference in unlit areas (case 3), which have about +30% of relatively perceived sky brightness. This assumes, however, that the observer is completely dark-adapted.

In a urban setting, the surrounding road lighting will most likely result in only partial dark adaptation, and so mesopic vision will apply: in case 1 and 2, the differences in relative sky glow luminance could be seen as negligible.

Obviously, if mesopic metric is applied for road lighting designing, there won't be any differences between the two sources in case 1 and 2.

MODELLING STARRY NIGHT LIGHT POLLUTION

A number of people have modeled light pollution in various ways. The first model was made by Walker[14] and it was an important step to start modeling the sky brightness of the cities.

Garstang[4] has done detailed calculations for a number of observatory sites, creating maps showing how the skyglow varies at different altitudes and azimuths from each site. Further Burton[15] has analyzed satellite data from the Defense Meteorological Satellite Program (DMSP; run by the U.S. Air Force) to estimate skyglow in the close vicinity of urban areas[16]. This has the advantage of considering actual satellite data at high resolution, both spatially and in terms of intensity. However, limited consideration is given to atmospheric scattering, especially over large distances. DMSP data have been linked with a calibrated scattering model in Europe by Cinzano et al.[17] Chalkias et al. have modeled light pollution for the outskirts of urban areas by integrating GIS and remote sensing techniques and produced visibility analysis maps[18].

Recently Aubé[19], Kocifaj[20], Cinzano et al.[21] and Baddiley[22] have proposed different light pollution numerical models that can simulate human induced sky radiance under a variety of conditions. All of these models are sophisticated research tools that are designed to give accurate outputs (even if they could be very sensitive to the inputs given) and they show good agreement with our prior considerations.

It should be pointed out that the interaction of artificial light with the environment shows an extremely complex and nonlinear behavior (which cannot be analytically solved so far) and relies on multiple variables interactions, such as the optical properties of the atmosphere, the

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[15] Burton W. 2001. The NOVAC–DMSP light-pollution map project.

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[21] Cinzano P, Falchi F. The propagation of light pollution in the atmosphere. Mon. Not. R. Astron. Soc. 427, 3337–3357, 2012.

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spectral reflectance properties of ground, the presence of masking by terrain and obstacles, the characteristics of lighting devices.

We can summarize the main results obtained from these models as follow:

- Scattering from air molecules and aerosols have differing properties and the Ångström Coefficient lies between the limits of the Mie and Rayleigh theories: The more polluted air, the lesser the AC. Also AC decreases gradually moving away from city center.
- Close to towns, ground reflection dominates the zenith sky radiance, while direct upward emission dominates the zenith sky radiance when observer is located far from the city. At a distance from towns, skyglow is dominated at low to mid elevation angles by direct radiance above the horizon (the maximum scatter is usually located at some distance in front of the source, due to enhanced scatter at shallow angles).
- While light travelling near the horizon has been historically identified as having a significant impact on sky brightness, especially for remote observers, recently Aubé[23] and Luginbuhl et al.[24] showed that it is not as critical as previously thought – mostly because many of these concerns were identified with simplified models that had a very basic implementation of the second order of scattering and that did not account for blocking obstacles or topography (omitting the effect of light blocking by objects, such as buildings and vegetation, could lead to an overestimation of the sky brightness by a factor of more than two: this discrepancy is more important for low to mid elevation angles).
- The picture of decreasing skyglow by only limiting ULOR (or light emission above 90°) might be too simplistic, because light pollution is first a question of performance (i.e. the capacity that an installation has to minimize the quantity of installed lm/km to reach a reference set of lighting criteria): Large differences may exist between different lighting systems, depending on light output pattern and spatial distribution of lighting power on the territory[25]. In 2007 LRC proposed a light pollution assessment based upon a virtual calculation 'box' surrounding an outdoor lighting installation, following the property boundary and containing a top plane[26]: "glow" is defined as the overall average illuminance

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[23] Aubé M. Light pollution modelling and detection in a heterogeneous environment. In Proc. Starlight 2007 Conference, La Palma, Spain, 19–20 April 2007 (eds Marin C, Jafari J) pp. 351–358, 2007.

[24] Luginbuhl CB, Duriscoe DM, Moore CW, Richman A, Lockwood GW, Davis DR. From the ground up II: sky glow and near-ground artificial light propagation in Flagstaff, Arizona. Publ. Astron. Soc. Pac. 121, 204–212, 2009.

[25] Gillet M., Rombauts P. Precise evaluation of upward flux from outdoor lighting installations (applied in the case of roadway lighting). Light Trespass Symposium London, 2001.

[26] Brons, J. A., J. D. Bullough and M. S. Rea. Outdoor site-lighting performance: A comprehensive and

on the side and top planes of the box. This definition does not take into account the potential effects of light travelling in different directions on sky glow, but allows comparison of the density of light leaving a property. The same year, Italian Trento province adopted a similar approach to evaluate light pollution[27]. The pros of this method are that there is no restriction on lighting products: one could use a decorative luminaire (with high ULOR) within an installation, but mitigate glow via canopies, vegetation or other means that would reduce the amount of light leaving the site.

- Higher angle beams scatter little into horizontal directions. In this case we have a local incremented zenith sky radiance just above the luminaire (see also the point below).
- Obstacles taller than light fixtures generally cause lower angles direct light to be blocked and higher angles direct light to be reflected more towards zenith direction and in all reducing skyglow at larger distances (but incrementing zenith sky radiance above the observer). Basically to have obstacles taller than lighting fixture is more or less equivalent to a reduction of the net ULOR of the luminaire. When obstacles are smaller than the light fixtures, their impact is very low.

BEYOND STREET LIGHTING

The total flux emitted from a city is due to collective effects of many sources embedded into various environments (city parks, streets, industrial zones, etc.), while a considerable portion of light emissions can even originate from automobile lighting, sports lighting, industry, advertisement boards and also private households. In an extensive experiment, Novák et al.[28] compared the illumination levels of a city before and after switching off public lighting and concluded that its contribution to sky glow might be as low as 50% or even less.

Hence we talking about acting in less than 50% of potential sources of light pollution. But we must also consider that while almost near-zero ULOR could be easily implemented for street lighting, for other applications it could not.

Speaking about ULOR, it should be noted that parameter with relative argument is more permissive with high polluting lights than low-emission fixtures.

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quantitative framework for assessing light pollution. Lighting Research and Technology 40(3): 201-224, 2008.

[27] LEGGE PROVINCIALE 3 ottobre 2007, n. 16 “Risparmio energetico e inquinamento luminoso”.

[28] Novák T., Sokanský K., Dostál F. Public Lighting Part Measurement for Night Sky Glare Increasing before and after Switching off Big Area (Liberec District in the Czech Republic). Proceedings of the 11th International Scientific Conference Electric Power Engineering, University of Technology, 857-861, 978-80-214-4094-4, 2010.

For example, 1% maximum ULOR for 1000W floodlight means more than 1.000 lm of maximum uplight while 1% maximum ULOR for 20W LED luminaire for bike lanes means 20 lm of maximum uplight: the upward light emitted by any floodlight may be equal to 500 LED luminaires. Moreover, given that the LED fixture is emitting 2.000 lumen and that the laboratory surface have a diffuse reflectance of at least 2%, it is physically impossible to measure fewer than 20 lumens (or 1% maximum ULOR).
The same problem is found with 0 cd/klm (or 0,49 cd/klm) limit (used in many Regions in Italy).

Since most of the proposed criteria (i.e. reducing ULOR to 0% or limiting CCT) – as we have seen before – have little impact on minimizing light pollution and could not affect every artificial source, equitable criteria should focus on effective mitigation strategies and at the same time may allow people to have the right light for their needs.

Equitable criteria

While it is difficult to accurately model skyglow, at this point it is presumed that the most important factors are light output and distribution from the luminaire, reflected light from the ground and surroundings and aerosol particle distribution in the atmosphere.
Whereas it is impossible to carefully assess boundaries' reflections and atmosphere composition, let's start with a simple argument: If the quantity of light going up into the sky is reduced, then sky glow is reduced.
Thus, if we want to reduce sky glow, we could:

1) minimize the amount of light emitted upward directly from the luminaire;
2) avoid wasting downward light flux outside the area to be lit;
3) reduce overall light levels to the minimum necessary;
4) reducing lighting levels or shut off lights when they are no longer needed during the night;
5) remove unneeded lights;
6) limiting lighted hours of outdoor sales areas, parking areas, signs, etc.;
7) limiting lighting installations.

It is easy to understand how points from (1) to (3) are strictly related to energy performance criteria, especially PDI parameter: point (1) is about increasing luminaire efficacy and thus reducing W/lx ratio; point (2) is about reducing 1/(lx·m^2) ratio; point (3) is about reducing power consumption. Hence, asking for energy efficiency criteria can automatically reduce sky glow.

Points from (1) to (4) are also strictly related to lighting design, while points from (5) to (7) could be evaluated by appropriate political assessments: New technology or technical solutions are useless without political awareness and direction.

If it were possible to narrow down the problem of road lighting to functional requirements such as ground illuminance (or luminance) and uniformity, there would not be too much to say: nowadays street LED luminaires always have near-zero ULOR and could easily provide a luminaire efficacy higher than 105 lm/W. Nevertheless LED streetlights usually produce very directional light rather than a “diffused light” (as in HID luminaires): This creates a specific, well-lit area while avoiding light trespass and wasting flux outside the area to be lit.
LED technology could also turn on and off almost immediately and can provide dimming capability from 0% to 100%.
A typical section view illustrating light pollution and useful light from a pole-mounted outdoor luminaire (see Figure 14) displays all LED characteristics mentioned above.

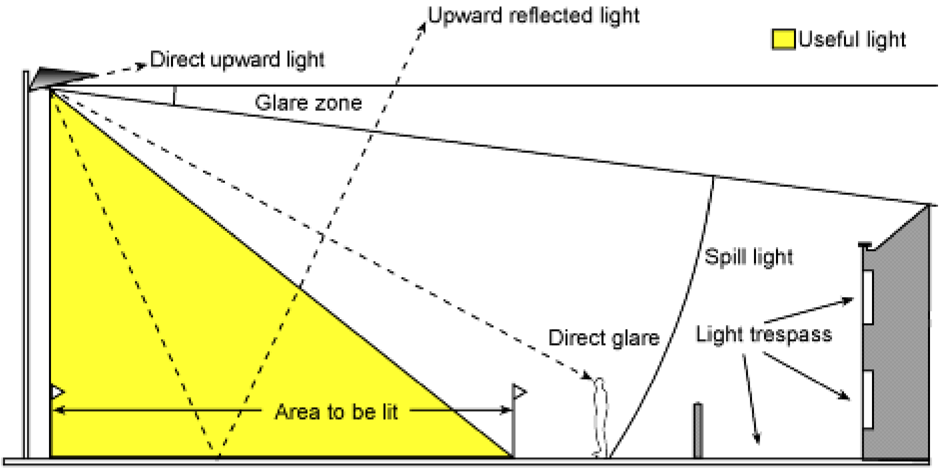

Figure 14. Example of useful light and light pollution from a typical pole-mounted outdoor luminaire.

Yet road lighting encompasses so much more than street lighting. Parks, monuments, urban landmarks, pedestrian and entertainment areas but also parking lots and cycle lanes, they all require “ad hoc” design that cannot rely solely on ground illuminance (see next chapter for further details).
Moreover, bright areas are perceived even brighter if they are adjacent to dark areas (as in Figure 14): if we only focus on minimizing the amount of light hitting at the eyes but not the luminance contrast between the streetlights and the background, we may still experience discomfort glare - not to mention the adverse psychological effect of walking amidst darkness (again, as the men in Figure 14).

It looks like we have reached a position of stalemate: so far we have seen that so many variables contribute to light pollution, that many of them are unmanageable and that we have to consider different lighting design for different areas.

Luckily, we may find a leitmotif in what we found:

- in city center there is a need for diffuse light, due to parks, monuments, pedestrian and entertainment areas - but light are shielded by surrounding buildings;
- rural area have limited barriers and few amusement areas and so luminaires should have limits to near horizon flux;
- protection area should have nearly-zero upward flux and might be as dark as possible;
- street lighting can have nearly nearly-zero upward flux without compromising their performances;
- limiting CCT may not be an effective solution.

This is the reason why both CIE and IESNA have outlined four environmental zone to ensure that the lighting goals of an environment are appropriately defined and met.

Referring to IES TM-15-11 (BUG rating system), it defines six uplight ratings for luminous flux (maximum zonal lumens) emitted above 90° by luminaires (see Figure 15). There are two uplight zones, designated UL for vertical angles from 90° to 100° and UH angles from 100° to 180°.

		Uplight Rating					
	Secondary Solid Angle	U0	U1	U2	U3	U4	U5
Uplight / Skyglow	UH	0	10	50	500	1000	>1000
	UL	0	10	50	500	1000	>1000

	LZ0	LZ1	LZ2	LZ3	LZ4
Allowed Uplight Rating	U0	U1	U2	U3	U4

Figure 15. IES TM-15-11 rating system for uplight flux.

However, there are limits to what can be measured in photometric laboratory (as we have seen in the previous paragraph) and so we cannot correctly assess any real difference between U0, U1 and U2 ratings. And still it is hard to understand the need of U5 rating (that virtually means no limits to upward flux).

The BUG rating system have been bettered and incorporated in the 2011 IDA/IES Model Lighting Ordinance as shown in Figure 16:

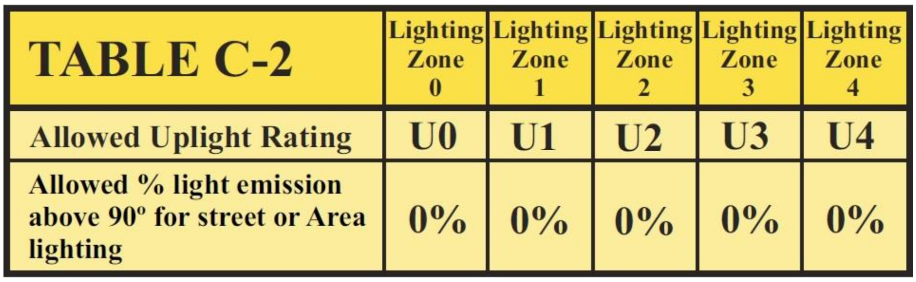

TABLE C-2	Lighting Zone 0	Lighting Zone 1	Lighting Zone 2	Lighting Zone 3	Lighting Zone 4
Allowed Uplight Rating	U0	U1	U2	U3	U4
Allowed % light emission above 90° for street or Area lighting	0%	0%	0%	0%	0%

Figure 16. IDA/IES Model Lighting Ordinance.

In this case different uplight ratings are allowed for different lighting zones, but only luminaires with 0% ULOR are allowed for street and area lighting. Again, we cannot asses any real difference between U0, U1 and U2 and, with ULOR criterion, we are more permissive with high polluting lights than low-emission fixtures.

By becoming aware of these problems, Italian GPP criteria (which are now mandatory[29]) proposed a modified BUG system that could attain better results in lowering light pollution, while providing the lighting people need.

Since Italian (and European) topography has specific features, Italian GPP criteria have defined four lighting zones based on European town planning schemes and zoning:

- LZ0: No ambient lighting (Protection zones). Areas where the natural environment will be seriously and adversely affected by lighting. Impacts include disturbing the biological cycles of flora and fauna and/or detracting from human enjoyment and appreciation of the natural environment. Human activity is subordinate in importance to nature. The vision of human residents and users is adapted to darkness or low to really low lighting levels, and they expect to see little or no lighting. When not needed, lighting should be extinguished.
- LZ1: Low ambient lighting (rural zones). Areas of human activity where the vision of human residents and users is adapted to low light levels. Lighting may typically be used for safety, security and/or convenience but it is not necessarily uniform or continuous. After curfew, lighting may be extinguished or reduced as activity levels decline.

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[29] The insertion of GPP Criteria in tender documents is now mandatory in Italy following the enactment of the new procurement code, Legislative Decree n. 50 of 18 April 2016, where Art.34 provides for the application of GPP Criteria (CAM) in public tenders.

- **LZ2: Moderately ambient lighting (residential and commercial zones outside city centers)**. Areas of human activity where the vision of human residents and users is adapted to moderately high light levels. Lighting is generally desired for safety, security and/or convenience and it is often uniform and/or continuous. After curfew, lighting may be reduced in most areas as activity levels decline.
- **LZ3: High ambient lighting (town centers)**. Areas of human activity where the vision of human residents and users is adapted to high light levels. Lighting is generally considered necessary for safety, security and/or convenience and it is mostly uniform and/or continuous. After curfew, lighting may be reduced in some areas as activity levels decline.

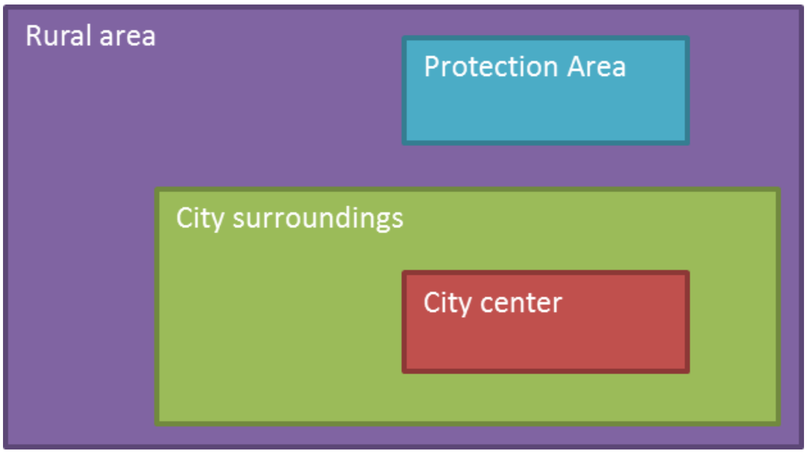

Figure 17. Schematic representation of lighting zones.

Then, we have rethought uplight ratings, considering photometric laboratories' limits and reducing IDA/IES emissions as much as possible:

	U1 (lm)	U2 (lm)	U3 (lm)	U4 (lm)	U5 (lm)
UH	≤ 50	≤ 150	≤ 400	≤ 600	≤ 1000
UL	≤ 50	≤ 100	≤ 200	≤ 300	≤ 500

	LZ1	LZ2	LZ3	LZ4
Street lighting	U1	U1	U2	U2
Area lighting, roundabout, parking lot	U1	U2	U3	U3
Pedestrian area and bike lane lighting	U1	U2	U3	U4
Green area lighting	U1	U2	U3	U4
City center with historic lantern	U2	U3	U4	U5

Figure 18. Italian GPP scheme for limiting light pollution.

Rather than defining only two lighting applications, we have different upward ratings for different kind of fixtures and lighting zones: in this way, we believe our criterion is fair and equitable as possible.

As for what concerns glare and lighting trespass, we asked to achieve G*2 luminous intensity class or above[30] for all kind of fixtures.
Future improvements may include BUG glare ratings, knowing that under conditions of high ambient lighting, glare from luminaires will be less problematic, even for the same luminous intensity.

Lighting design for pedestrian areas

At the Professional Lighting Design Convention in Berlin in 2009, French lighting designer Roger Narboni declared that "architectural lighting is dead" - setting a challenge to move away from simply beautifying buildings to lighting for people. Lighting design have become essential element in reflection on towns, by proposing diversified, attractive lighting schemes, corresponding to the new expectations of town dwellers.
Urban lighting, by its power of attraction, its symbolic dimension as well as its capacity to represent emotions, may underline the characteristic of a site. Lighting ambience may also reveal what is at stake in a town by transforming the supposedly negative image of a quarter, by catching the eye of the local residents through color or light intensity. Architectural illumination may help a little-known area be rediscovered by literally showing it in a new light.
Because of its capabilities, urban lighting is a high-performance tool when it comes to revealing the invisible, affirming structuring lines, transfiguring a site, illustrating the evolution of a streetscape, presenting a construction site. It may thus help to effect a positive change on the vision people have after dark of their current and future surroundings and, enabling them to adopt it as their own.

If we overbound lighting design with excessive requirements, we will be used having the same lights everywhere and for everyone - and maybe the wrong lighting design somewhere.
The beneficial effects of artificial lighting in pedestrian areas can be related to the subjective aspects of social safety and amenity. For feeling secure and have an agreeable situation, citizens must be provided with good vertical illuminance, uniformity and face recognition – and with luminaires pleasant to the eyes if possible.

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[30] See EN 13201-2

The mounting height of a luminaire (and therefore the angle at which the light hits the object) has a significant impact on vertical illuminance: Looking at the example in Figure 19, with a full cut-off luminaire it is almost impossible to achieve good vertical illuminance (if we don't want to use extremely high mounting height).

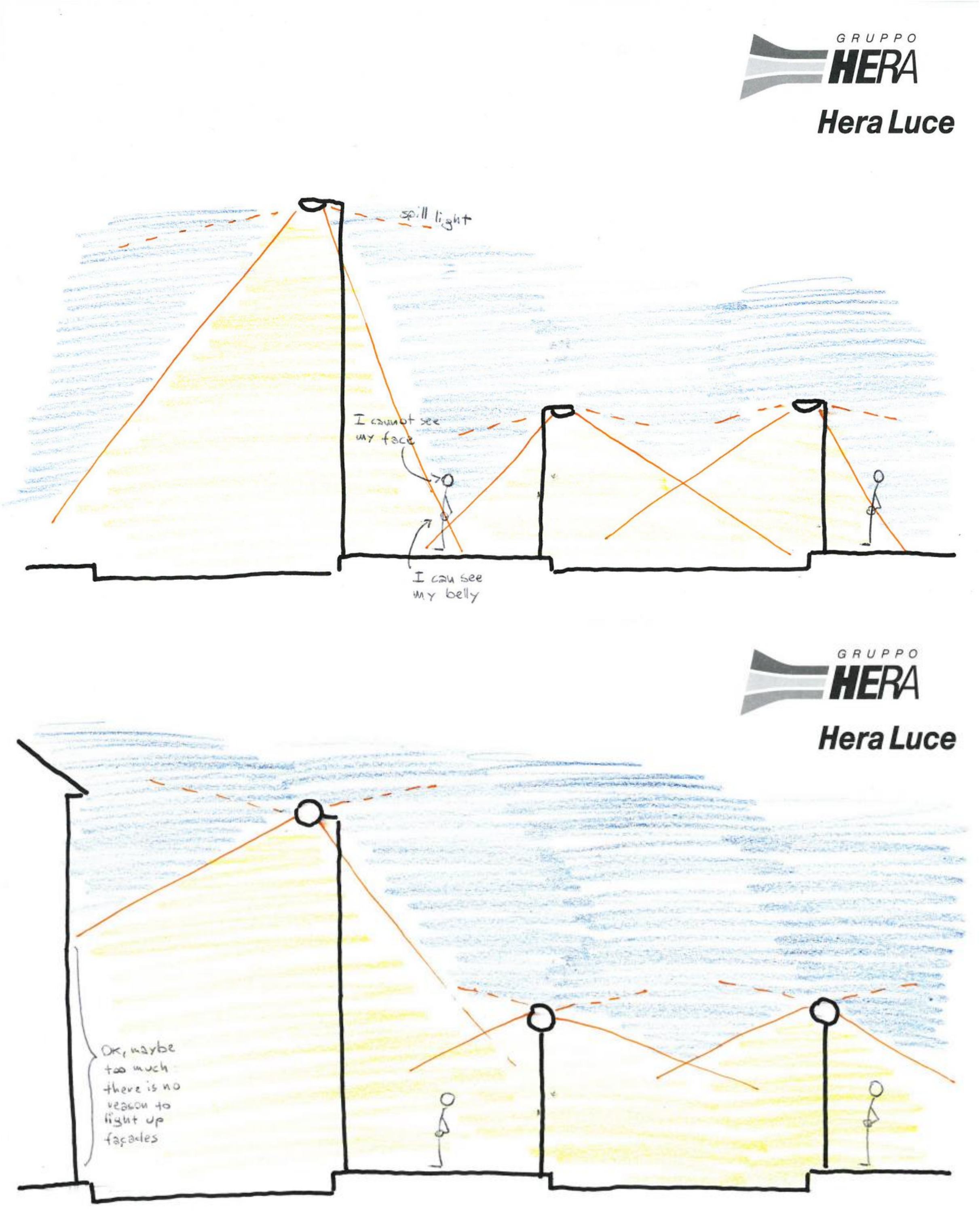

Figure 19. Full cutoff versus non-cutoff luminaires for vertical illuminance.

The problem is more pronounced among urban amenity lighting, with low mounting height: With near zero ULOR, the luminaire's throw angle is not high enough to provide good vertical illuminance.

Conclusions

We have seen how light pollution is a complex problem, and how many criteria may offer little substantive responses. If we focus only on CCT or ULOR we could miss some important aspects of lighting design process and we could neglect the needs of people living in the cities. Urban lighting should not be implemented without the adoption of a suitable planning tool, without defining a comprehensive and coherent strategy that avoids the random development noticeable in many achievements, namely without an identification of homogeneous areas of intervention, without a direction that promotes an effective control of light pollution, of the inadequate and unconscious proliferation of points of light, without a policy of renewal of the existing equipment.

If we want to provide good lighting design for road lighting, we should include the following aspects:

- people should have the right light for their needs;
- individual districts must be provided with character identification;
- illumination should follow the rhythm and pace of social life (we need to choose between permanent, and seasonal illumination as well as decreased light levels in certain areas);
- light pollution has to be reduced by modernizing lighting systems and maybe reducing illumination in some parts of the city only to define spatial borders of the area.

Italian GPP criteria provides for a simple yet effective upward light limitation, that can define the right limits in the right zones and allowing lighting designer to ensure the highest levels of safety and well-being for citizens and at the same time allowing vertical illuminance where needed.

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