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Dynamic Light

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DYNAMIC LIGHT
MANUAL ON TRANSFERABLE TECHNICAL SOLUTIONS

DYNAMIC LIGHT—TOWARDS DYNAMIC, INTELLIGENT AND ENERGY EFFICIENT PUBLIC LIGHTING

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DYNAMIC LIGHT

MANUAL ON TRANSFERABLE TECHNICAL SOLUTIONS

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Chapter – 1: Luminaire Technology

LIGHTING SYSTEM COMPONENTS

Street lighting system components can be divided into three broad categories:

- Optical systems, which cover luminaires (including reflectors, refractors and lenses), lamps or light sources, and the control gear.
- Support systems consisting of poles and their foundations.
- Electrical systems (including service cabinets) covering energy supply, control and metering facilities.

1.1 TERMINOLOGY AND GEOMETRY

A standard LED chip without any accessories can have three different types of light distributions. These distributions govern the design of optics and reflectors to achieve a desired light distribution in a luminaire.

1.1.1 Light quality

Luminous flux: It is the total amount of visible light emitted by a light source in all directions. It is measured in lumen unit – lumen (lm), symbol : Φ

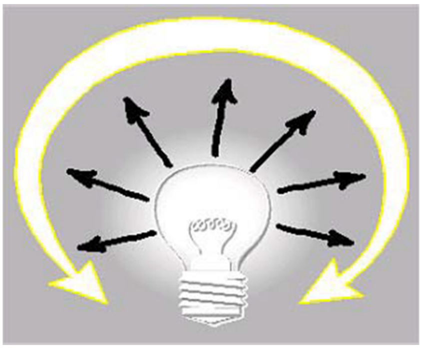


Fig.1.1: Luminous Flux [1]

Luminous intensity: It is a fundamental photometric quantity and represents the spatial distribution of luminous flux within a given solid angle from the light source. It is the ratio of luminous flux and the solid angle. It is measured in candela, or cd, with 1 cd = 1 lm/square radian.

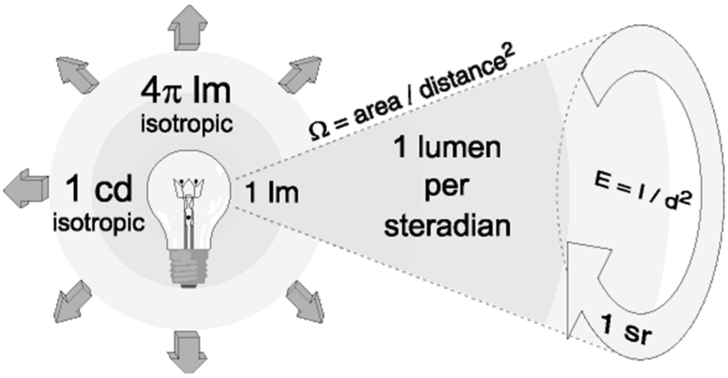


Fig.1.2: Luminous Intensity [1]

Luminance: It is the ratio of the luminous intensity of a surface to the projected area of the surface unit – candelas per square meter (cd/m2).

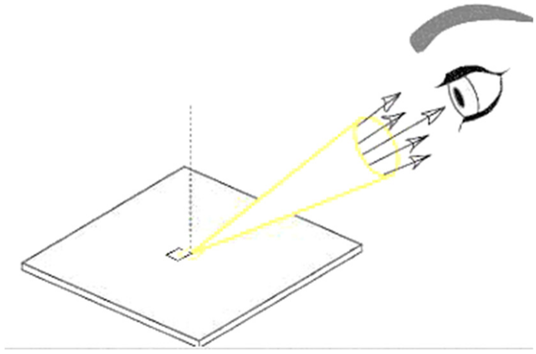


Fig.1.3: Illuminance [1]

Illuminance: It is the incident flux per unit area, is measured in lux (lx) on horizontal and vertical plane and indicates the amount of luminous flux from a light source falling on a given surface.

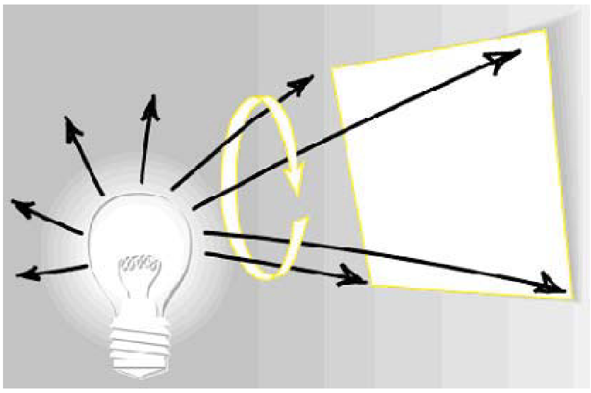
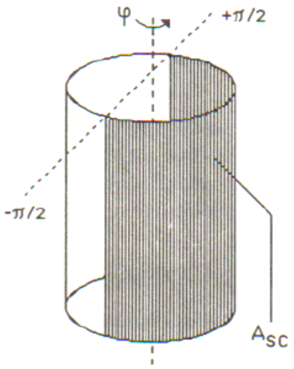


Fig.1.4: Illuminance [1]

Horizontal Plane and Vertical Planes: Illuminance is the quantity of light falling on a surface and is measured in lux. There are two aspects of illuminance - vertical and horizontal.

Horizontal illuminance (Eh) is the value of illuminance on a designated horizontal plane or at level ground.

Vertical illuminance (Ev) is the value of illuminance on a designated vertical plane typically at a height of 1.5m above ground.



Semi-cylindrical Illuminance (E_{sc}): It is defined as the averaged illuminance on the curved surface ASC of an upright half cylinder.

$$E_{sc} = \frac{1}{\pi}\int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} E_v\,(\varphi)d\varphi$$

Fig.1.5: Semi-Cylindrical Illuminance [12]

Gutorov [13] defined the mean cylindrical illuminance (ECyl) as a new concept and Epaneshnikov et al. [14] related it to the lighting of places with a high density of pedestrians and with an "open" character, such as railway and underground entrance halls, exhibition rooms, congress meeting halls, etc.

Horizontal and Hemi-spherical Illuminance: It is important for pedestrians and cyclists that the lighting reveals potentially dangerous obstacles lying in their path and any irregularities in this. The horizontal illuminance is therefore usually used as the basic lighting parameter. Since most objects are not flat but three dimensional, some road lighting standards specify the strength of the lighting at ground level in terms of the hemispherical illuminance rather than the horizontal illuminance.

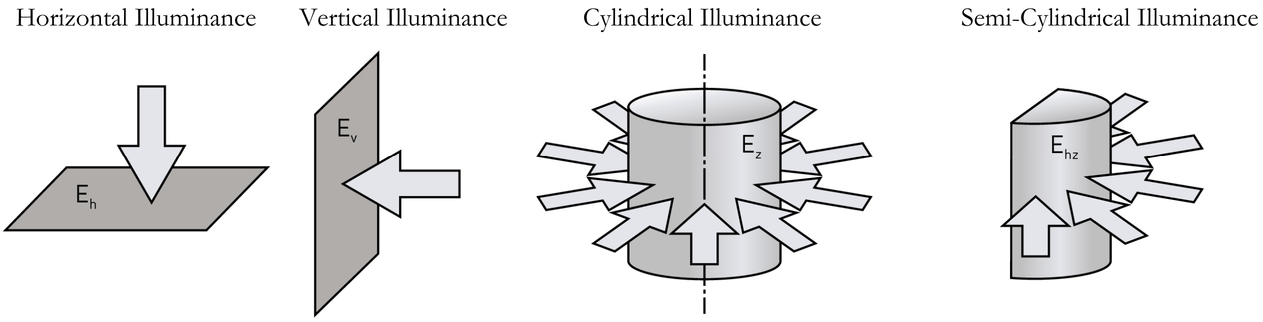


Fig.1.6: Common terminology for Public lighting [https://www.trilux.com/se/lighting-practice/indoor-lighting/specific-lighting-requirements/lighting-of-offices-and-vdu-workstations/illuminance/]

Uniformity: Levels of illumination along the carriageway will vary as a result of luminaire mounting height, luminaire spacing and luminaire output. It is important that the contrast between the illumination levels along the carriageway be minimised. The motorist's eyes should not have to adjust too much for the variations.

Uniformity is measured as a ratio between road surface illumination levels e.g. max. to min. or max to average. Uniformity values vary for various roadway elements. Uniformity is as important as providing enough illumination.

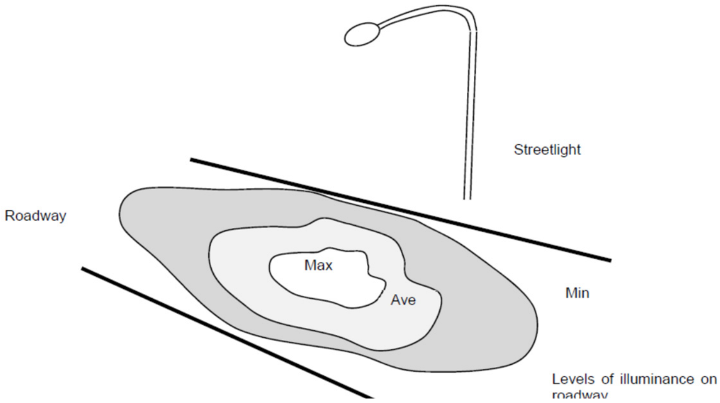
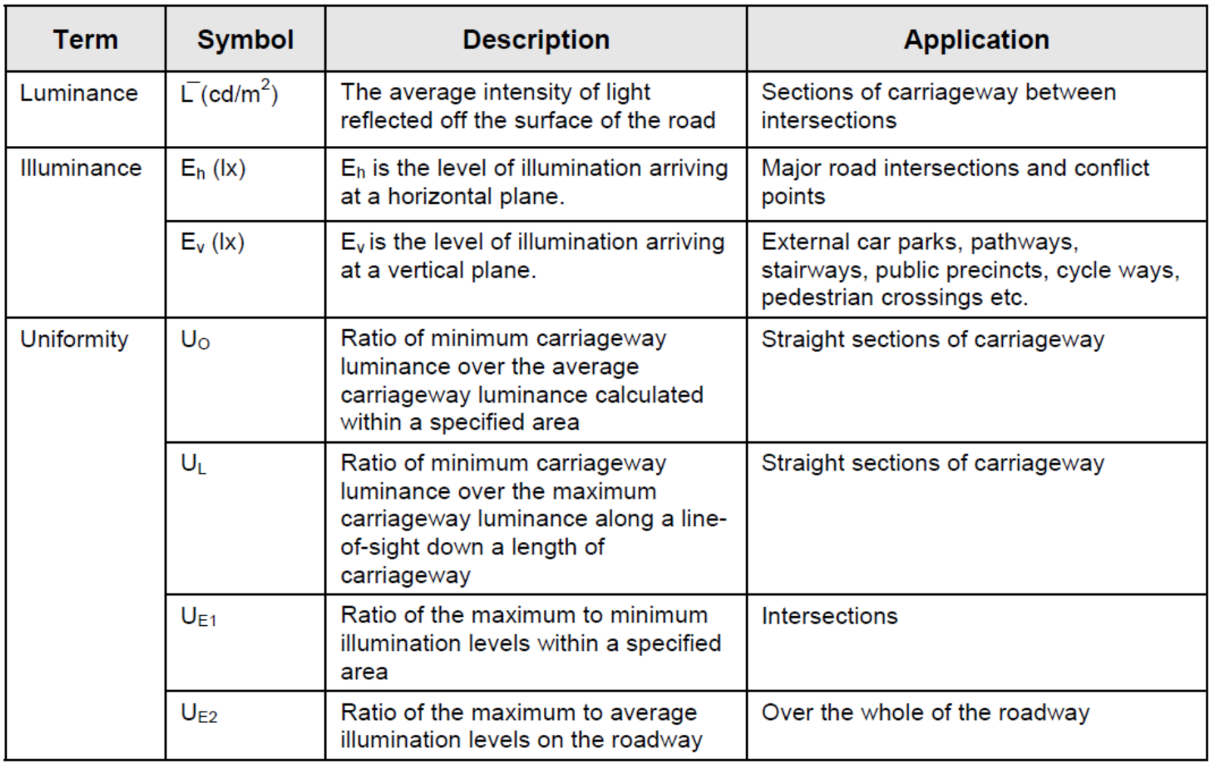


Fig.1.7: Common terminology for Public lighting [7]



Term	Symbol	Description	Application
Luminance	$\bar{L}$(cd/m^2)	The average intensity of light reflected off the surface of the road	Sections of carriageway between intersections
Illuminance	E_h (lx)	E_h is the level of illumination arriving at a horizontal plane.	Major road intersections and conflict points
	E_v (lx)	E_v is the level of illumination arriving at a vertical plane.	External car parks, pathways, stairways, public precincts, cycle ways, pedestrian crossings etc.
Uniformity	U_O	Ratio of minimum carriageway luminance over the average carriageway luminance calculated within a specified area	Straight sections of carriageway
	U_L	Ratio of minimum carriageway luminance over the maximum carriageway luminance along a line-of-sight down a length of carriageway	Straight sections of carriageway
	U_{E1}	Ratio of the maximum to minimum illumination levels within a specified area	Intersections
	U_{E2}	Ratio of the maximum to average illumination levels on the roadway	Over the whole of the roadway

Fig.1.8: Common terminology for Public lighting [7]

Inverse Square Law:

For calculating illumination at a point P on a plane surface in Figure 1.9:

$E = \frac{I}{d2}$ for a point directly below the light source.

$E = \frac{I_\theta}{d^2} cos\theta$ for a point at some angle θ elsewhere on the plane.

Or $E = \frac{I_\theta}{h^2} cos^3\theta$

E = Illuminance in lx

d = the distance from the source to the point (m)

θ = the angle of the light from the normal

I_θ = the intensity of the source in the direction θ (cd)

h = the perpendicular distance from the source to the plane (m)

Notice that an inverse square law is evident here. Thus, if the mounting height of a luminaire were doubled, the illumination levels would fall to one quarter of their original value.

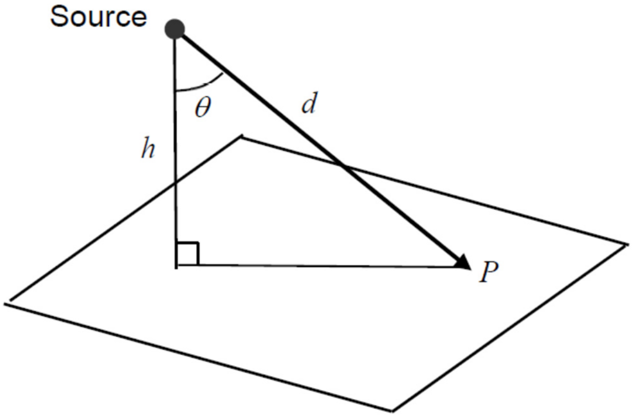
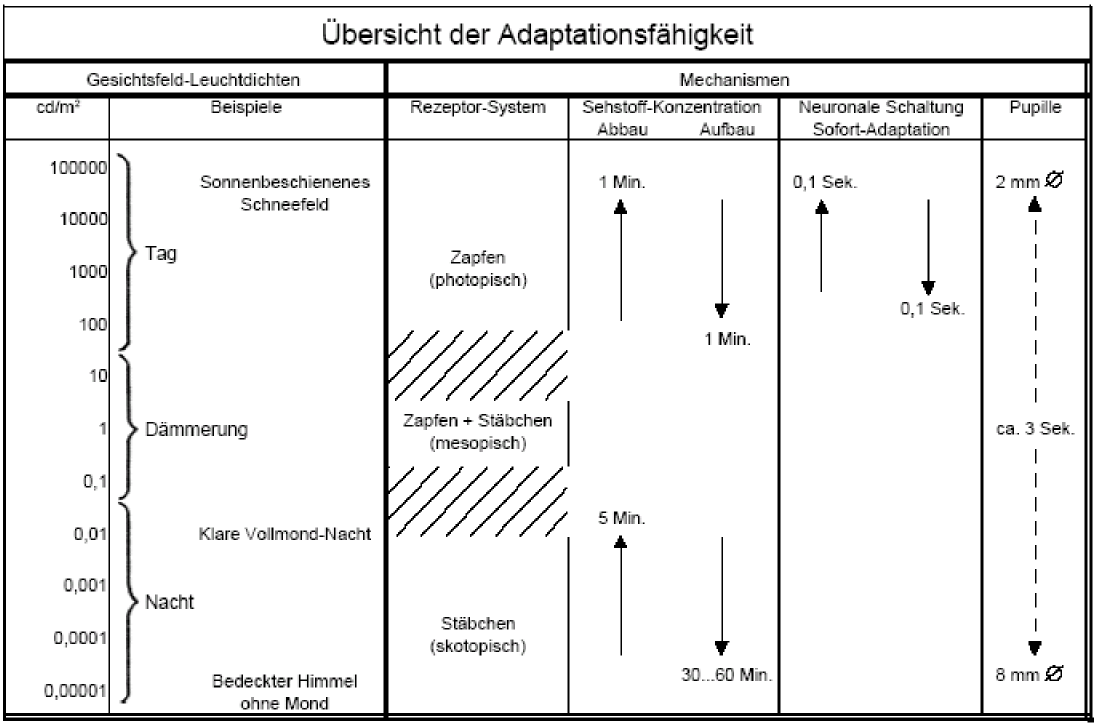


Fig.1.9: Inverse Square Law [7]

Adaptation: It is the mechanism by which the eye changes it's sensitivity to light. On coming out of a bright room and entering a dark one, we at first see "nothing"– only after a certain period of time do objects start to appear out of the darkness.

Dark adaptation: Dark adaptation is essentially the reverse of light adaptation. It occurs when going from a well light area to a dark area. Initially blackness is seen because our cones cease functioning in low intensity light. Also, all the rod pigments have been bleached out due to the bright light and the rods are initially non-functional. Once in the dark, rhodopsin regenerates and the sensitivity of the retina increases over time (this can take approximately one hour). During these adaptation process reflexive changes occur in the pupil size.



Übersicht der Adaptationsfähigkeit

Gesichtsfeld-Leuchtdichten			Mechanismen				
cd/m²	Beispiele		Rezeptor-System	Sehstoff-Konzentration Abbau	Sehstoff-Konzentration Aufbau	Neuronale Schaltung Sofort-Adaptation	Pupille
100000	Tag	Sonnenbeschienenes Schneefeld		1 Min.		0,1 Sek.	2 mm Ø
10000							
1000			Zapfen (photopisch)				
100					1 Min.	0,1 Sek.	
10	Dämmerung						
1			Zapfen + Stäbchen (mesopisch)				ca. 3 Sek.
0,1							
0,01	Nacht	Klare Vollmond-Nacht		5 Min.			
0,001							
0,0001			Stäbchen (skotopisch)				
0,00001		Bedeckter Himmel ohne Mond			30...60 Min.		8 mm Ø

Fig.1.10: Adaptation Time [1,15]

Glare: The glare is defined as a visual state, which is perceived as unpleasant by an unfavourable luminance distribution or too high luminance contrasts. However, it can also lead to a reduction in the visual function.

Two types of glare effects are typically distinguished: **Physiological Glare / Disability glare**: Impaired vision. The causes of the physiological glare: purely physical effect of the light

Psychological Glare / Discomfort glare: Disturbance caused by light, luminous distribution is perceived as unpleasant.

Both forms can occur simultaneously, side by side, or separately.

Glare plays an important role in public lighting as:

- Reduces the ability to perceive small contrasts.
- Reduces facial recognition.
- It can impair important visual tasks in traffic such as detecting critical objects evaluating critical encounters.

Glare triggered by LED road lights is influenced by the following factors:

- The ratio between the illuminance from the glare source at the observer's eye and the background luminance.
- The angle between the glare source and the observer's line of sight.

Disability glare, which is caused by the scattering of light in the eye which reduces contrast sensitivity, and discomfort glare, which triggers a subjective sensation of discomfort.

While glare is a subjective sensation, it can be calculated objectively. In a particular illuminated environment, the human eye will be able to detect differences in luminance down to a certain threshold. This threshold can be compared for a situation in the same environment when a source of glare is added. By comparing these thresholds, the threshold increment can be derived. [2] (Premium Light Pro)

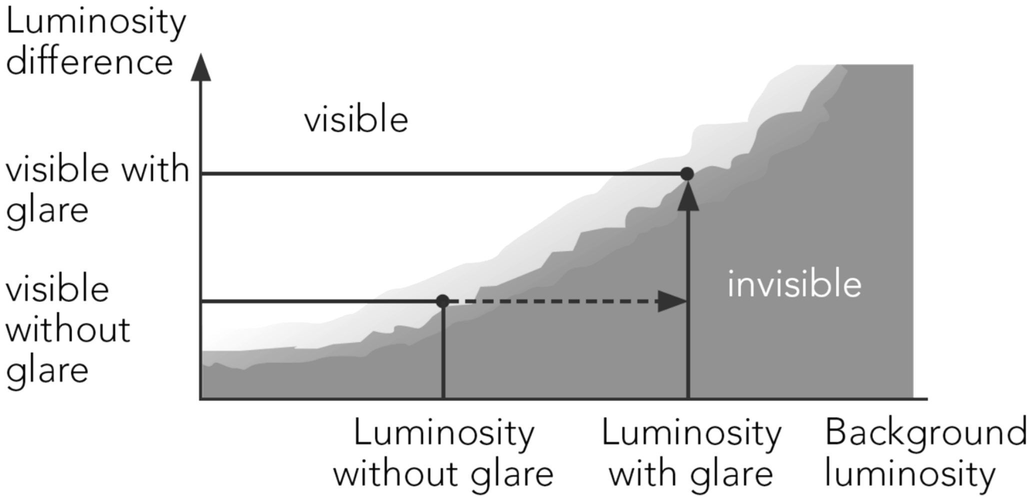


Fig.1.11: Visibility with and without glare [2] adapted from Premium Light Pro

However, glare being subjective there is no consensus for how it should be rated – although the 9-point DeBoer scale (ranging from "1" for "unbearable" to "9" for "unnoticeable") is the most widely used in the field of automotive and public lighting.

Different classifications have been introduced for discomfort and disability glare to classify different shield levels. Shield classes for disability glare range from level G1 to G6 and are further specified in EN 13201-2. Shield classes for discomfort glare are specified as D1 to D6

Shield Class	Maximum Luminous intensity in cd/klm			Total shielding
	At 70°	At 80°	At 90°	
G1		200	50	No requirements
G2		150	30	No requirements
G3		100	20	No requirements
G4	500	100	10	Above 95° to be zero
G5	350	100	10	Above 95° to be zero
G6	350	100	0	Above 95° to be zero

Table.1 & 2: Glare classes for disability glare [EN 13201-2 and VEJ]

Glare value classes	
D0	Not specified
D1	7000
D2	5500
D3	4000
D4	2000
D5	1000
D6	500

Road-Surface Luminance: A surface is made visible by virtue of light being reflected from it and entering the eye of the observer: the greater the amount of light entering the eye, the stronger will be the visual sensation experienced. Thus, the illuminance on a road surface, which refers only to the amount of light reaching that surface, gives no indication of how strong the visual sensation will be; or in other words, how bright the surface will appear. The brightness of the road surface will depend on the amount of light reflected from it in the direction of the observer.

The photometric measure for this is the luminance (L) of the surface. That it is the luminance and not the illuminance that determines the brightness.

Since brightness is finally determined not by illuminance but by luminance, the visual performance and visual comfort of a road user are directly influenced by the complex pattern of luminance existing in his view of the road ahead. The refection properties of cars, bicycles, pedestrians, obstacles and other objects in the field of view vary widely.

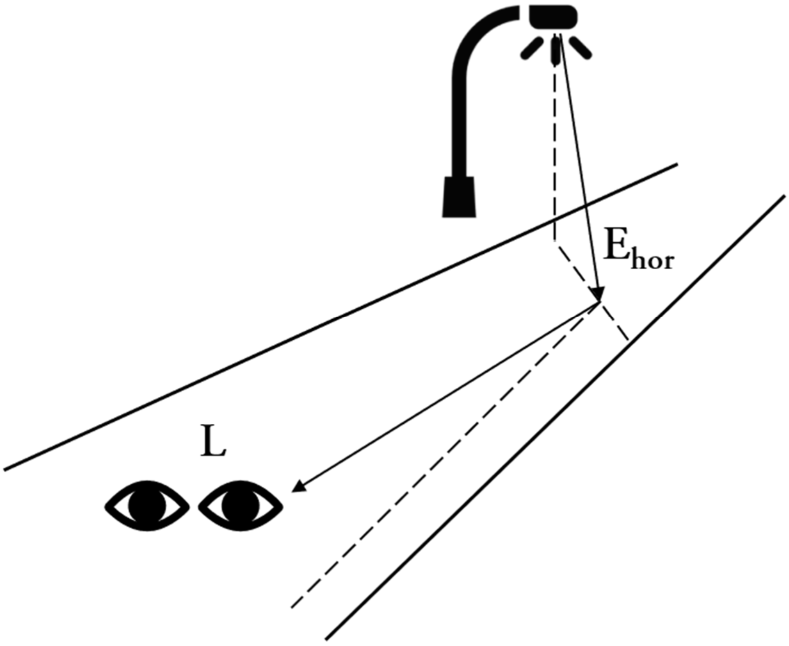
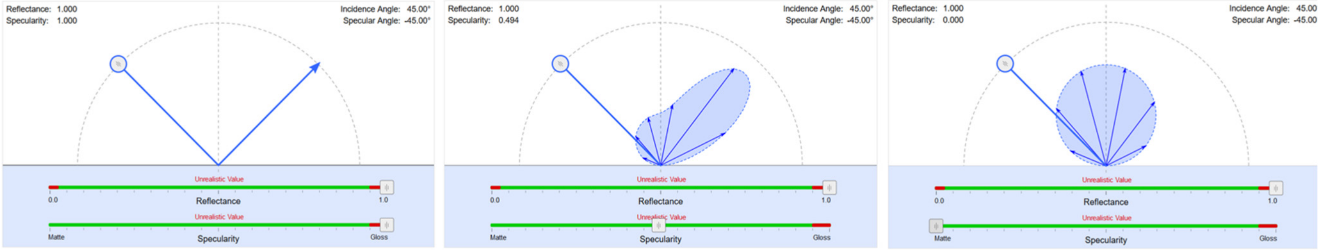


Fig.1.12: Light incident towards the road results in the horizontal illuminance, Ehor on the road, while the light reflected from the road surface results in the road-surface luminance,

Reflection: It is the property of light being able to be reflected. The amount of reflected light depends on the type of surface, angle of incidence and spectral composition of the light. The way the light is reflected also depends on the smoothness of the surface. Rough surfaces diffuse the light by reflecting it in every direction. In contrast, smooth surfaces like the surface of still water or polished glass reflect the light back undiffused, making the surface act as a mirror.



Reflectance: 1.000
Specularity: 1.000
Incidence Angle: 45.00°
Specular Angle: -45.00°

Reflectance: 1.000
Specularity: 0.494
Incidence Angle: 45.00°
Specular Angle: -45.00°

Reflectance: 1.000
Specularity: 0.000
Incidence Angle: 45.00
Specular Angle: -45.00

Fig.1.13: Directional/ Specular reflection, Mixed reflections and diffuse reflection [16]

1.2 THE SPECTRAL SENSITIVITY OF THE EYE

The perception of light by the eye is dependent on the wavelength of the incident radiation. This is called the spectral sensitivity of the eye. In daytime vision, called photopic vision (above about 3cd/sq.m), the relative spectral sensitivity is described by the V(λ) function.

In very dark conditions (below about 0.001 cd/sq.m), the scotopic vision takes over. In photopic vision the eye is most sensitive to light at wavelength of 555 nm and in scotopic vision the spectral sensitivity curve shifts to 507 nm.

Mesopic luminance region

Between the photopic and scotopic regions there is the mesopic region (low light levels ranging from 0.001 to 3 cd/sq.m), where both cones and rods are active. In the mesopic luminance region the spectral sensitivity is believed to be dependent on the visual task (e.g. target location and size) and luminance level. The upper and lower limits of the mesopic luminance region are not exactly defined. According to some definitions, the upper limit of the mesopic region is 10 cd/ sq.m.

As all the lighting quantities (e.g. luminous flux, illuminance, luminance) are based on the V(λ) function, the luminances actually perceived by the eye in the mesopic region are unknown at the present.

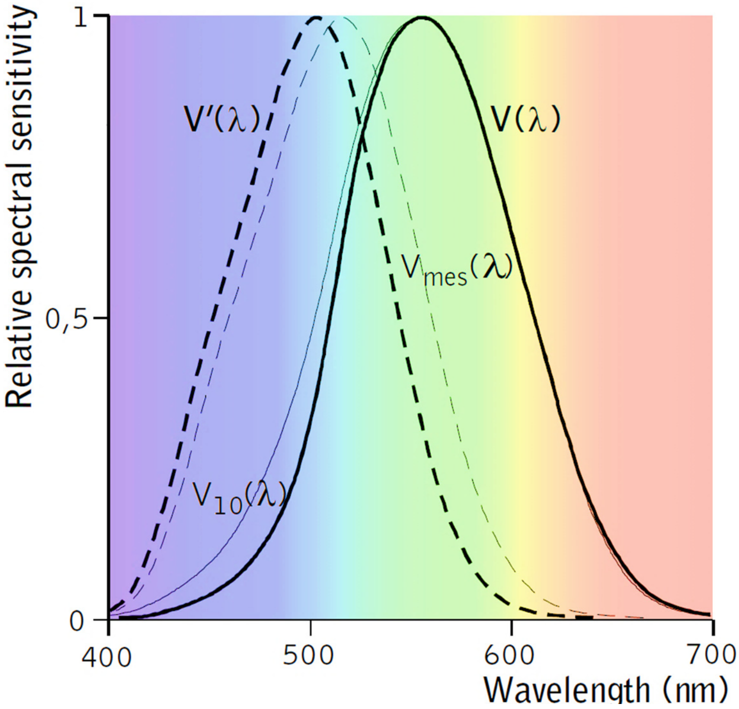


Fig.1.14: Spectral sensitivity functions of the eye. In photopic vision, when cones are active, the sensitivity follows the V(λ) function. At very low light levels only rods are active, and the spectral sensitivity follows the V´(λ) function. The Vmes (λ) is one example of the possible mesopic spectral sensitivity functions. [8]

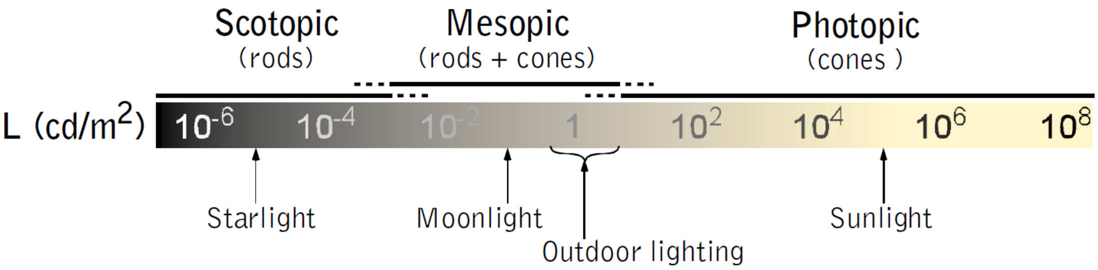


Fig.1.15: Photopic, mesopic and scotopic luminance regions. [9]

S/P – ratio of light sources

At present the photopic spectral luminous efficiency function V(λ) forms the basis of all lighting calculations and photometry. The luminous flux (lumen) values and luminous efficacy (lm/W) values of lamps are based on V(λ), as well as recommendations of luminance (cd/sq.m) and illuminance (lx) values. The V(λ) is valid for daylight conditions, but as luminance levels decrease, the calculations are not necessarily correct.

One way to consider the potential differences between photopic and mesopic efficacy of light sources is the S/P – ratio. The S/P – ratio is a metric of the scotopic-to-photopic luminous flux of a light source. This ratio describes the changes in the lamp's luminous efficacy, when the calculations are made wither with scotopic V´(λ) or photopic V(λ) weighting.

Figure 1.16 shows the spectra and S/P – ratios of a high-pressure sodium (HPS) lamp and a Metal Halide lamp, used for public lighting. The S/P – ratio of HPS lamp is S/P=0.6, because the radiation of the HPS lamp is more concentrated on the longer wavelengths, the luminous efficacy of the lamp decreases when the calculations are made with scotopic weighting. The Metal halide has considerably more radiation in the short wavelength region of the spectrum Thus the efficacy of the lamp increases when the weighting is made with the scotopic function and the S/P – ratios is S/P=2.4

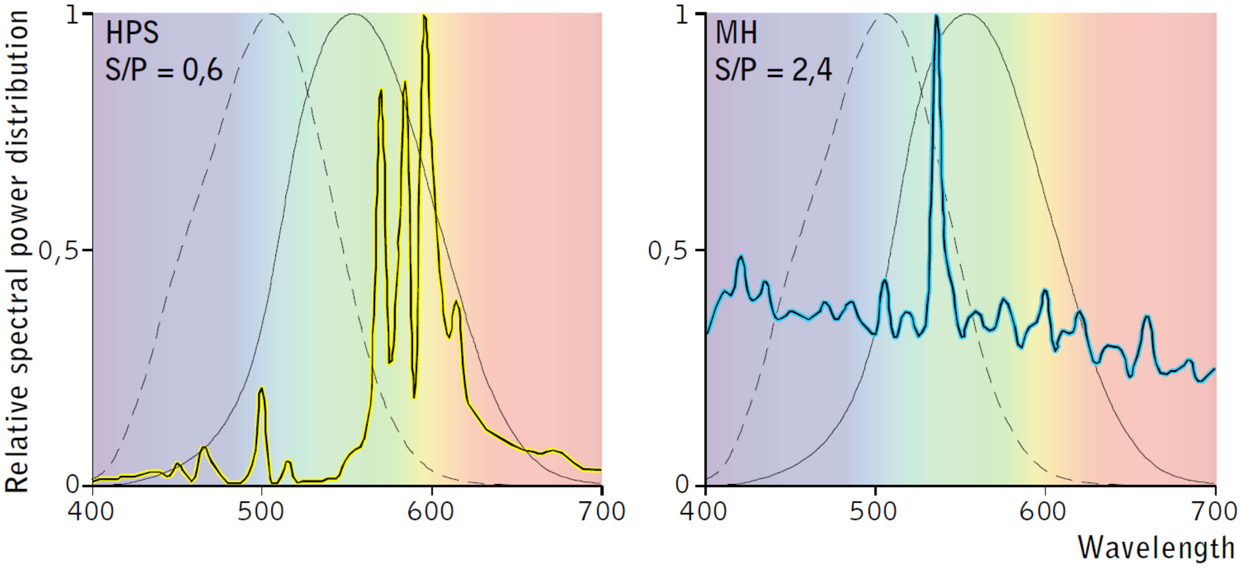


Fig.1.16: The spectral power distributions and S/P – rations of a HPS lamp and a Metal Halide lamp. The spectral sensitivity functions V(λ)- solid curve and V´(λ)- dashed curve are also shown. [8]

1.3 LAMPS: LED

EU regulations 874/2012 (energy labelling of electrical lamps and luminaires) and 1194/2012 (eco-design requirements for directional lamps, LEDs and related equipment) distinguishes between the terms “luminaires, lamps and light sources”. [2]

- “Luminaire” means an apparatus which distributes, filters or transforms the light transmitted from one or more lamps and which includes all the parts necessary for supporting, fixing and protecting the lamps and, where necessary, circuit auxiliaries together with the means for connecting them to the electric supply.
- A “Lamp” is defined as a unit whose performance can be assessed independently and which consists of one or more light sources. 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.
- The term “light source” means a surface or object designed to emit mainly visible optical radiation produced by a transformation of energy. The expression “visible” refers to a wavelength range of 380 – 780 nm.

In this context a “luminaire” can contain one or more “lamps”, whereas a “lamp” can be equipped with one or more “light sources”.

Lamps

A lamp is a device that transforms electric energy into visible light. Today, LED technology is superseding all other lamp technologies. The electrical component that produces light by the flow of electrical energy through a semiconductor is called a Light Emitting Diode- LED. A diode is the simplest possible semiconductor device.

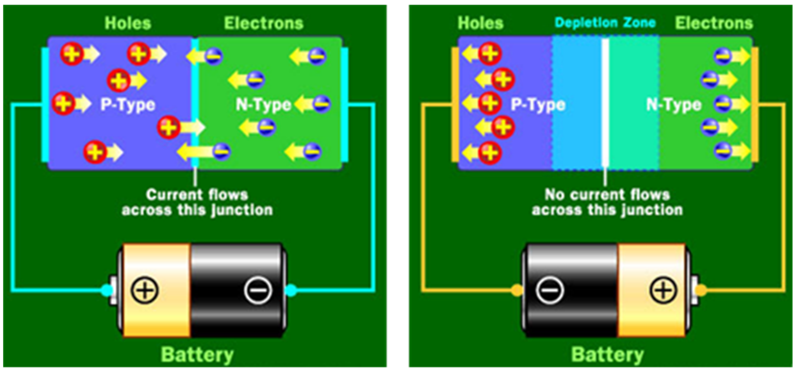


Fig.1.17: A diode allows current to flow in one direction but not the other. [17]

The connection surface between p and n conductive area is called depletion layer or band gap. In this area the positive charge of the p crystals and negative charge of n crystals is balanced by recombination.

When the voltage difference between the electrodes is high enough, the electrons in the depletion zone are boosted out of their holes and begin moving freely again. The depletion zone disappears, and charge moves across the diode.

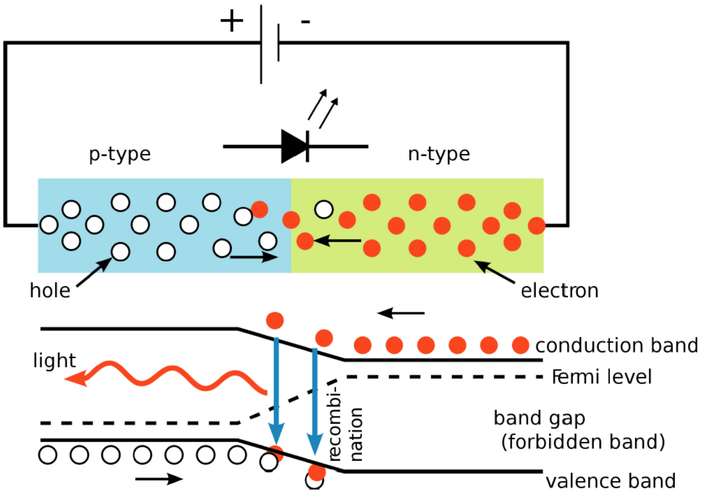


Fig.1.18: Production of light in LED. [18]

The colour (wavelength) of the LED is dependent on the band gap between the p and n pole measured in electron-volt (eV). The band gap can be set by choosing different semiconductor materials.

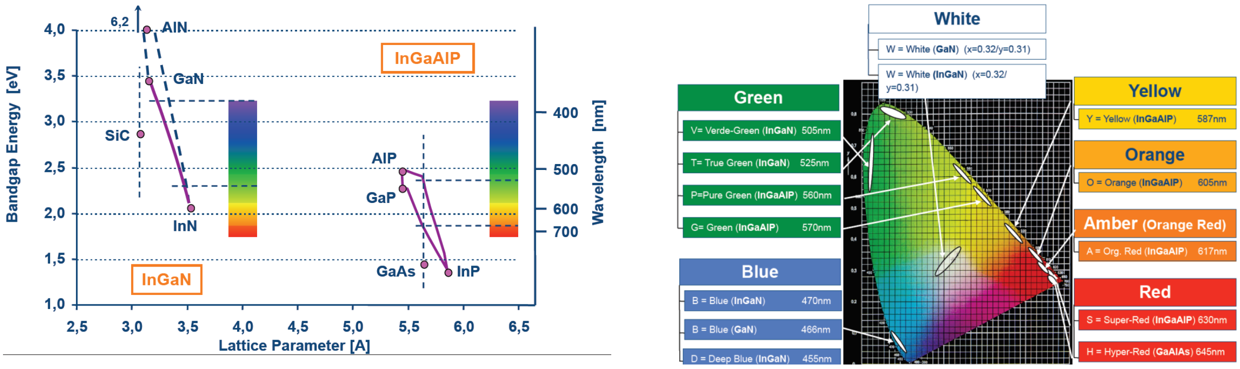


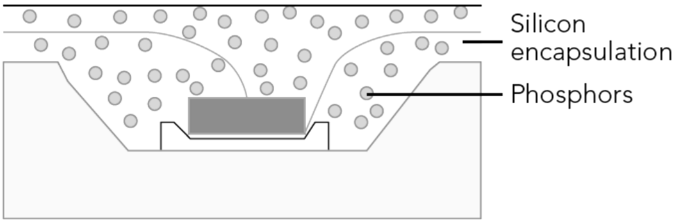
Fig.1.19: The colour of LED dependent on the band gap between p & n poles. [18]

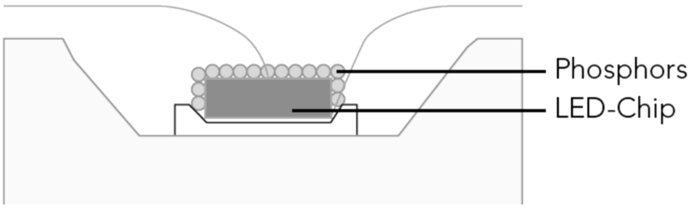
There are 2 basic methods to produce white light: Phosphorescence and additive colour mixing.

The most common way to produce white light by LEDs is the method using a blue LED with a phosphorous coating. It is the cheapest way as it needs only one LED chip and one coating.

For street lighting commonly blue LEDs are used, providing white light when encapsulated in a phosphor coating (yellow coating, cf. Figure 11 and Figure 12 illustrating different principles for white light generation based on phosphor coating).

Blue-emitting LEDs currently have the highest efficiency of all LED types, with a power conversion ratio of 55 %. The remaining 45 % is transformed into heat. Since a higher junction temperature (the temperature of the LED semiconductor material) reduces both efficacy and lifetime, a good thermal design is necessary. In order to dissipate the heat, the LED chip and the reflector cup are mounted on a heat sink. This heat sink should in turn transfer the heat to the luminaire, which dissipates the heat externally.





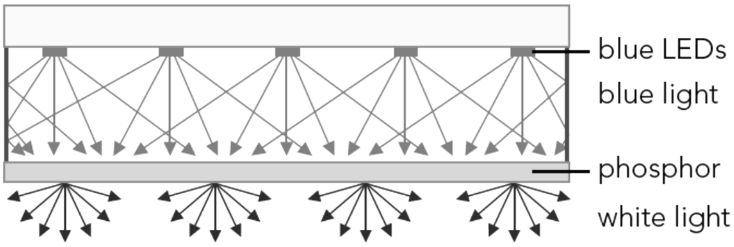


Fig.1.20: Principle of a remote-phosphor LED module creating white light [2] adapted from Premier Light Pro

Since the luminous flux of one individual LED is fairly low compared to the lux required for street lighting, several LED chips are assembled in one circuit board and can be combined with additional components. Thus, several levels of integration have to be distinguished. The following LED-related definitions are made in the Commission Regulations 874/2012 and 1194/2012:

- “Light-emitting diode (LED)” means a light source which consists of a solid-state device embodying a p-n junction. The junction emits optical radiation when excited by an electric current.

- “LED package” means an assembly having one or more LED(s). The assembly may include an optical element and thermal, mechanical and electrical interfaces

- “LED module” means 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; • “LED lamp” means a lamp incorporating one or more LED modules. The lamp may be equipped with a cap.

This distinction is in line with the segmentation of LED products commonly established within lighting industry [22], excluding level 2 (Table 2).

Integration Level	Description
Level 0	LED chip (or die)
Level 1	Packaged LED including electrical connection, mechanical connection and protection, heat dissipation device and basic optical components.
Level 2	Assembly of various LEDS (LED cluster) on a printed circuit board.
Level 3	LED module (or LED engine). A module with LED cluster, heat sink, electrical driver and sometimes an optical device. The LED module functions as a lamp.
Level 4	Luminaire consisting of LED module (Level 3) and housing and secondary optics
Level 5	LED lighting system including control features

Table.2: Levels of LED Integration [2]

LED Binning: Due to the production process of semiconductors the final products vary in their characteristics; LEDs show these variations as well. In order to avoid visible colour and brightness changes in LED applications the diodes have to be sorted according to specific parameters. This process is known as binning. LEDs are usually binned according to their:

- Luminous Flux
- Dominant wavelength
- Correlated Colour Temperature
- Colour Rendering Index
- Forward Voltage

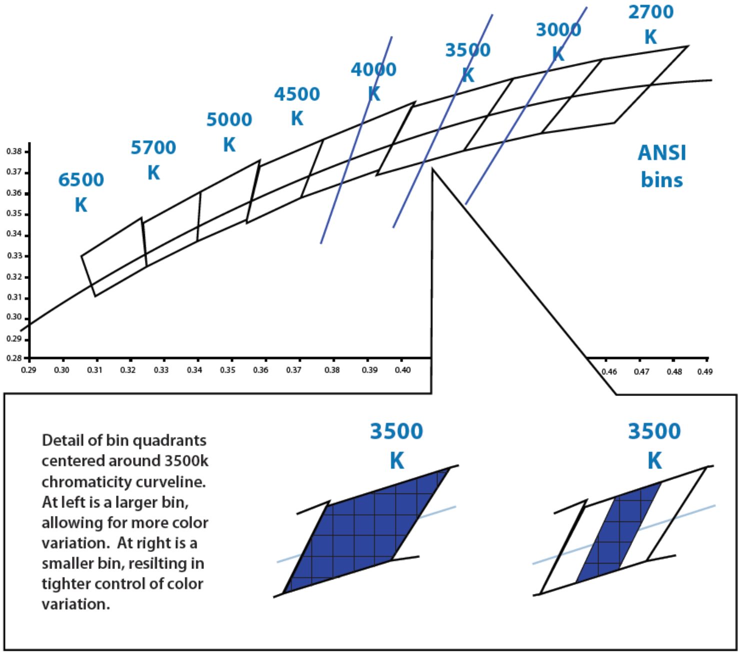


Fig.1.21: LED Binning [23]

MacAdam Ellipses: Region on the chromaticity diagram which contains all colours which are indistinguishable to the "average human eye". 1-step ellipse is often called a MacAdam unit of colour difference. SDCM: Standard Deviation of Colour Matching. It does not convey the direction of shift. Δu'v' is the Euclidian distance between two sets of chromaticity coordinates.

SDCM	CCT@3000K	ΔUV
1x	±30K	±0.0007
2x	±60K	±0.0010
4x	±100K	±0.0020
7-8x	±175K	±0.0060

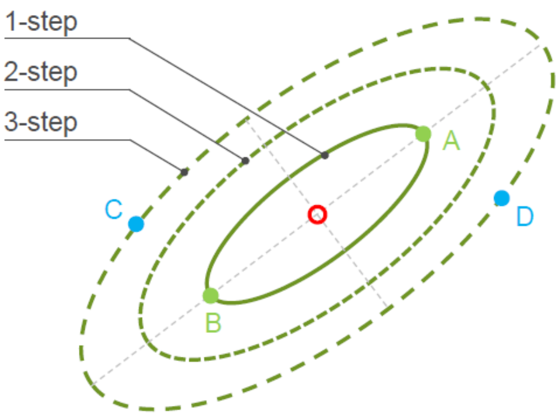


Fig.1.22: MacAdam ellipses and SDCM [24]

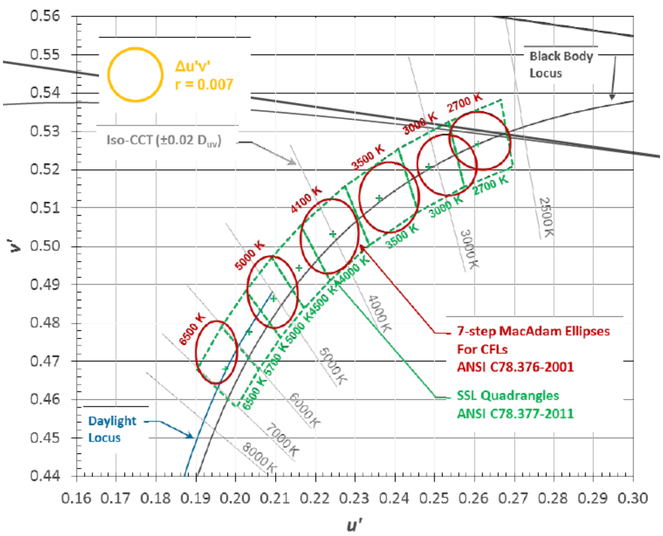


Fig.1.23: ANSI tolerances for CFL and SSL sources in the 1976 (u', v') chromaticity diagram. For this diagram, MacAdam ellipses are approximately circular around the black body locus, with one step equal to approximately 0.001. [24]

Colour Stability and Colour Consistency:

- **Colour Shift/Colour Stability: Comparison of spectral power distributions over time**

  - Many types of lamps emit light differently depending on the operating condition (ambient air temperature, for example). Sometimes these changes are recoverable.

  - For some lamps or luminaires, the materials or construction may change over time, resulting in changes to the spectral output.

  - Colour shift is generally independent of lumen depreciation, although they can be related.

- **Colour Consistency:** Comparison of initial spectral power distributions for a group of matching lamps or luminaires.

Operating Temperature: In general, the cooler the environment, the higher an LED's light output will be. Higher temperatures generally reduce light output. In warmer environments and at higher currents, the temperature of the semiconducting element increases. The light output of an LED for a constant current varies as a function of its junction temperature. Figure 9 shows the light output of several

LEDs as a function of junction temperature. The temperature dependence is much less for InGaN LEDs (e.g., blue, green, white) than for AlGaInP LEDs (e.g., red and yellow). [19]

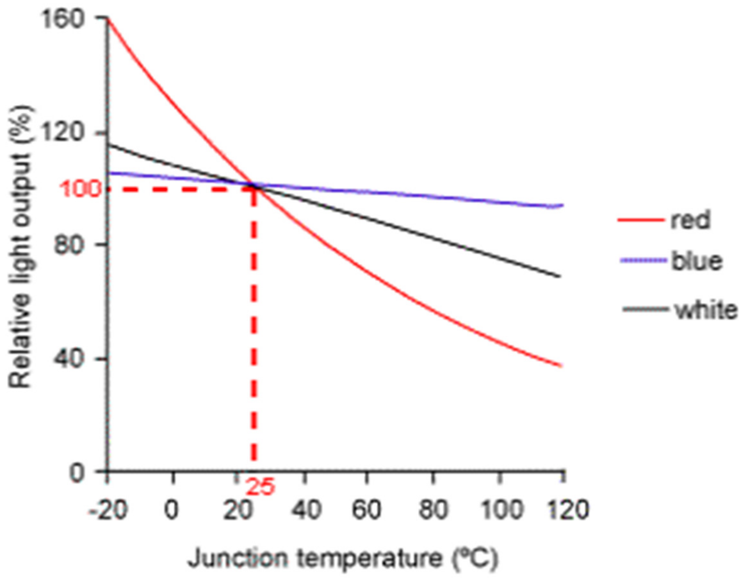


Fig.1.23: Relative light output of red, blue and phosphor-converted white LEDs as a function of the junction temperature. Data based on literature from LumiLeds. [19]

LED Lamp life: LEDs generally do not fail by burning out but will slowly reduce in light output over time; as solid-state devices they will continue to operate even after 100,000 hours, continuing to use electrical power even if they produce very little useful light. Even when light level reductions occur over a few minutes, people tend not to notice them until the light level reaches 80% of the initial value (Kryszczuk and Boyce 2002) [21]. For these reasons, it may be appropriate to consider this criterion as a basis for "useful" life for LED sources used in general lighting.

Lumen maintenance characteristics: Lumen maintenance depends on several factors:

- the LED package.
- the operating conditions such as ambient temperature or current through the LED
- the LED colour (different semiconductor materials will have different degradation properties; additionally, short-wavelength light will tend to cause more degradation in epoxy materials used to encapsulate the junction element; see Figure 9).

It is also important to note that the performance of a single LED in a system might not accurately represent the performance of the entire system. For example, LEDs near the centre of an array might experience higher overall temperatures and therefore experience greater reductions in performance than LEDs near the edge of an array (Narendran and Bullough 2001) [20].

Various coloured LEDs have different rates of lumen maintenance. As an example, Figure 1.24 shows lumen maintenance of red, green, blue and white indicator-type LEDs. [19]

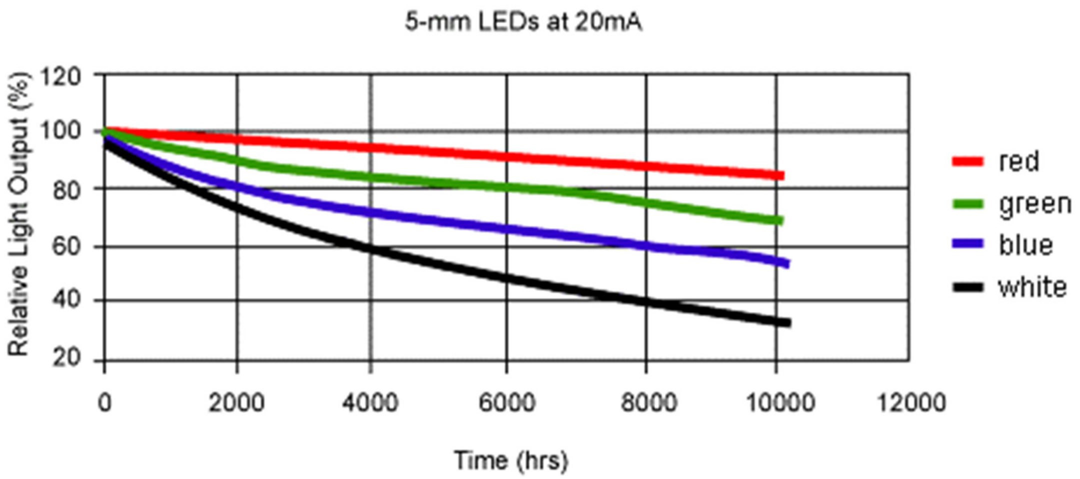


Fig.1.24: Lumen maintenance of several colours of indicator-type LEDs as a function of operating time. [19]

The current through an LED is also a large determinant of its lumen maintenance characteristics. Operating LEDs at higher than rated currents accelerate the degradation mechanism by creating higher junction temperatures (Figure 1.25).

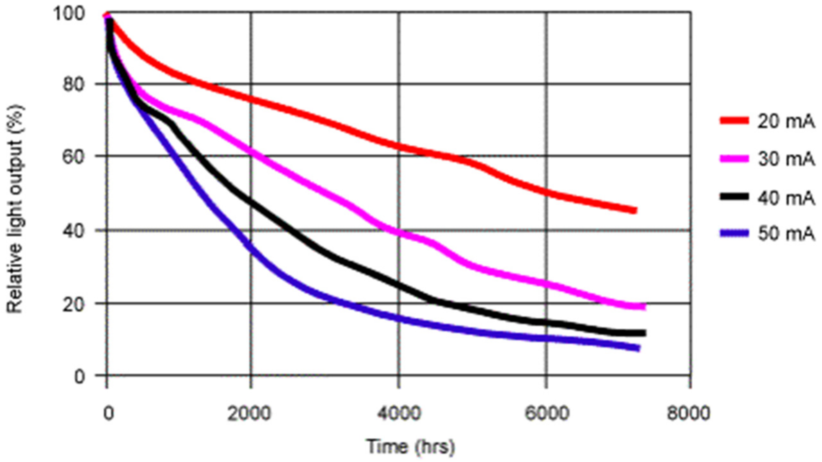


Fig.1.25: Overdriving phoshpor-based white indicator LEDs and the impact on lumen maintenance operating time. [19]

LED Driver: An LED lighting system consists of a dimmer or controller, a driver and a luminaire. To dim the light, you move the slider or turn the wheel and the dimmer sends a signal to the driver. The driver translates that signal to an electrical current that powers the LED.

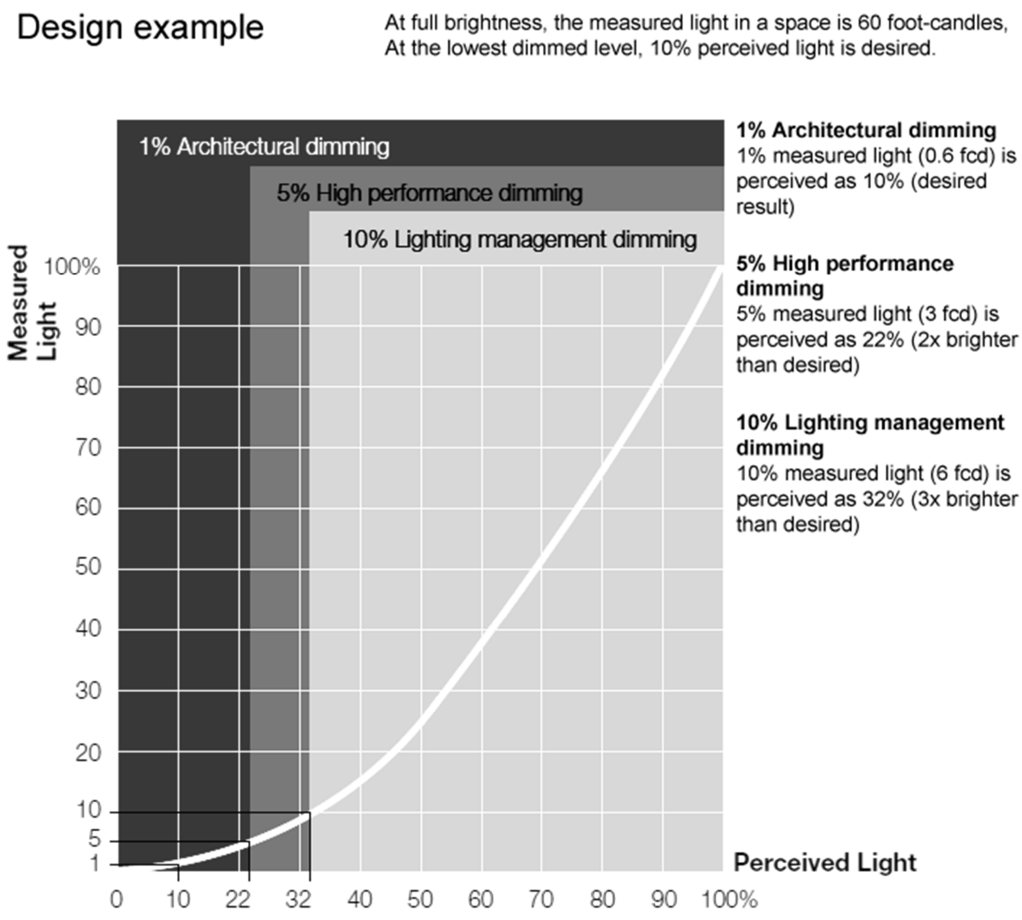
- The driver switches the light on and off
- The driver arranges the dimming
- The driver supplies the electrical current to the LEDs
- The driver is either inside the luminaire or used externally
- Some drivers are programmable (current settings / dimming curve) and dimmable (via DALI, 1-10V or DMX)

Measured light vs. perceived light: The human eye responds to low light levels by enlarging the pupil, allowing more light to enter the eye. This response results in a difference between measured and perceived light levels.

A lamp that is dimmed to 10% of its maximum measured light output is perceived as being dimmed to only 32%. Likewise, a lamp dimmed to 1% is perceived to be at 10%.

$$\text{Formula: Perceived Light (\%)} = 100 \times \sqrt{\frac{\text{Measured Light (\%)}}{100}}$$

Source: IESNA Lighting Handbook, 9th Edition, (New York; IESNA, 2000), 27-4.



Design example

At full brightness, the measured light in a space is 60 foot-candles,
At the lowest dimmed level, 10% perceived light is desired.

1% Architectural dimming
1% measured light (0.6 fcd) is perceived as 10% (desired result)

5% High performance dimming
5% measured light (3 fcd) is perceived as 22% (2x brighter than desired)

10% Lighting management dimming
10% measured light (6 fcd) is perceived as 32% (3x brighter than desired)

Fig.1.26: Design example. Source: IESNA Lighting Handbook, 9th Edition, (New York; IESNA, 2000) adapted from Lutron.

1.4 LUMINAIRES

The luminaire is the complete lighting apparatus consisting of the housing as well as all parts required for mounting and function, including the lamps, control parts, control gear, wiring and so forth. LED light sources are usually mounted in specifically designed flat luminaires that make optimal use of their optical properties.

Fig.1.27: Luminaire Examples (WE-Ef, Selux)

Mark of conformity and quality marks [2]

CE: According to the EU any product available in the market must comply with all relevant EU directives. The CE marking ensures that the product legally binds with all the regulations. +The CE mark (Communautés Européennes, European Community) is not a test mark like the ENEC or other national quality marks, but a conformity marking. It has to be highlighted that the CE symbol is not issued by a (third party) testing institute, but by the manufacturer himself.

The monitoring authorities recognize a product with a CE marking without further testing as being marketable. Conformity is only checked by market surveillance authorities within spot checks or if products are suspected being non-compliant.

For street lighting luminaires the CE mark of conformity covers the following legislation

- Directive 2014/35/EU on the harmonisation of the laws of the Member States relating to the making available on the market of electrical equipment designed for use within certain voltage limits (low voltage directive)
- Directive 2014/30/EU on the harmonisation of the laws of the Member States relating to electromagnetic compatibility (recast)

ENEC [2]: The ENEC mark (European Norms Electrical Certification) is a European safety mark with uniform test conditions across Europe. The ENEC Agreement describes the procedure for the granting and use of a commonly agreed mark for certain electrical equipment complying with European Standards.

The joint test conditions are stipulated in the EN 60598 series of standards. In order to ensure the product quality guaranteed by the ENEC mark, manufacturers must also have a quality assurance system.

A product with ENEC marks from another European country is treated as if it had been certified by the national inspection body in its own country. This simplifies the free movement of goods in the European economic area, including Switzerland – and increasingly in the Eastern European market.

Safety criteria [2]

Luminaires for street lighting must be protected against foreign matter (both solid and liquid), mechanical impacts as well as voltage fluctuations in order to guarantee their continuous proper operation.

Ingress Protection [2]: The resistance of luminaires against foreign matter is indicated by the so-called Ingress Protection (IP) code, a two-digit number defined by the IEC 60529 standard. The first digit represents the resistance against solid matter, while the second rates its resistance against liquids. For street lighting, IP65 luminaires should be used to ensure sufficient resistance to dust, particulates and inclement weather. [2]

IP Code	Description First digit	Description Second digit
0	No Protection	No Protection
1	Protected against solid bodies greater than 50 mm	Protected against dripping water/condensation
2	Protected against solid bodies greater than 12 mm	Protected against rain water up to 15 ° from the vertical
3	Protected against solid bodies greater than 2.5 mm	Protected against rain water up to 60 ° from the vertical
4	Protected against solid bodies greater than 1 mm	Protected against water splashing in all directions
5	Protected against dust (no harmful deposits)	Protected against water jets from all directions
6	Fully protected against dust	Protected against wave-like water jets from all directions
7		Protected against immersion
8		Protected against the effects of prolonged immersion under water

Table. 3: Ingress Protection (IP) rating [IIEC, 2015]

Mechanical Impact [2]: The resistance of luminaires to mechanical impacts is indicated by their Mechanical Impact (IK) code, a number defined by the IEC 62262 standard. As outdoor luminaires may be hit by loose tree branches or other debris in strong winds or even may be subject to outright vandalism, a minimum of IK08 is recommended.:

IK Rating	Impact strength in Joules
00	-
01	0.15
02	0.2
03	0.35
04	0.5
05	0.7
06	1
07	2
08	5
09	10
10	20

Table. 4: Mechanical Impact (IK) rating

Support Systems [2]: The EN 12767 ("Passive Safety of Support Structures for Road Equipment") stipulates the criteria in order to minimise the danger to vehicle occupants in case of collisions. According to the standard, support structures of road equipment are classified into three different categories of passive safety:

- High energy absorbing (HE)
- Low energy absorbing (LE)
- Non-energy absorbing (NE)

Four levels of occupants' safety are specified for support structures, with level 4 representing non-harmful support structures that are assumed to cause only minor damage. The other three levels are determined by impact tests using lightweight passenger cars with speeds of 35, 50, 70, and 100 km/h. The test data is used to derive the acceleration severity impact (ASI) and the theoretical head impact velocity metrics, which describe the danger to passengers.

Voltage protection: Transient over-voltages (increases in voltage above the standard design voltage that last from microseconds to a few milliseconds) may cause damage to LED modules and control gear. Their resistance to such fluctuations is measured by the overvoltage protection rating.

While EN 61547 regulates minimum criteria for overvoltage protection for LED lighting, it specifies a mere 0.5 kV phase to neutral wire/earth – insufficient for more serious situations such as lightning strikes. Many street lighting projects mandate overvoltage protection up to 10 kV for this reason. [25]

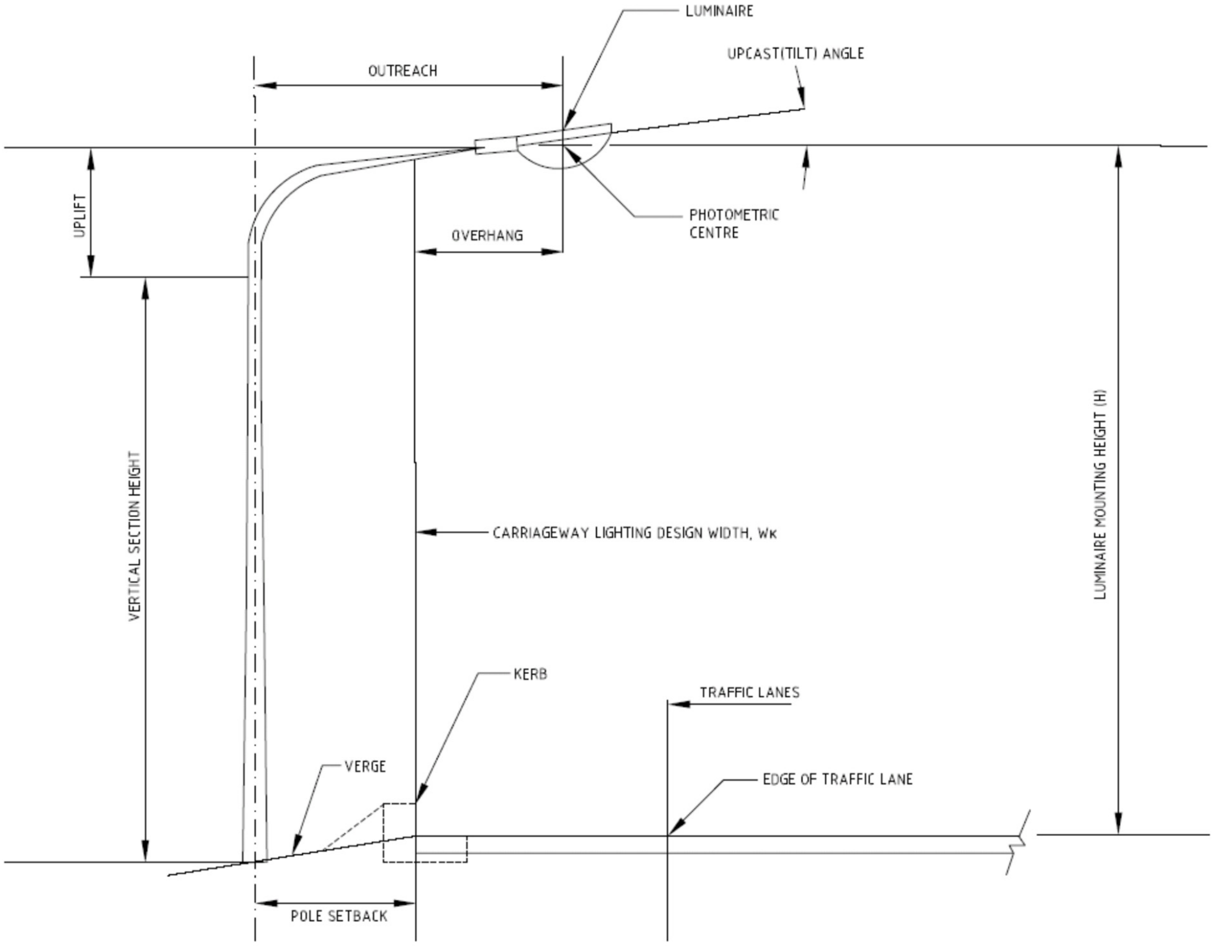


Fig.1.28: Geometry and Terminology used in a Typical Road Lighting Installation [7]

European Standard EN 13201

The European standard EN 13201 “Street lighting” defines the quality criteria under the following topics:

- PD CEN/TR 13201-1:2014: Guidelines on selection of lighting classes
- EN 13201-2:2015: Performance requirements
- EN 13201-3:2015: Calculation of performance
- EN 13201-4:2015: Methods of measuring lighting performance

- EN 13201-5:2015: Energy performance indicators

Selection of lighting classes [2]

PD CEN/TR 13201-1:2014 defines a parameter system for a detailed description of all typical lighting situations in road traffic. Using the European standard, the lighting requirements can be determined according to the specific conditions of the roads. Various lighting parameters, such as the geometry of the traffic area, type of traffic use and environmental influences are used to identify lighting classes for which qualitative and quantitative lighting requirements are described.

PD CEN/TR 13201-1:2014 uses a selection procedure for determining lighting classes M1 to M6, C0 to C5, and P1 to P6. It does not give guidelines for the selection of lighting classes HS, SC and EV, which are available at national level for each country.

The selection criteria for each subclass (as designated by their digit) are based on the geometry of the road, its traffic usage, and its environment. The effective criteria (based on PD CEN/TR 13201-1:2014) include:

- Design speed or speed limit
- Travel speed (for lighting class P)
- Traffic volume
- Traffic composition
- Separation of carriageway
- Junction density
- Parked vehicles
- Ambient luminosity
- Facial recognition (for lighting class P)
- Navigational task

Certain parameters (in particular traffic volume, traffic composition and ambient luminosity) may change from season to season, or during different hours of the night. Thus, road sections may be shifted to a different road class.

[PD CEN/TR 13201-1:2014; EN 13201-2:2003; EN 13201-2:2015]

1.5 PERFORMANCE REQUIREMENTS, MEASUREMENT & CALCULATION METHODS

Part 2 of EN 13201 provides specifications for the different lighting classes which are defined by a set of photometric requirements depending on the needs and requirements of the specific road users and road types.

The lighting classes simplify the development and application of street lighting products and their maintenance in the member states. In order to broadly harmonize the requirements, the lighting classes were defined on the basis of the national standards of the member states and the CIE 115:2010 standards.

Part 2 introduces a number of additional metrics which are used to define minimum or maximum criteria for each subclass. [2]

M class roads are routes for motorized traffic with medium to high driving speed. To fulfil the criteria of the standard, care must be taken to maintain a minimum average road surface luminance, a minimum uniformity of the luminance of the road surface (with separate minimum values given for dry and wet conditions), a minimum uniformity of luminance along the centres of the driving lanes, a maximum level of glare, as well as ensure that the illuminance outside the carriageway does not fall off too quickly.

C class roads represent conflict areas where motorized vehicles have to expect other road users (such as pedestrians or cyclists) or otherwise have to navigate complicated traffic situations, such as complex road intersections, roundabouts, queuing areas, and so forth. While lighting systems for C class roads still need to meet a minimum uniformity of the luminance of the road surface, most other criteria for M class roads are not applicable or impracticable (for instance, many conflict areas do not have a clear strip of land next to the carriageway suitable for calculating how quickly the illuminance falls off beyond the carriageway).

Instead, they are required to maintain an average horizontal illuminance on the road area. While C class roads – unlike M class roads – do not have mandatory criteria for minimizing glare, Annex C of EN 13201-2 provides informative criteria for this class.

P and HS class roads are intended for pedestrians and pedal cyclists on footways, cycle-ways, emergency lanes, and other road areas lying separately or along the carriageway of a traffic route, as well as residential roads, pedestrian streets, parking places, schoolyards and so forth. Criteria for P class roads include a minimum maintained average illuminance on the road area, and a maintained minimum illuminance on the road area. If facial recognition is important, additional criteria for vertical plane illuminance (at a point) and minimum semi-cylindrical illuminance (on a plane above a road area) must be adhered to. As an alternative to the P class, the HS class bases its criteria on the overall uniformity of road surface luminance as well as the average hemispherical luminance.

SC class roads are an additional class for pedestrian areas where facial recognition and feelings of safety are especially important. They require minimum levels of maintained semi-cylindrical illuminance.

EV class roads are an additional class for situations like interchange areas where vertical surfaces need to be perceived clearly.

Additionally, the informative Annex A of EN 13201-2 introduces six different luminous intensity classes for the reduction of glare where the normal metric (threshold increment) cannot be calculated. Classes G*1, G*2, and G*3 correspond to the traditional "semi cut-off" and "cut-off" concepts, while G*4, G*5, and G*6 correspond to full cut-off. See section 2.1.1.4 for the definition of these terms.

EN 13201-3 describes the mathematical methods and procedures which should be used to calculate the lighting performance characteristics defined in EN 13201-2.

EN 13201-4 describes the methods that should be used for measuring lighting performance. There are four basic types of situations when measurements should take place:

- at the final testing phase measurements should be taken in order to verify compliance with standard requirements and/or design specifications.
- at pre-determined intervals during the street lighting lifetime in order to quantify lighting performance degradation and determine the need for maintenance.
- continuously or at pre-determined intervals in order to adjust the luminous flux of the luminaires, if the road uses adaptive street lighting (e. g. the luminance or illuminance is controlled in relation to traffic volume, time, weather, or other environmental factors).

Energy performance indicators [2]

EN 13201-5 describes the two energy performance metrics power density indicator (PDI) DP (measured in W/(lx · m2)) and the annual energy consumption indicator (AECI) DE (measured in (Wh)/m2) which already have been introduced in the previous chapter. These indicators should always be used together for the assessment of the energy performance of a particular lighting system.

The power density indicator defines how to calculate the energy performance of a particular street lighting installation and makes it possible to compare different setups and technologies for the same street lighting project (as different locations will have a different geometry and environmental conditions, PDI values can only be used to compare different setups for the same installation). The following information is needed in order to calculate the power density indicator for any given area:

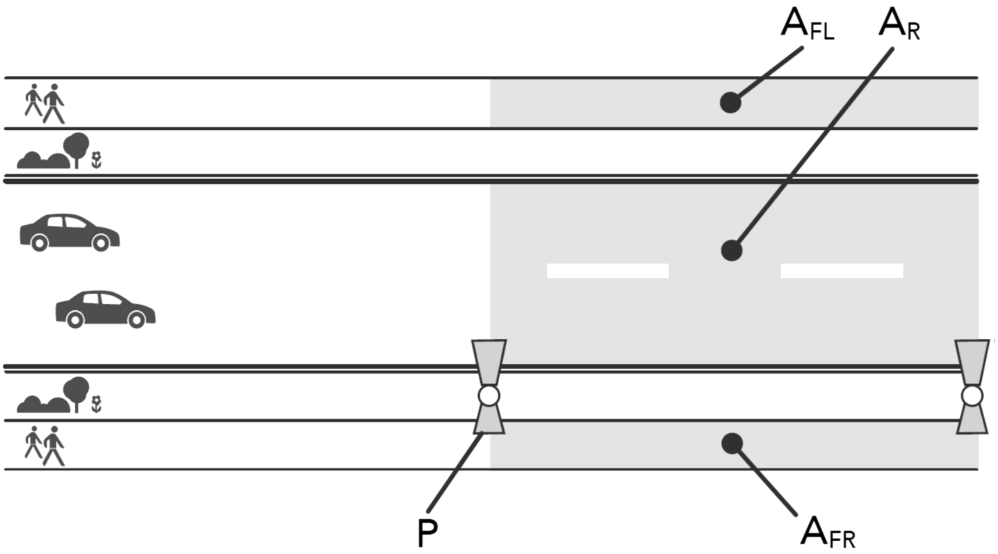


Fig.1.29: Example layout for PDI/AECI calculation [2] adapted from Premier Light Pro

- The **total system power P** of the lighting system(either the entire installation or a representative section), which includes both the operational power of all the individual lighting points (light sources and any associated devices gear) as well as of devices not part of the individual lighting points but necessary for their operation (such as centralized control systems and switches).

The **maintained average horizontal illuminance E** – (in [lx]) of each sub-area (as well as the size of each sub-area). Peripheral strips used for calculating how quickly the illuminance falls off beyond the carriageway are excluded. The illuminance can be derived from metrics which have already been established for selecting the lighting class of the road.

The full equation for calculating PDI is:

$$D_p = \frac{P}{\sum_{i=1}^{n}(E_i\, X\, A_i)}$$

With Ei being the maintained average horizontal illuminance of the sub-area, Ai being the size of the sub-area "i" lit by the lighting installation (in m²), and n being the number of sub-areas to be lit. For street lighting classes which do not use the maintained average horizontal illuminance (that is, street lighting classes other than M), section 4.2 of EN 13201-5 provides conversion guidelines.

Since the lighting class usually changes throughout different seasons and throughout the night, the PDI should be calculated separately for each relevant class. In order to compare the energy consumption differences between two different setups not just for a particular street lighting class, but throughout an entire year of operation, it is necessary to calculate the AECI. For this purpose, it is necessary to divide the year into separate operational periods where different values for P are applied. The full equation for calculating the AECI is:

$$D_E = \frac{\sum_{j=1}^{m}(P_j\, X\, t_j)}{A}$$

with Pj being the total system power associated with the jth period of operation (in W), tj being the duration of the jth period of operation profile when the power Pj is consumed (in h), A being the size of the area lit by the same lighting arrangement (in m2), and m being the number of periods with different operational power values Pj.

Total accumulated durations of tj should add up to an entire year. Time periods when the lighting is not operational (such as during the day) should also be included in the calculation, since even during these periods the system still consumes standby power.

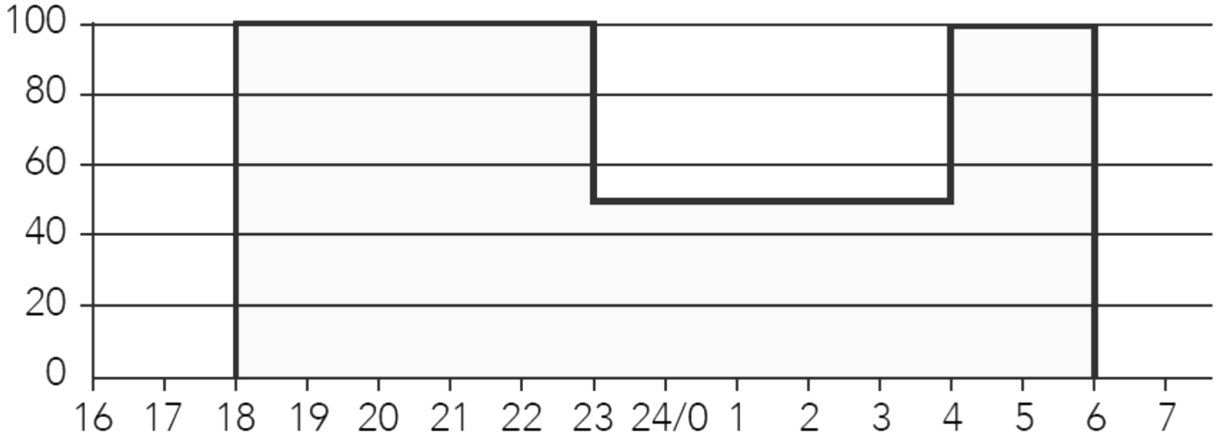


Fig.1.30: Sample time-based light output: Full power during the evening and early morning, half power late at night [2] adapted from Premier Light Pro

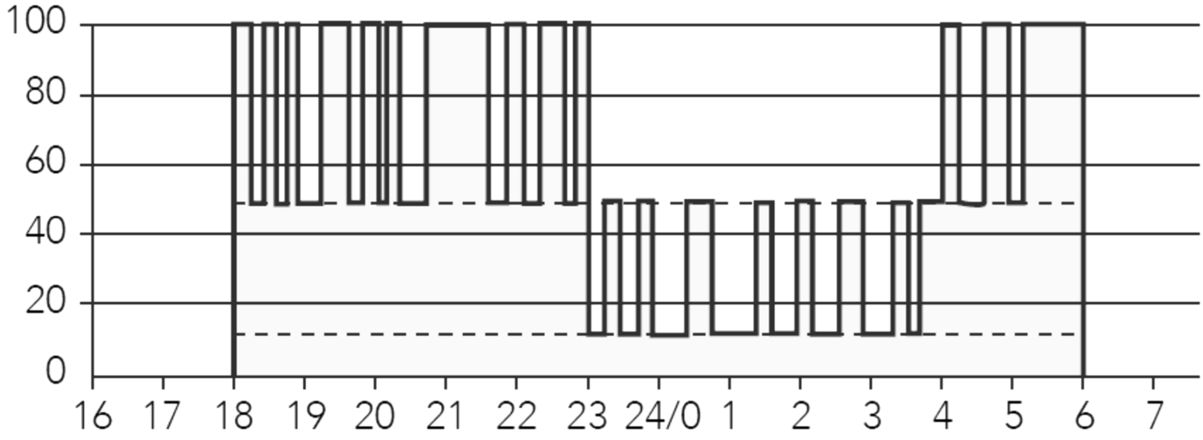


Fig.1.31: Time-based light output with vehicle or presence detectors – full power when presence is detected [2] adapted from Premier Light Pro

Annex A of EN 13201-5 provides sample PDI/AECI values for a large range of lighting classes, carriageway widths, and lamp types (based on lighting products available in 2014). A few sample values are shown below (all for carriageway widths of 7 m).

Annex C of EN 13201-5 provides a simplified method for comparing lighting systems for M lighting classes based on the average maintained horizontal illuminance E. Annex D presents a sample scheme for showcasing energy performance indicator information.

Lighting class	High pressure mercury	Metal halide	High pressure sodium	Low pressure sodium	LED
M1		45 / 5.0		34 – 41 / 4.0 – 5.3	25 – 32 / 3.0 – 3.8
M2	100/10.8	50 / 4.6		31 – 40 / 3.2 – 4.2	24 – 27 / 2.4 – 2.5
M3	84 / 6.0	47 / 3.6	40 / 2.8 – 3.1	34 – 38 / 2.5 – 2.6	23 – 25 / 1.5
M4	90 / 5.0	60 / 3.1	41 – 47 / 2.3 – 2.5	34 – 42 / 1.8 – 2.4	23 / 1.1
M5	86 / 3.2	30 / 0.9	47 / 1.7	38 – 45 / 1.1 – 1.6	24 / 0.8
M6	85 / 1.9	37 / 0.6		45 – 49 / 0.2 – 1.2	20 – 27 / 0.4 – 0.5

Fig.1.32: Sample DP (in [W/(lx·m2)]) / DE (measured in [(kWh)/m2]) values for a two-lane road for motorized traffic [2] Premier Light Pro

Conflict Points: Roadway features that influence the passage of motorists and pedestrians and that require particular attention when preparing the lighting design. Where different streams of road users travelling at different speeds come together, there is a risk of conflict, even collision. At crossroads, roundabouts, T-junctions and pedestrian crossing aids, that risk can be mitigated by a higher lighting level.

"conflict area" denotes an area where special visual attention is required. Examples of conflict areas on the roads are crossroads and T-junctions, roundabouts, lay-bys for buses, toll stations, roadworks and the pedestrian crossing aids and pedestrian crossings.

Another criterion identifying conflict areas is that they are typically used by motorised traffic travelling at speeds over 30 km/h, so an additional risk is presented by the need for faster response times and the difference in velocity between motorised and non-motorised traffic. That risk can be countered by optimised lighting.

Lighting raised to an appropriate level is a basic requirement for a conflict area. Because no single observer position can be defined to determine luminance, the yardsticks used for assessment are average horizontal illuminance and uniformity. At the same time, care must be taken to ensure that more light does not mean more glare. The luminaires used need to be designed for good visual comfort.

The standard sets out a step-by-step selection procedure based on the area with the highest lighting class requirements. It starts with the lighting level of the approach road with the highest lighting class. The step-up between adjacent areas must be no more than two lighting classes. It is also advisable to create adaptation zones before and after the conflict area – especially where traffic travels at 50 km/h or more – to bridge the gap between brightness levels and enable the eye to adapt.

In comparison to crossroads, which are a typical conflict area (see grey box below), roundabouts are a generally safer type of junction. But roundabouts are still classed as conflict areas and have special lighting requirements. To ensure visual guidance, lighting needs to be from the outside of the roundabout, not from the central island.

Assessment criteria

The assessment criteria for conflict areas are regulated by EN 13201 and depend on lighting situation, velocity, type of road users, etc. Tables in the standard are used to establish the maintained values required. Below are a few examples of parameters:

- Intersection density: The more closely spaced intersections there are, the better they need to be illuminated.
- Roundabouts need to be illuminated if the approach roads are illuminated.
- Footpaths and cycle paths at roundabouts also need to be adequately illuminated. Guidelines for pedestrian crossings on approach roads are provided in Germany by the R-FGÜ 2001 and DIN 67523.
- Marked differences in lighting level should be avoided.

Pedestrian crossings and street crossing aids

The ubiquitous presence of cars in the cities, towns and villages has made it to make it possible for pedestrians to cross the road safely at designated points. The design of pedestrian crossings is very precisely regulated by law, not only with regard to the markings on the road and the identifying sign 293 of the German Road Traffic Ordinance (StVO) but also as far as lighting is concerned – because the safety of pedestrians crossing the road naturally also needs to be guaranteed at night. Guidelines for the construction and configuration of pedestrian crossings apply throughout Germany ("Richtlinien für die Anlage und Ausstattung von Fußgängerüberwegen (R-FGÜ 2001)").

Importance of Vertical illuminance

Pedestrians using the crossings need to be clearly recognisable from both traffic directions, including at night or when the road is wet from rain – and not only on the crossing itself but also in the waiting areas. So supplementary, stationary lighting is normally required and needs to comply with the design requirements set out in the standards DIN 13201 and DIN 67523.

Vertical illuminance is needed to make persons stand out brightly against the background. At pedestrian crossings, it is usually provided by asymmetrical luminaires positioned so that both crossing and waiting.

In pedestrian crossing lighting the focus is on vertical illuminance and contrast to ensure that pedestrians in a waiting area or on the crossing stand out from the background. Pedestrian crossings are dealt with in the annex of DIN EN 13201-2, which also refers to the national standards of the individual member states. In Germany, the pedestrian crossing guidelines R-FGÜ 2001 (Richtlinien für die Anlage und Ausstattung von Fußgängerüberwegen) and DIN 67523 “Lighting of pedestrian crossings (sign 293 StVO) with additional lighting” need to be observed:

- If the existing street lighting fails to reach the values required in the standards, stationary supplementary lighting needs to be installed.
- To ensure uniform assessment of the lighting at pedestrian crossings, a rectangular, horizontal assessment field is agreed (see also Fig.1.33): - 30 lux-maintained illuminance is required at defined points on the central axis 1 m above the ground.
    - Illuminance must be no lower than 4 lux at any of the defined assessment points in the assessment field, not even in the waiting area 1 m away from the road.
- The lighting must illuminate the pedestrian crossing and the adjacent waiting areas “from the relevant direction of travel” – lighting directly above the central axis of the crossing is not permitted.
- A different light colour from that of the general street lighting makes for greater visibility.
- Pedestrian crossing signs can double as lighting.
- In contrast to street lighting, pedestrian crossing lighting may not be deactivated at any time during the night.
- For 100 metres on either side of a pedestrian crossing, the luminance of the road needs to be at least 0.3 candela/m^2. If necessary, the level of the existing street lighting needs to be raised accordingly.
- Pedestrian crossing lighting needs to be separately switchable.

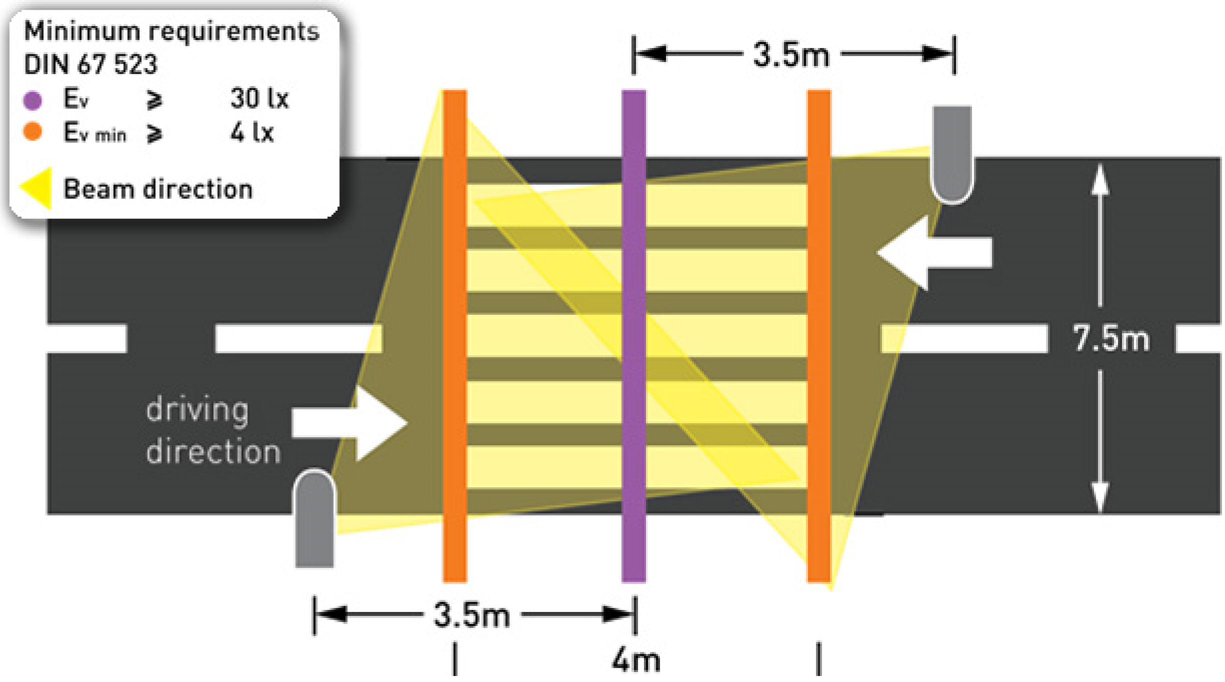


Fig.1.33: Pedestrian Crossing: lighting requirements [https://www.ledil.com/application_example-2/pedestrian-crossings-with-strada-2x2-px-and-pxl/]

1.6 LIGHT POLLUTION

Artificial lighting can have detrimental effects on humans and animals, and this includes the undesired outdoor spread of light, or light pollution. For humans, the effects range from excessive illumination of the night sky in and near cities to disruptions of the sleep cycle by badly positioned outdoor lighting in residential areas. Animals on the other hand use natural light sources as a navigational aid and thus may become confused or scared away by artificial illumination. Many animals perceive different ranges of wavelengths than humans.

Studies have shown that LED road light sources attract fewer insects than other technologies, with "warm white" LEDs (colour temperature of 3000 K) resulting in significantly lower numbers than with "cold white" LEDs (colour temperature of 6000 K). [11]

One way of reducing light pollution is to use luminaires which direct the light only on the areas to be illuminated. Directional light sources incorporating LEDs are especially suited for achieving optimised light distribution. Light emissions above the light source are generally not desired.

The light emitted upwards from the luminaire is quantified by the upward light output ratio (abbreviated as ULOR or RULO):

ULOR = upward lumen output of luminaire/ total lamp lumen output

Depending on their vertical light distribution, luminaires are divided into four basic types [IIEC]:

- Full cut-off luminaires: a maximum of 10 % of the total lumens of the lamp are emitted at an angle of 80 ° above the nadir, and 0 % at angle of 90 ° above the nadir.
- Cut-off luminaires: a maximum of 10 % of the total lumens of the lamp are emitted at an angle of 80° above the nadir, and 2.5 % at angle of 90 ° above the nadir.
- Semi-cut-off luminaires: a maximum of 20 % of the total lumen of the lamp can be perceived at an angle of 80 ° above the nadir, and 5 % at angle of 90 ° above the nadir.
- Non-cut-off luminaires: emit light into all directions.

This traditional definition of cut-off is extended to six different luminous intensity classes in EN 13201-2, which also includes maximum values for an angle of 70 ° and above. See section 2.2.2 for further details on EN 13201-2.

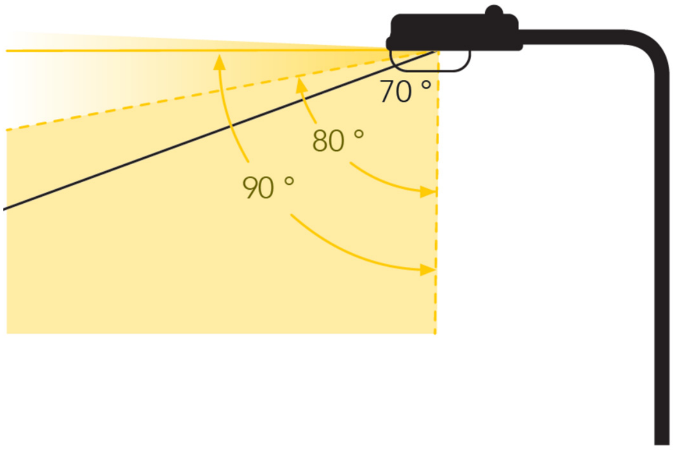


Fig.1.34: Definition of cut-off criteria [10]

5.5.4 BUG Rating

The BUG system is the most another way to classify a luminaire's optics and has been adopted by the IESNA. The BUG system has replaced the cut-off classifications in IESNA, although both classifications may still be used by suppliers.

BUG stands for "Backlight", "Uplight" and "Glare". The acronym describes the types of stray light escaping from an outdoor lighting luminaire. There are different zones that are used to determine where the light is distributed and how it affects each rating.

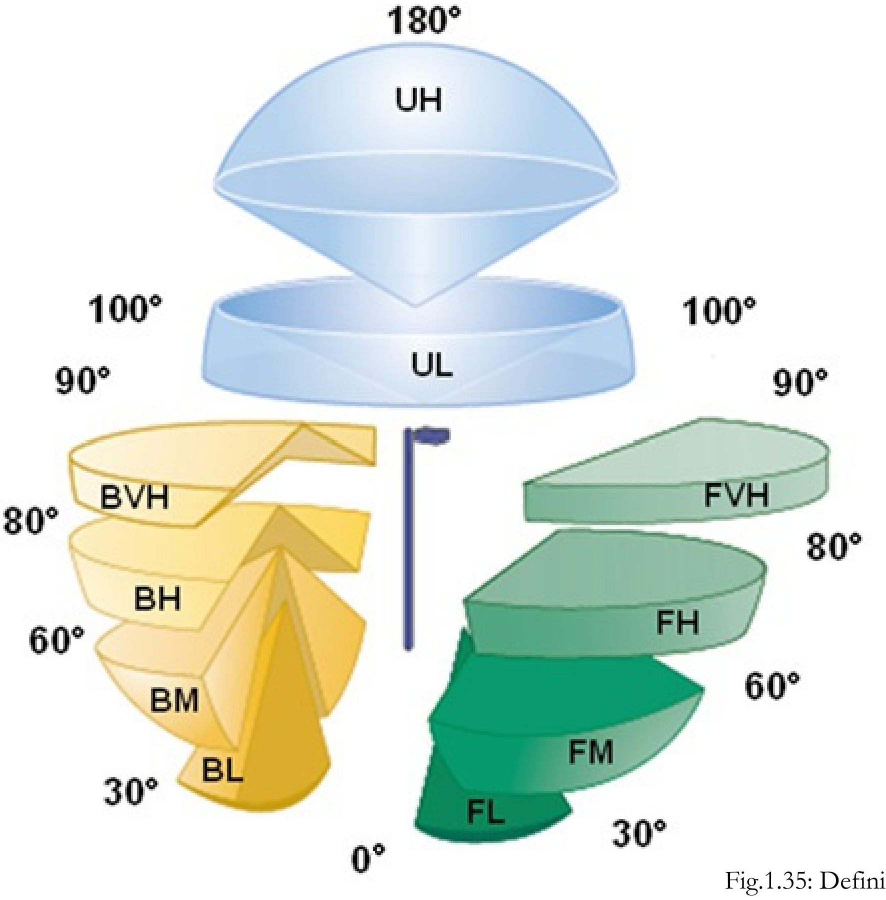


Fig.1.35: Definition of cut-off criteria [10]

Zones

Backlight Sub-Zones

- BVH: Backlight Very High (80-90 degrees)
- BH: Back light High (60-80 degrees)
- BM: Back light Mid (30-60 degrees)
- BL: Back light Low (0-30 degrees)

Uplight Sub-Zones

- UH: Uplight High (100-180 degrees)
- UL: Uplight Low (90-100 degrees)

Glare (Front Light) Sub-Zones

- FVH: Forward light Very High (80-90 degrees)
- FH: Forward light High (60-80 degrees)
- FM: Forward light Mid (30-60 degrees)
- FL: Forward light Low (0-30 degrees)

Backlight, creates light trespass onto adjacent sites. The B rating takes into account the amount of light in the BL, BM, BH, BVH zones, which are directions opposite from the area intended to be illuminated.

Uplight, is mainly responsible for causing artificial sky glow. Lower uplight (zone UL) causes the most sky glow and negatively affects professional and academic astronomy. Upper uplight (UH) is mostly contributing to energy wastage.

Glare or Grating takes into account the amount of frontlight in the FH and FVH zones as well as BH and BVH zones.

IES TM-15-11: It defines six uplight ratings for luminous flux (maximum zonal lumens) emitted above 90 degrees by the luminaire (Table 1). There are two uplight zones, designated UL for vertical angles 90 to 100 degrees and UH for angles 100 to 180 degrees (FIG. 3).

	U0	U1	U2	U3	U4	U5
UH	0	10	50	500	1000	>1000
UL	0	10	50	500	1000	>1000

Table.4: IES TM-15-11 Uplight Ratings (maximum zonal lumens) [3]

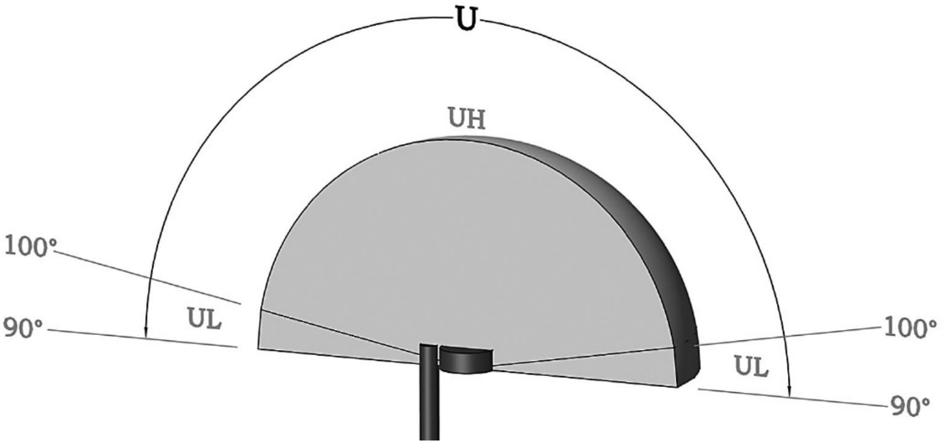


Fig.1.36: Definition of cut-off criteria [10]

Few Key Factors to Consider When Designing a Public Lighting Project

1. Road Luminance is a measure of how visible the road is to a motorist. Luminance is dependent on the light distribution of the luminaires, the lumen output of the lamps, the installation design of the road lighting, and the reflection properties of the road surface. The higher the luminance level, the better the lighting. Based on industry standards, a 75% RP is considered sufficient in most road conditions.

2. Uniformity is a measure of how evenly distributed the light on the road is, which can be expressed as Overall Uniformity (UO) and Longitudinal Uniformity (UL). A good overall uniformity ensures that all spots and objects on the road are sufficiently lit and visible to the motorist. The industry accepted value for UO is 0.40.

On the other hand, a good level of longitudinal uniformity ensures comfortable driving conditions by reducing the pattern of high and low luminance levels on a road (i.e. zebra effect). It is applicable to long continuous roads.

3. Glare is the blinding sensation when the brightness of the light exceeds the adaptation level of the human eye to light. It produces discomfort and reduces road visibility. It is measured in Threshold Increment (TI), which is the percentage increase in required luminance to compensate the effect of glare (i.e., make the road equally visible as in the absence of glare). The industry standard for glare is 10% TI.

4. Surround Ratio (SR): Road lighting should light up not only the road, but also the adjacent areas so motorists can see objects in the periphery and anticipate potential road obstructions (e.g., a pedestrian about to step onto the road). The SR is the visibility of the road's periphery relative to that of the main road itself. As per industry standards, SR should be at least 0.50, as this is ideal and sufficient to create a proper adaptation to the eyes.

5. Colour Rendering Index measures the ability of the artificial light to show or reproduce the colours of the road or objects on the road, relative to a natural light source. The natural light source (the sun) has CRI of 100. The higher this index the better the visibility will be. For all types of road CRI ≥ 70 is recommended.

Chapter – 2: Dynamic Light

2.1 LIGHT CHARACTERISTICS FOR DYNAMIC LIGHT CONTROL

Light Distribution: The way the luminous intensity of reflector lamps and luminaires is distributed is indicated by curves on a graph. These are known as intensity distribution curves (IDCs). The form of presentation is normally a polar diagram.

Variable Light Distributions: The streetscape is the framework for social activities; it also acts as a stage for performances, everything from the celebration of festivals, national days to a playground for the children.

Taking the discussion, a step further and looking at the evolution and development of the city, we are witnessing a changing scale of the cities in which new developments are continuously competing with the old city. In such constantly evolving functions and uses for spaces, it is necessary that the built environment and its elements are able to adapt and modify according to the changing needs.

Public lighting has to be able to easily respond to any changes in functions and needs. The LED technology and the control systems today make it possible to have various different LED light sources with different characteristics in one single luminaire. These features can make the modern LED luminaires truly multi-functional, performing different functions at the same time and being able to fulfil different requirements not only in long term but also short term.

Public lighting for the first time will be able to respond to even hourly changes in uses and not only long-term changes. A single luminaire can provide solutions for various functions, for example a busy commercial area can have office spaces, restaurants, eating joints, places to socialise and relax, entertainment and event spaces all compacted into one space. Variable light distribution will allow a single luminaire to provide good quality lighting for all these and many more functions. The small size of the light source makes it possible to have a number of lighting solutions combined into a single luminaire. Solutions can be provided for changing functions, activities, time and seasons or weather; the possibilities are as vast as our imagination. Dynamic lighting control will be able to provide lighting that is suitable as well as encouraging for such varying activities and functions.

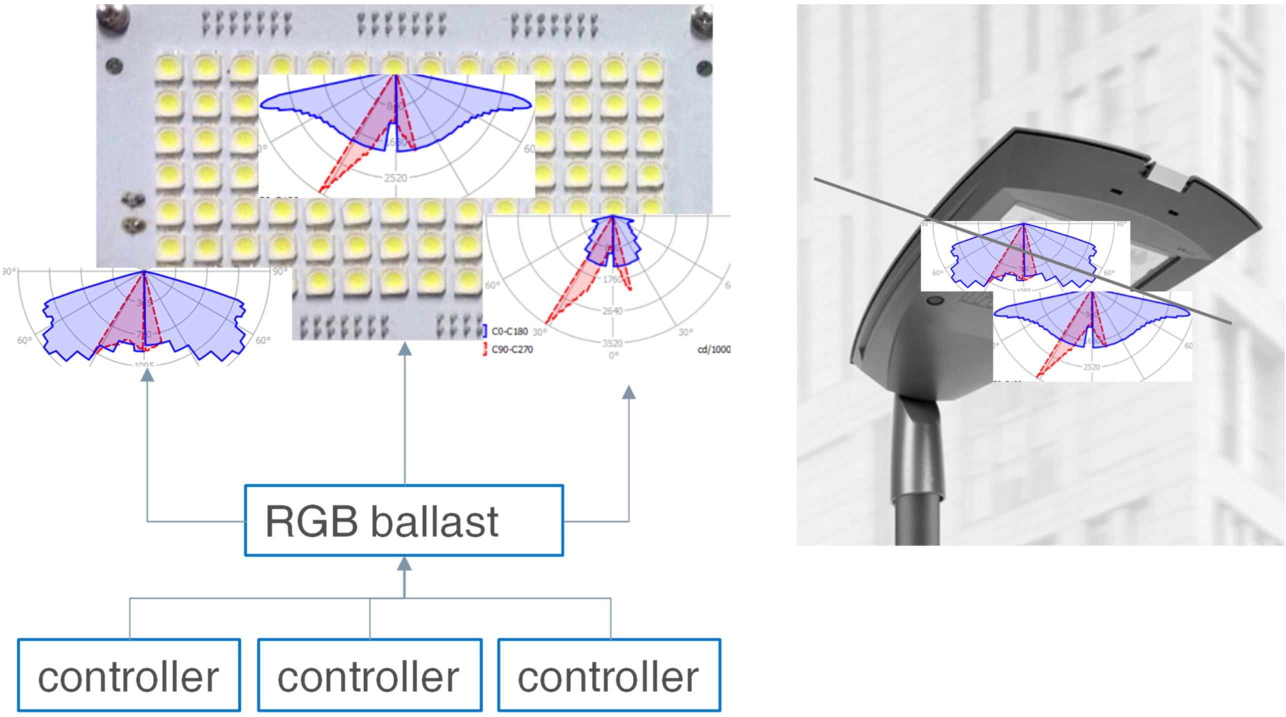


Fig.2.1: Prof. Volker & Steblau, LUX Europa 2017, Ljubljana [26]

Luminaires with multi-variable light distribution can ***create the right quality of light, for the right user, for the right function, at the right time and right quantity***.

They can further help in:

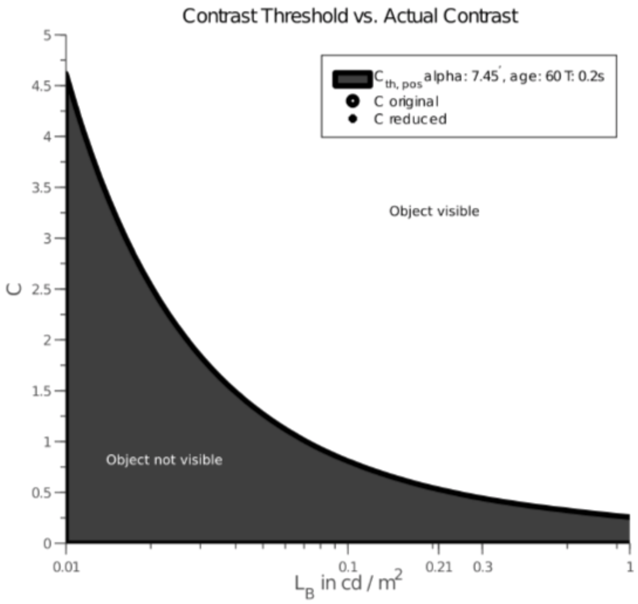
- Improving visibility
- Result in increased Energy efficiency
- Reduce Light Pollution

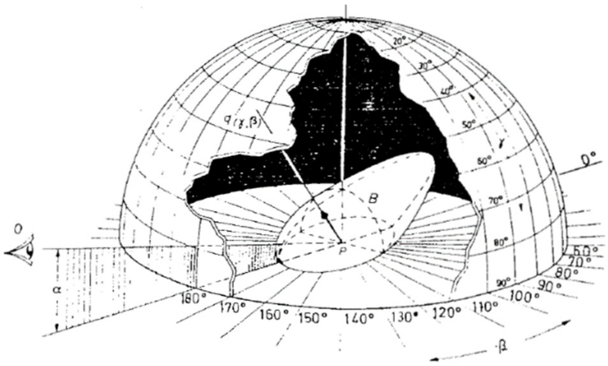
1. Improving visibility: Through variable light distribution the visibility at night can be dramatically improved.

Factors influencing visibility:

- Size of object
- Reflexion degree of object
- Reflexion degree of surrounding

- Glare sources





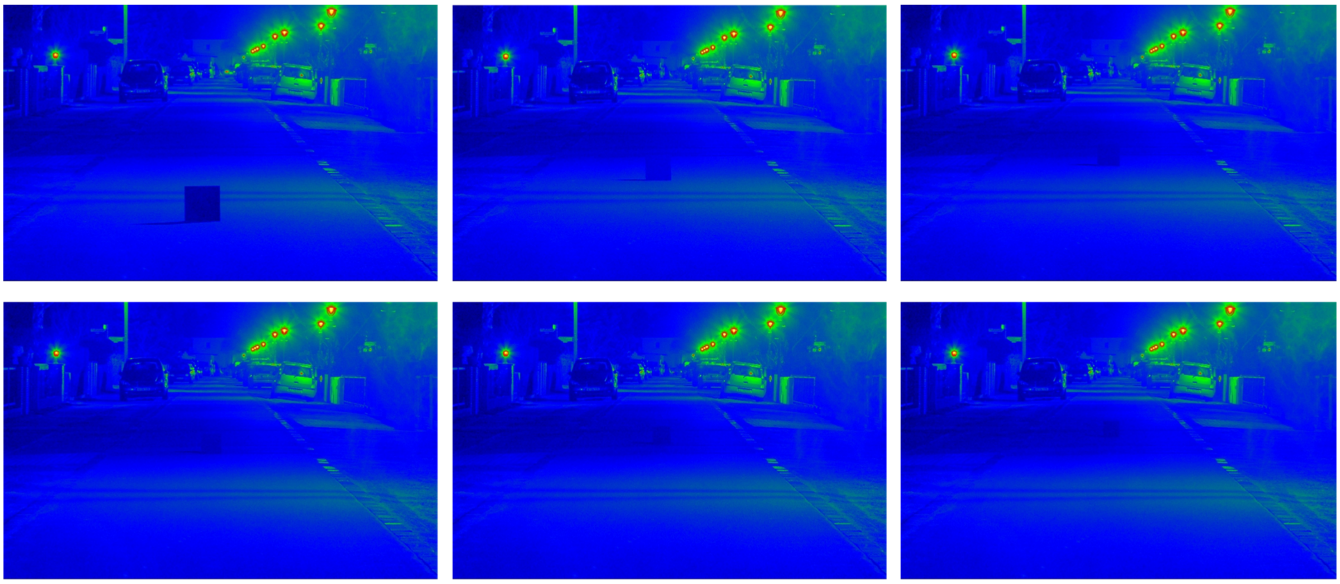


Fig.2.2: Prof. Volker & Steblau, LUX Europa 2017, Ljubljana [26]

Changing Reflectance of surfaces:

The road surface luminances in road and street lighting in dry conditions are largely in the mesopic region i.e. below 3cd/sq.m even on well illuminated roads.

In wet conditions the luminances and luminance distributions of road surfaces change significantly in comparison to dry conditions. In areas with specular reflection towards the observation point the luminances of the road surfaces increase substantially and form very bright areas. On the other hand, the darker areas of the road surfaces increase in size and decrease in luminance. This results in a very low luminance uniformity of the road surface. The road surface luminance measurements indicate remarkable changes caused by wetness to road surface luminances and luminance uniformity. These in turn result in bad visual conditions and decreased visibility.

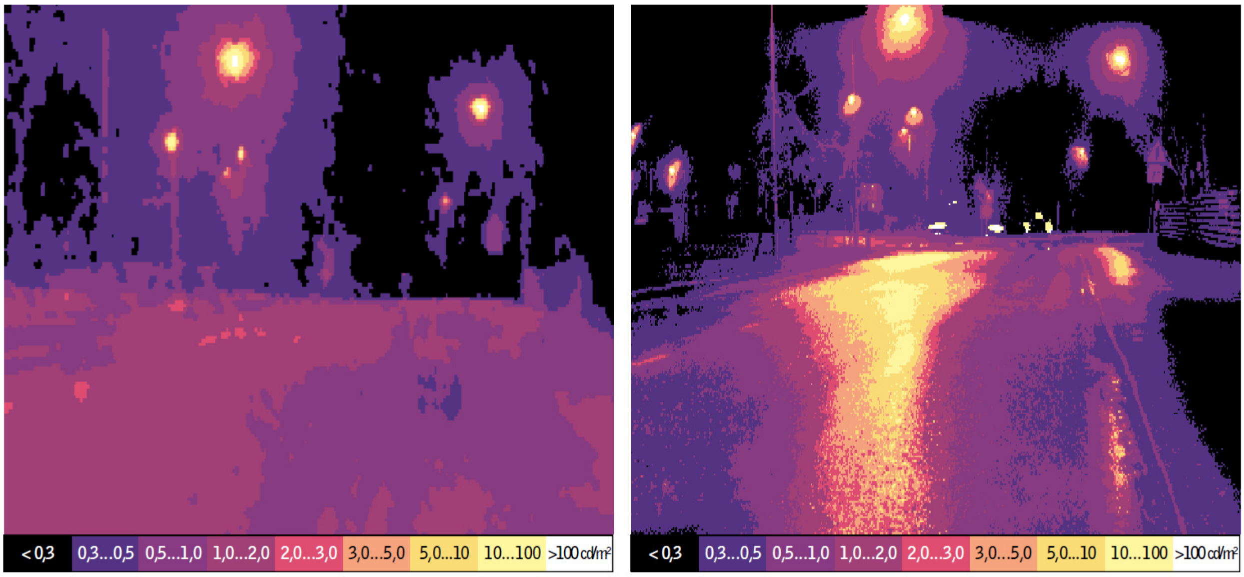


Fig.2.3: Road surface luminance in dry (left) and wet (right) conditions. [8]

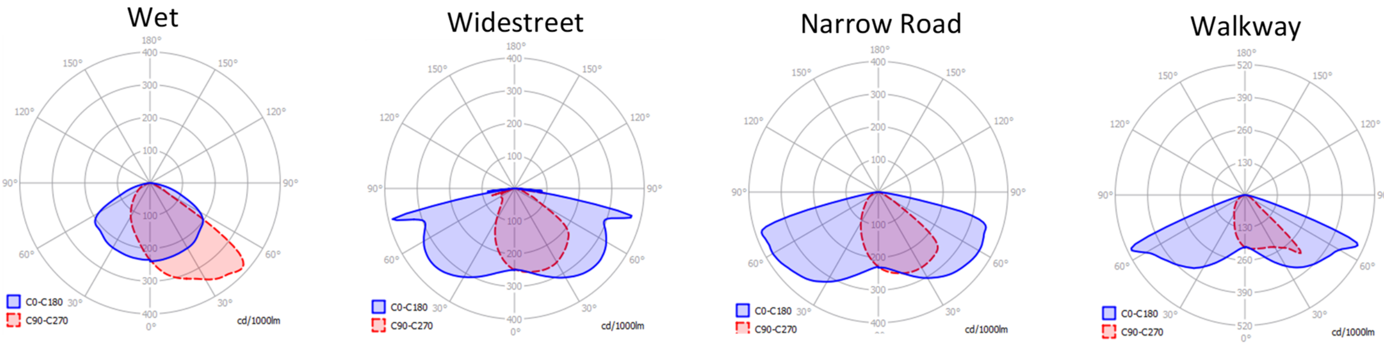


Fig.2.4: Variable light distributions to cater to different surface conditions/ luminance. [Prof. Volker & Steblau, LUX Europa 2017, Ljubljana [26]]

Varying light distributions and directions can be used to highlight important access routes, it can be used in identifying and demarcating roads, pavements, and bicycle tracks. Light of certain characteristics can be used in differentiating between various modes of transport either based on the speed of movement or frequency of use.

For example, a LED luminaire in a historic market square can have 2 different light distribution, providing light for the square and also providing light to the historic facades during the regular shopping hours. As the day progresses the façade component could be dimmed to provide a warm white light and eventually switched off, and at the same time the market could be illuminated with different colour temperature.

Urban lighting for the first time can not only be controlled on a day to day basis but on hourly basis as well. This complete control over the entire properties of the luminaire ranging from lumen output, direction of light, colour of light, luminance distribution etc. offers the possibility to react and respond to the urban landscape and its changing situations.

The variable light distribution is already widely available in interior lighting, allowing tailor made light distribution according to use, user and frequency of use.

Example- UNICO from XAL Leuchten

Fig.2.5: Multiple Light distributions integrated into a single luminaire.

Light Intensity: The way the luminous intensity of reflector lamps and luminaires is distributed is indicated by curves on a graph. These are known as intensity distribution curves (IDCs). The form of

2.2 LIGHTING MANAGEMENT

Lighting management systems provide a considerable energy saving potential in public lighting situations. Each individual light point can be activated and deactivated or dimmed as required. In addition, operating condition, energy consumption and failure information can also be collected and stored.

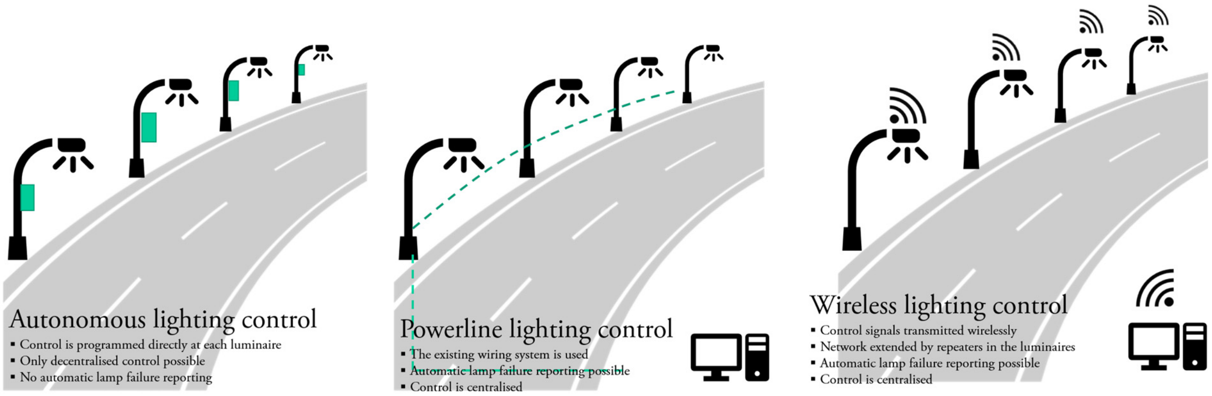


Fig.2.6: A wide range of control options are available for street lighting- autonomous, powerline, or wireless technology.

Individual lights or groups of lights can be digitally switched or dimmed as required to adapt public lighting to meet the actual needs and demands or to type of users, frequency of us, or time of use. Some evident advantages are:

- energy conservation
- lighting level tailored to the situation
- lower greenhouse gas emissions
- more efficient maintenance
- greater safety, damage can be repaired more swiftly.

Control systems for Public Lighting [4]

1. Autonomous lighting control: The simplest variant is autonomous lighting control, where the control unit is integrated in the ballast. With this stand-alone solution, no additional control lines or controllers are necessary. Technically, it works by being fitted with a so-called “astro-clock” programmed with location data. The lighting can then regulate itself autonomously according to the programmed times and lighting level. Depending on the range of features – which varies from one type of luminaire and manufacturer to another – different brightness levels can also be programmed.

The advantage of autonomous lighting control is that no additional components such as control units or control lines are necessary. However, each device needs to be individually programmed. If settings are subsequently changed, each luminaire has to be reprogrammed on site by a specialist. In addition, the system does not provide feedback on failed light sources, etc.

Tele management systems: Unlike autonomous lighting control systems, tele-management systems regulate luminaires from a central control unit. Each luminaire is assigned an address, enabling it to be precisely controlled and monitored. From the central control point, the luminaire controller can be addressed, or its programming changed via the Internet.

In the other direction, information about the lighting installation, e.g. error reports, can be transmitted for analysis. Data is transmitted between control unit and luminaire or electronic ballast in one of two ways – by powerline communication or by wireless communication.

1. Powerline communication: In a powerline lighting control system, signals are transmitted via the existing wiring system. They are picked up by an appropriate receiver, which turns them into an exportable form (e.g. DALI). Control is basically only possible with electronic ballasts (EBs), for which the signals are made accessible by a coupling module. A luminaire controller is also required to issue the control commands. The advantages of powerline solutions are maximum flexibility and reliability.

2. Wireless communication: In contrast to powerline communication, the control signals in a wireless system are not carried by cables but by radio waves. However, the principle is very similar. Here too, a controller is needed to transmit the signals wirelessly to the ballasts. If the ballast does not support the wireless standard, a coupler again needs to be used to translate the wireless signals for the ballast. The couplers also generally serve as repeaters, amplifying the incoming signals, so very remote luminaires can also be controlled.

Data transmission, both by powerline and by wireless technology, is reliable and permits bidirectional communication between controller and luminaire. Reprogramming can be done from a central point. And thanks to a common standard, usage is manufacturer-independent. The technology is fairly complex, however, so installation and programming should be performed by specialist companies.

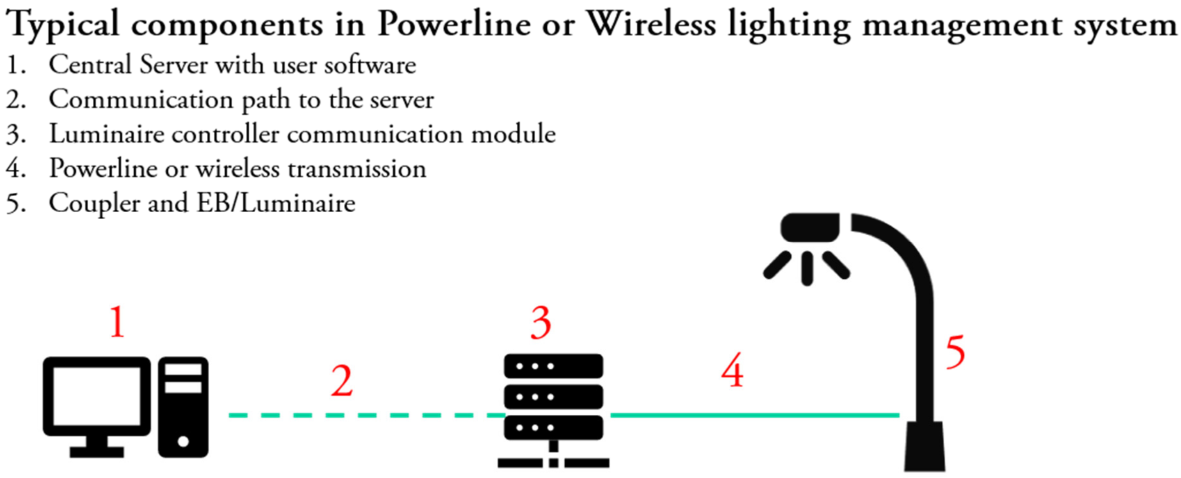


Fig.2.7: Components in a powerline, or wireless technology.

Both systems require the implementation of ICT (Information and Communications Technology) systems of varying degrees of complexity. While they provide additional options or saving energy, they also require additional resources and expertise for implementation and maintenance. Added complexity increases the risks of system failures. Thus, procurers and planners should consider whether expertise and support are available after implementation, even on relatively short notice.

Dynamic control [2]

With dynamic public lighting management, the greatest extent of control is possible. Such a system allows the light points to be controlled individually or in groups and also allows the central control server to collect information on the status (e. g. failures, energy consumption, operating or ambient temperature, ambient light, traffic, and the presence of pedestrians). Changes to the programming can also be done on the central control server instead of requiring changes to the physical hardware.

However, as mentioned above this added flexibility comes with considerable added complexity and thus added costs. The control software must be implemented and maintained, and the local operators in charge of the system must be trained in its use. Furthermore, the added complexity increases the risk of programming failures. The lamps should be installed with fail-safe systems that guarantee basic traffic safety at night even when receiving no or erroneous commands from the control system [2]

State of the art intelligent management systems are generally controlled by a central command centre, which is often a server maintained in the offices of the local authorities. This server monitors a high number of lamps and sends commands which determine the status of the individual lamps. The commands are not received by the lamp control systems directly but first pass through concentrators which then pass on the messages to local area networks consisting of a limited number of lamps and the controlling actuators.

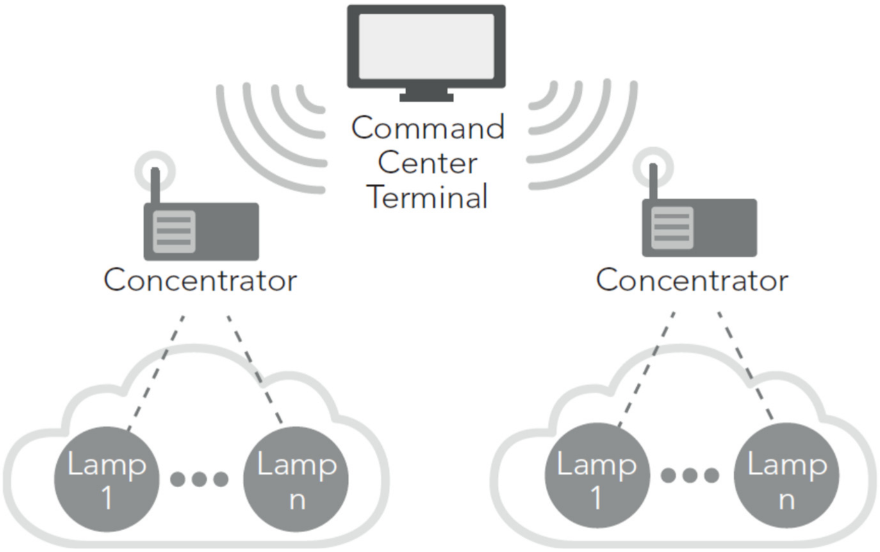


Fig.2.8: A typical control system architecture. [2] adapted from Premier Light Pro

Technological criteria

Two technological concepts are required for deciding on the control system architecture – the communication technology (how the information is transmitted) and the communication protocol (how the information is encoded).

There are two layers of communication in a street lighting system that need to be bridged with communication technology: Command centre to concentrators, and concentrators to individual lamps. They can either transmit information via cable or as wireless signals, and both options have implications for the communication protocols that are available.

Cable-bound communication between the command centre and the concentrators generally uses standard Ethernet communication protocols, which are a well-established technology [5]. While Ethernet cables are theoretically possible between the concentrators and the lamps, this would require additional cabling and thus additional costs. Instead, cable-bound local networks for street lighting generally use power-line communications (PLC), which modulate the signals of their power line in order to exchange information. [5]

Wireless communication between the command centre and the concentrators require that the comparably large distances can be bridged via wireless signals. Suitable protocols include Wi-Fi (802.11), GPRS (General Packet Radio Services) or WiMax.Wireless signals between the concentrators and the individual lamps can be implemented as a mesh, which has the advantage that a lack of line-of-sight doesn't break the connection between individual nodes. If necessary, the signal strength can be boosted via repeaters.

Suitable protocols for this layer include:

- DALI (Digital Addressable Lighting Interface): An IEC-adopted standard that has been developed for controlling ballast circuits used for lighting equipment monitoring. However, it can only control up to 64 nodes.

- ZigBee, a low-cost, low-power, and low-data rate alternative for wireless networks. However, it has

shortcomings in terms of package delays and may cause slowdowns in network performance.

- 6LoWPAN (IPv6 over Low power Wireless Personal Area Networks). This standard does not define a specific routing protocol for a particular system. This allows for more flexibility but requires additional effort defining the protocols used for a particular installation [6].

2.3 CONTROL STRATEGIES

Various strategies at different levels of complexity for public lighting control have been developed over the years, each with its own advantages and disadvantages. Some may even be combined for more complex strategies.

Astronomical timer: Astronomical timers have precise information about sunrise and sunset times for any given geographical position. These can be calculated in advance with a very high level of accuracy for long time spans. However, lighting control strategies based on astronomical timers might not take specific geographic aspects into account, such as large hills or mountains blocking the sun at dawn or dusk. Furthermore, astronomical timers can make no predictions about weather conditions such as storms which might require artificial lighting even during daylight hours.

Astronomical timers might establish a simple on-/off scheme for illumination that specifies the time of activation of the lighting in the evening and the deactivation in the morning. Alternatively, it might specify periods later at night during periods when less traffic is expected during which the lighting remains active but at reduced operating intensity. One of the main advantages of astronomical timers is that they do not require any complex ICT systems to operate. [2]

Daylight harvesting: In contrast to using astronomical timers, daylight harvesting strategies use photo sensors to detect the ambient light and adjust the artificial lighting if the ambient light levels fall or increase beyond certain threshold values. This approach works especially well with dimming and can adjust to extended periods of twilight as well as inclement weather. However, the photo sensors require regular cleaning in order to ensure their proper function. Furthermore, it must be decided whether a single photo sensor is controlling the lighting for a large area or whether each group of lamps or even each individual lamp has its own sensor. The first option reduces the system complexity but cannot reflect all localized conditions (such as especially shaded areas or smaller weather systems) and represents a single point of failure for the system.

Traffic detection: On many roads, traffic may be consistently low, especially late at night. Thus, reducing their level of illumination in compliance with the requirements stipulated in EN 13201 offers potentially large energy savings. In order to ensure that traffic participants can still navigate these roads safely, traffic detection systems can be installed which increase the level of illumination again when needed. The most common technology for detecting traffic – whether motorized vehicles, cyclists, or pedestrians – are motion sensors.

Types of motion detectors include the following:

1. **Ultrasonic motion detectors** detect the shift in sound waves bouncing back from a moving object. This type of sensor does not require line of sight. It is cheap, can detect objects irrespective of their materials, and is little affected by air flows of up to 10 m/s (36 km/h). However, they have a low detection range and can be affected by humidity and high temperatures.

2. **Microwave motion detectors** detect shifts in microwaves bouncing back from a moving object, similar to radar speed guns. They are able to detect even small motions and are not affected by the ambient temperature of objects. However, they are costly and may cause false detection due to movements outside the specified zone.

3. **Infrared sensors detect** the heat of an object or a person relative to their surroundings. They are purely passive sensors – thus, they do not emit sound or radiation in order to collect information. However, they might trigger false detection from warm air, rainfall, or hot objects.

4. **Video processing uses video cameras** as smart sensors, identifying moving objects via smart algorithms. They can monitor a larger area than other detection system and detect not only the motion but also the presence of objects. They also have a low probability of false responses. However, the data processing algorithms are fairly complex, resulting in both added cost for the software as well as added electricity consumption due to their processing power requirements. Furthermore, they are dependent on light, though this can be compensated with infrared filters to some degree.

Chapter – 3: Dynamic Light and Energy efficiency

3.1 INFLUENCE OF DIFFERENT DIMMING STRATEGIES ON ENERGY CONSUMPTION/ EFFICIENCY

3.1.1. General operation times of public lighting systems

Public lighting systems are used to ensure traffic safety in closed periods in dark areas. Here, the lighting is used depending on the illuminated traffic zone,

- to avoid traffic accidents
- to enable facial recognition
- increase the attractiveness of areas, buildings or monuments or
- to differentiate special areas or traffic zones.

The height of the lighting level and the operating times as well as the lighting times are determined in particular by the dark times that change over the year. The switch-on and switch-off times of lighting systems are thereby are dependent on thresholds of the natural lighting level, which are determined via simple receivers (twilight sensors). The evening switch-on thresholds usually are determined by values of 20 - 40 lx. Morning turn-off thresholds are usually lower because the dark-adapted human eye can detect objects and persons even at these lower levels of illuminance.

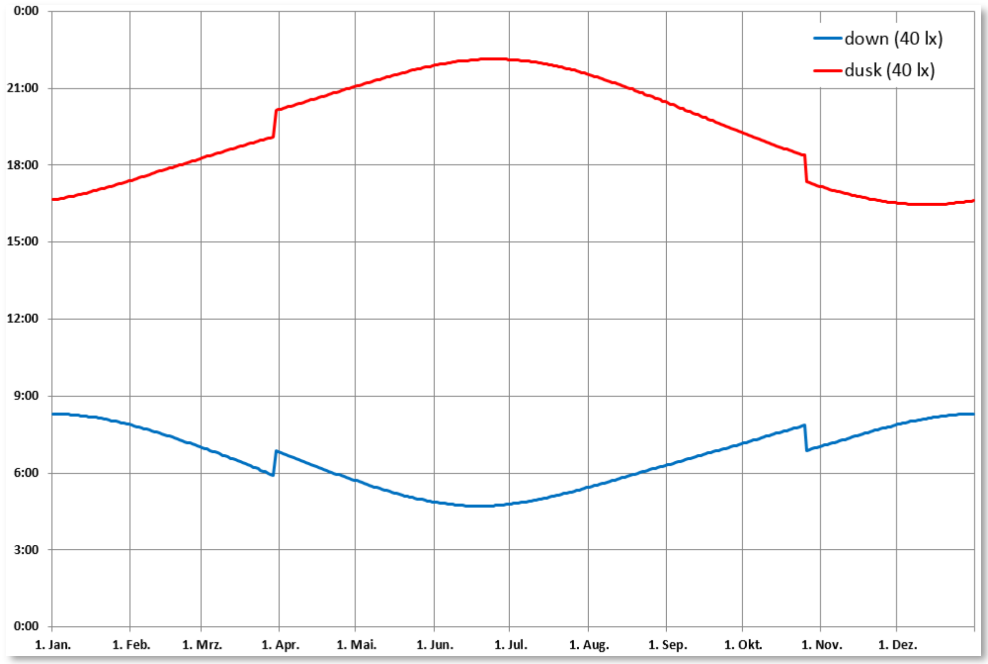


Figure 3.1: Regime of switch on and switch of times of street lighting systems

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For energy saving reasons, complete shutdowns of public lighting systems are common in periods of very low-traffic. In order to save energy exists also the strategy of switching off individual points of light (e.g. every second light point) in times of low traffic density. However, these two practices are highly controversial from a normative and photometric point of view.

The operating hours of street lighting systems in Germany are between 4,000 - 4,200 h (see below figure 1). In the months April to September only one third of the total annual lighting period is incurred. Two thirds of the lighting times are in the remaining times between October and February. Figure 2 shows the monthly average lighting times for street lighting systems in a German city.

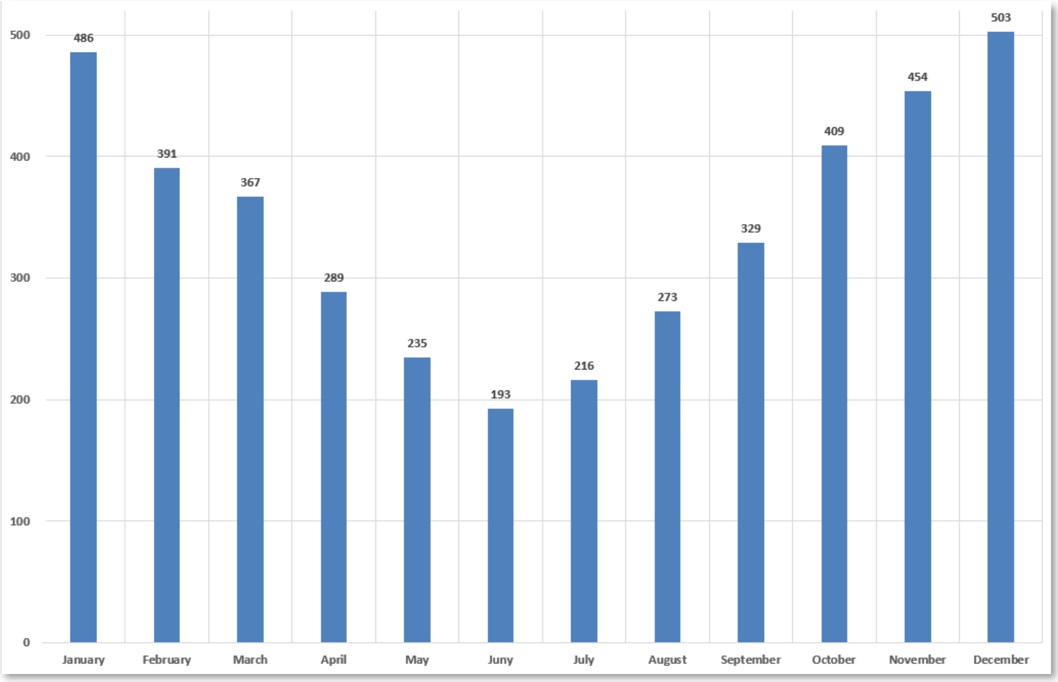


Figure 3.2: Monthly operation durations of public lighting systems in Germany

The energy efficiency of technical systems is defined as magnitude of energy consumption reduction to fulfill a task. The main influencing factors here are the effectiveness of the system for converting the energy used as well as the temporal optimization of the technical processes in order to achieve the result.

3.1.2. Dimming strategies

In respect of energy consumption is essential when over the day the dimming or energy reduced operation of lighting systems starts. Generally, the most of traffic participants are expected between 5 – 9 h and 15 - 20 h. Typical traffic volumes for the Schönfließer Straße in Glienicke/ Nordbahn are shown at the following figure.

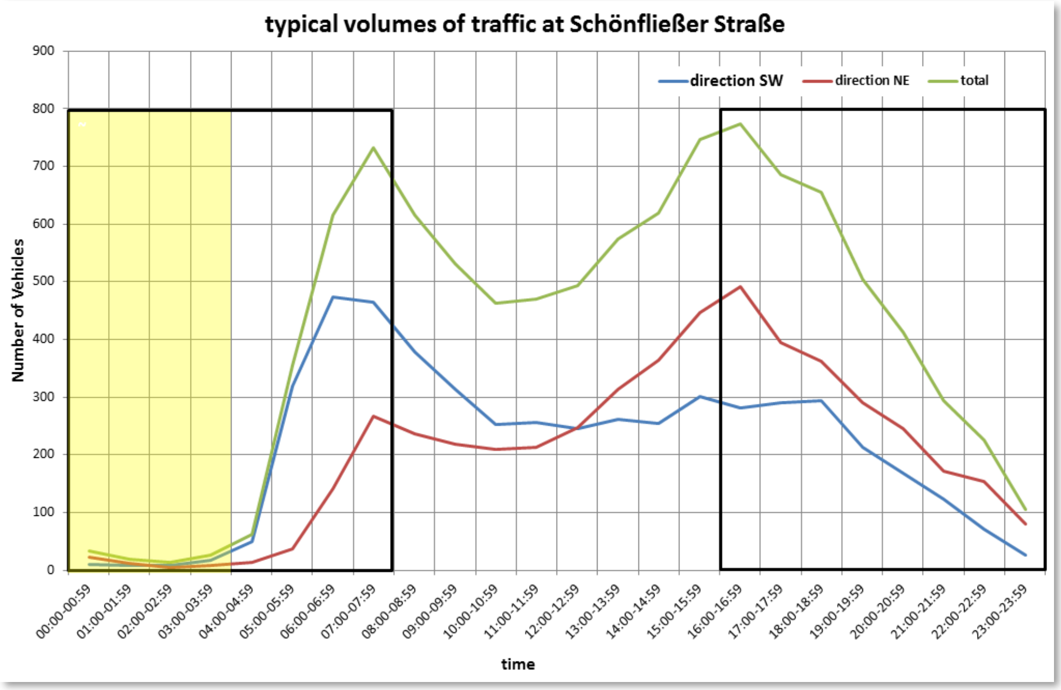


Figure 3.3: Typical traffic volumes at the Schönfließer Straße in Glienicke/ Nordbahn

Energy reductions (dimming) by street lighting systems generally start between 20 - 22 h in the evening and end between 5 – 7 h in the morning. For this cases are the durations of full energy level operation diagrammed on the figure 4 and figure 5.

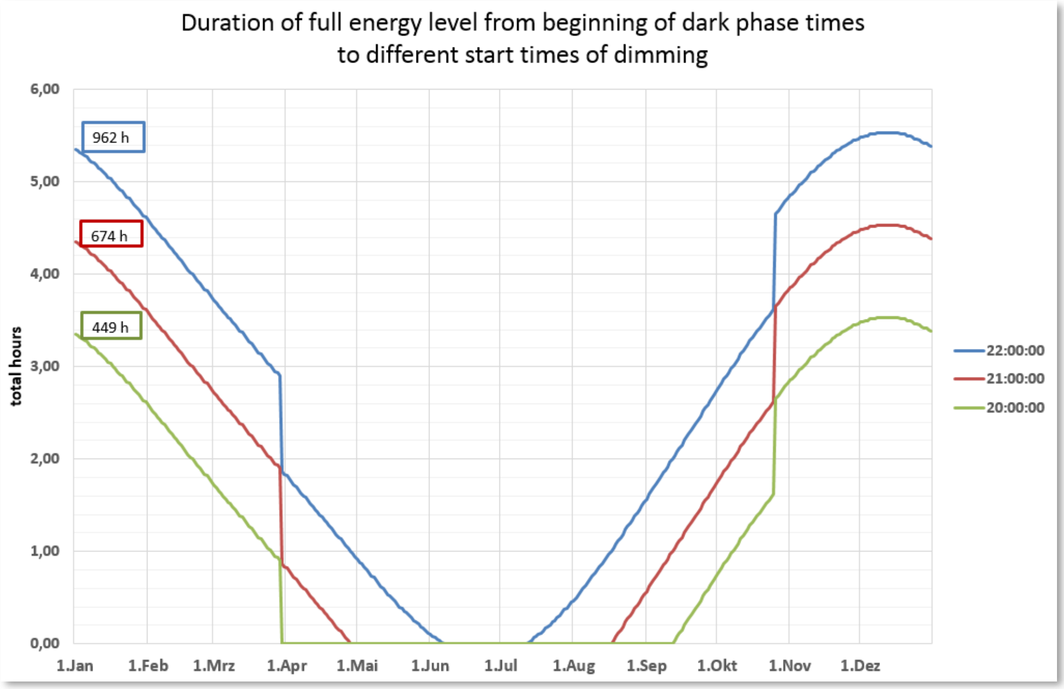


Figure 3.4: Duration of full level energy state by different start times of dimming

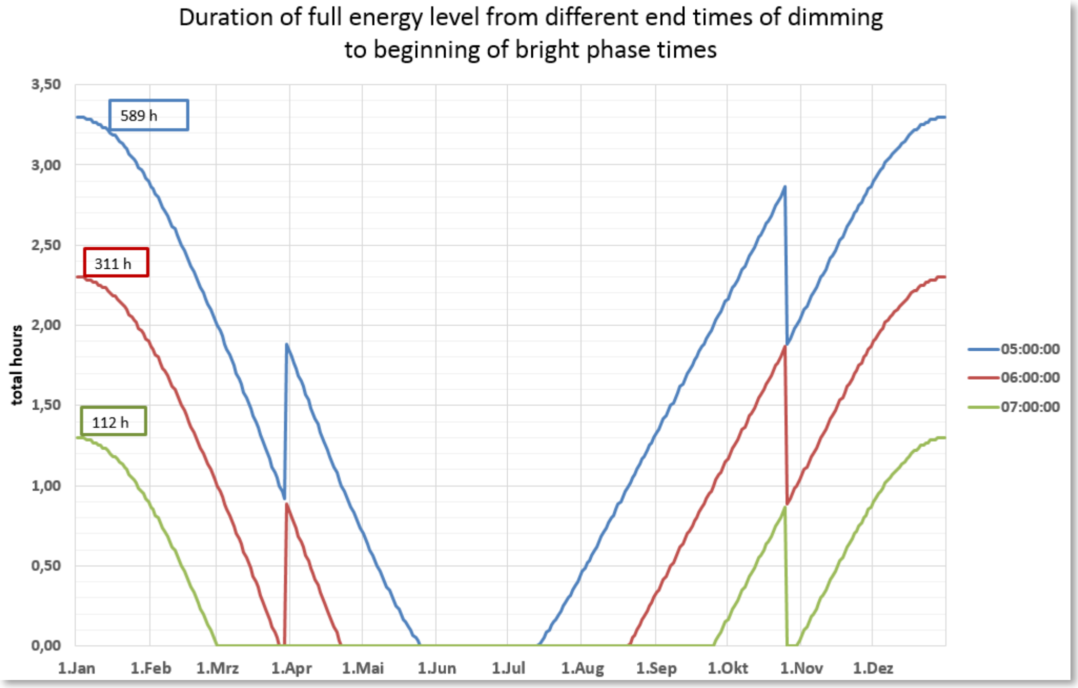


Figure 3.5: Duration of full level energy state by different end times of dimming

Based on this data for Berlin for a switch on and switch off illuminance level by 40 lx is possible to determine following reduced (dimmed) and full level operation durations.

Table 1: Durations of **full level** operation by different start and end times of dimming

	20:00 h	21:00 h	22:00
05:00	3.062	2.837	2.549
06:00	3.340	3.115	2.827
07:00	3.539	3.314	3.026

Table 1: Durations of **reduced (dimmed) level** operation by different start and end times of dimming

	20:00 h	21:00 h	22:00
05:00	1.038	1.263	1.551
06:00	760	985	1.273
07:00	561	786	1.074

For a **dim level of 50 %** it is possible to calculate following **energy saves** for these start end times of dimming without changing the existing light sources:

	20:00 h	21:00 h	22:00
05:00	37,3 %	34,6 %	31,1 %
06:00	40,7 %	38,0 %	34,5 %
07:00	43,2 %	40,4 %	36,9 %

3.2 INFLUENCE OF VARIOUS ELECTRICAL EQUIPMENT INCLUDING LEDS AND THEIR EFFECTS ON ENERGY CONSUMPTION.

3.2.1 Energy efficiency and dimming and power reductions of conventional light sources

In conventional street lighting with primarily gas discharge lamps as light sources, the efficiency of the system is determined by the type of lamp and the luminaire materials used as well as the adaptation of the light output characteristics to the lighting task. The amount of the light (light intensity distributions) used to illuminate the visual tasks as well as the light output ratio of the luminaires form the essential parameters for the efficiency of lighting systems. Thus, the energy losses by generating of visible light (UV and IR components), the losses of ballasts and optical losses through filters and reflectors are essentially seen as system losses.

Conventional light sources permit only a limited use in dynamic control systems, because the lifetime and the technical characteristics of the gas discharge lamps are adversely influenced thereby. In addition, in the case of reduced power operation (dimming) of gas discharge lamps, the lamp efficacy is reduced compared to the full power operation. The losses of the impedances, which are mandatory used for the current limitation of the gas discharge, remain virtually at the same level like in non-dimming mode.

Light sources based on gas discharge also require up to 30 minutes to achieve their full luminous flux. This is especially given for fluorescent and compact fluorescent lamps. A re-ignition of the metal halide lamps after short supply voltage interruption is only possible with voltages of more than 10 kV or after a cooling pause of approx. 3 - 10 min. Special sockets for high ignition impulses are necessary for this purpose.

About the above reasons, the conventional street lighting systems limit solutions to increase efficiency based on free adopting the light level to user's needs. Therefore, energy saving potentials are exploited by switching off lamps in multi-lamp systems or every second light point. In single-lamp systems, especially in the case of high-pressure sodium lamps, which are still the most frequently used lamp types in street lighting, impedance transformers are usually used to achieve an increase in efficiency at times with low traffic intensity. In this case, the following fixed power reduction steps can be realized:

Lamp type	full power of system [W]	reduced power of system [W]	rel. reduction [%]
HPS 50 W	61	41	32,8 %
HPS 70 W	88	58	34,1 %
HPS 100 W	123	84	31,7 %
HPS 150 W	181	97	46,4 %
HPS 250 W	285	133	53,3 %
HPS 250 W	280	125	55,4 %
HPS 400 W	429	215	49,9 %

Also, the using of electronic ballasts allows to dim the power and light output of conventional light sources. In this case a physical limit of 40 % of full power is given. Underneath of this level the plasma in some gas discharge lamps (HIT) is not stable. The dimming with electronical ballasts carries not a proportional saving to the power reduction ratio.

The following figure illustrates the dependency of the dim level and the luminous flux of different conventional and led light sources.

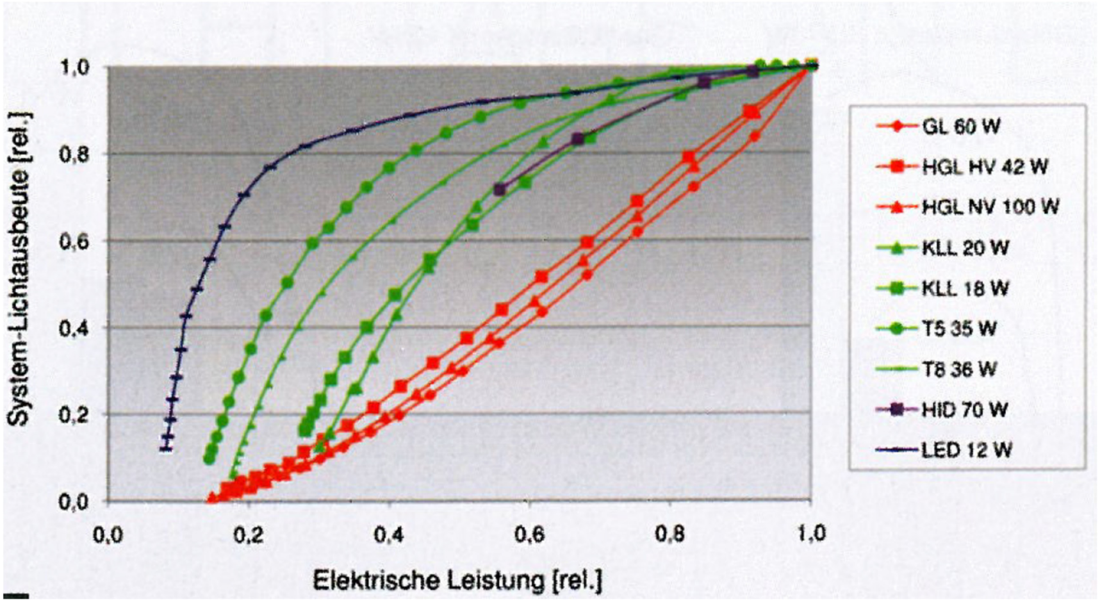


Figure 3.6: Correlation between relative electrical power and rel. light output (luminous flux) of different light sources [1]

3.2.2 Energy efficiency and dimming of LEDs

In consequence of technical developments at the field of LEDs and their use in public lighting systems following advantages concerning energy efficiency are achieved:

- increase of energy efficiency of led lamps
- decrease of system loses of luminaires (decrease of visible light ratio, increase of ballast loses)
- possibilities of continuously power adjustment
- no loses of light output efficiency by dimming
- further possibilities for optimizing the light distributions
- possibilities of power reduction independent of electrical networks (stand-alone-solutions for dimming)

Compared to the power reduction of conventional lamps the dimming of led lamps exists a **linearity between the power reduction and decrease of luminous flux**. Also does **not exist a natural limit of the reduction of dim level**. Furthermore, a benefit in extension of the life time is given by dimming of LEDs, because the operation of LEDs with low currents reduces the junction temperature. Also **minimizes the power reduced operation of LEDs the temperature depended stresses of optical components** (led board and reflectors).

A further benefit by dimming of led light sources the **relatively low loses of the used electronical ballasts** and drivers compared to the electrical ballast used by conventional lighting systems. Also, a **stepless dimming of LEDs** is possible. Merely manufacturers of led luminaires limit the led current by 100 mA. An important feature of led luminaires are the standard accessories of the communication between several luminaires and extern components.

In summary the use of led light sources establishes more opportunities and is a basis to build smart lighting systems.

[1]: Proceedings of the Congress 19. Lichttechnische Gemeinschaftstagung LICHT 2010, Chr. Kaase

3.3 ENERGY MANAGEMENT AND MONITORING

The principle of energy management lies in the systematic and long-term implementation of a low investment set of measures with the aim of progressively achieving significant energy savings, next to savings on operating costs and improvement of workload management.

The operating costs of a public lighting system are roughly the same across Europe (specifically 50% on electricity and 50% on service and maintenance). Costs associated purely with payment for the electricity consumption for public lighting system (PLS) often add up to more than 10% out of the overall electricity consumption costs for the entire city estate. The importance of monitoring the PLS is thus undoubtful.

From the point of view of applicability of the energy management in the public lighting system, other parameters need to be monitored in addition to energy consumption. From public lighting passport, which is ideally on-line and paired with the data acquisition system, stem the technical data for individual luminaires and light sources. To optimize operating costs, it is advisable to know at least the date of installation or replacement of the source, and the time of operation of the individual light sources.

Monitoring can form part of an established management system which allows for monitoring and evaluation of the key parameters of public lighting system (electricity consumption) for the entire system, for individual branches and even for individual luminaires.

3.3.1 Benefits of remote monitoring and control system. (Municipality and users)

Monitoring without analysis is just as useless as analysis without monitoring. This is a simple answer to the question, whether the data from the annual billing of energy consumption suffice for the evaluation and execution of energy management, as well as, the reaction to the second extreme, where attempts are being made to fit buildings/ public lighting systems with as many meters and sensors as possible.

A very common question from the field is, when it is worth to install remote automated readings and when the use of manual readings is preferable, and at what frequency.

For most of the energy management outputs, monthly or weekly manual readings are entirely sufficient. This solution is proven and in line with the principles of proper management. For the purposes of data management and detailed evaluation, however, data need to be more detailed, at least based on hourly readings. In case of public lighting there are other factors that come to consideration and speak in favor of automatic remote monitoring, those are, the time-consuming manual monitoring on all PL switchboards or the possibility of comparing the switchboards to each other.

The reasons behind the installation of the remote monitoring system need to be carefully considered not only due to the acquisition costs associated, but in the long run, primarily due to the operating costs of the system. At the same time, it is necessary to consider what potential benefits can be expected and, on which parts of the PLS would operation of such a system pay off. The key task lays in the organization of a complete data monitoring and evaluation concept (which should form part of a coherent PL concept and PL strategic plan).

This concept should answer to the following questions:

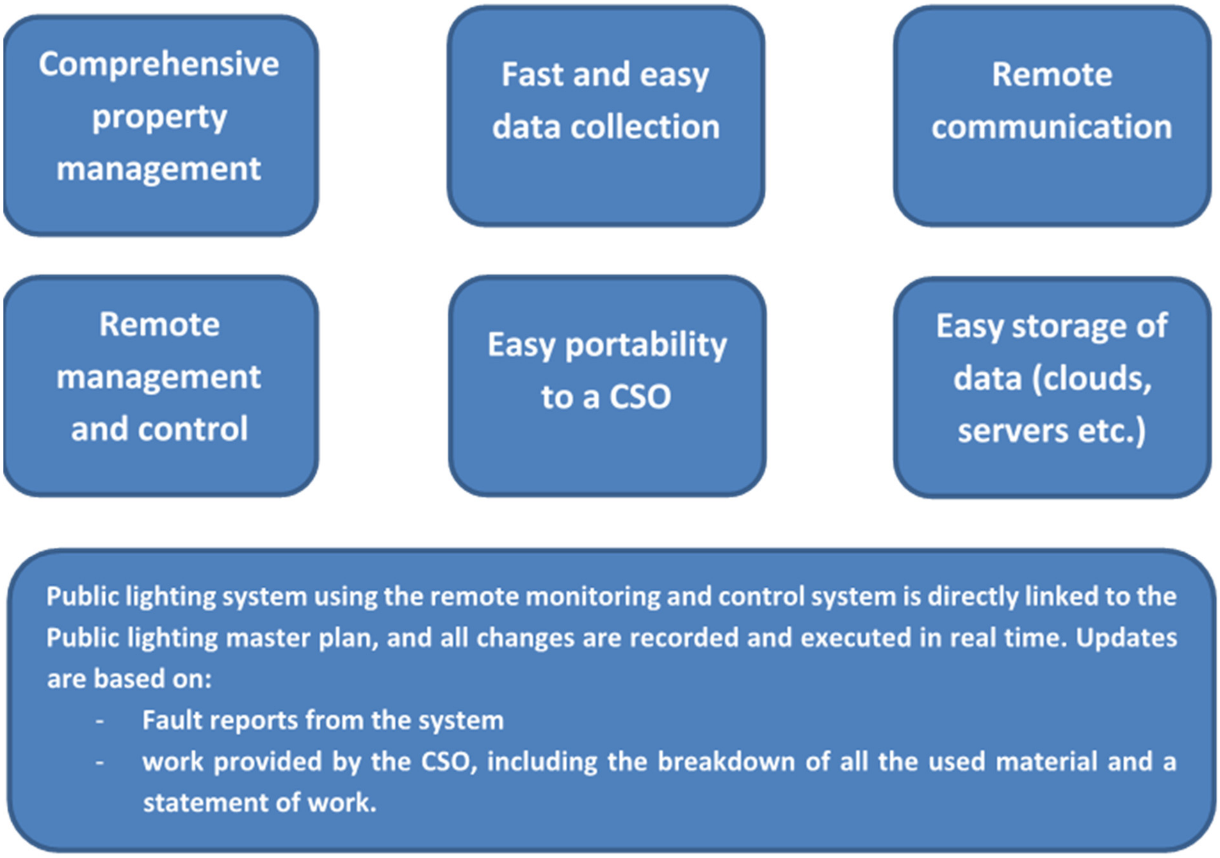
- Why is the system being installed?
- What is expected from the introduction of the system?
- Will there be remote readings set up on all meters?
- Will the installation be done in one go or gradually? And in what time horizon, or rather, following what schedule?
- Who will be responsible for the entire system, for the management, maintenance and finally, for data use and connected evaluation of the effect of the remote reading system?
- What will be the total acquisition and operating costs?

3.3.2 Benefits of remote monitoring

Remote public lighting system monitoring allows for remote management and control via virtual dispatching, while the entire management can be easily transferred to a commercial service organization.

Data collection along with evaluation and subsequent management is most often ensured by service organization's data servers or cloud repositories. The owner of the public lighting is thus left without the worries and expenses related to the operation of the municipal PL dispatching center.

Figure 1: Benefits of remote monitoring



Comprehensive property management

Fast and easy data collection

Remote communication

Remote management and control

Easy portability to a CSO

Easy storage of data (clouds, servers etc.)

Public lighting system using the remote monitoring and control system is directly linked to the Public lighting master plan, and all changes are recorded and executed in real time. Updates are based on:

- Fault reports from the system
- work provided by the CSO, including the breakdown of all the used material and a statement of work.

In addition to gathering the information, smart PL allows for remote communication and control of individual elements via mobile networks or Internet. The whole message can also be easily transferred to a commercial service organization (CSO). Data collection and subsequent management can be ensured by data servers of the service organization or by cloud storage. The owner of the public lighting ceases to be concerned about the costs and expenses associated with the operation/ management of the PL dispatching center in the municipality.

Another advantage of the remote monitoring is in regular evaluation of electricity consumption of public lighting based on remote readings from individual switchboards in defined time periods. Based on the evaluation of the results, acceptable limits of inputs to the lighting system are determined, and the system is maintained within these limits (this leads to elimination of any undesired values). The difference between the planned consumption and the metered one may derive from the following causes:

- Higher losses in the power grid - higher voltage drops at long connectors from the switchboard.
- Increase in power losses due to increased transient resistance in a pole terminal block, etc.
- The power consumption of the luminaire may change during operation if it is equipped with constant light output (CLO) technology.
- Remote reading of consumed electricity may not be performed in real time. e.g. if performed for 1-hour period, PL activation and deactivation is detected within the hourly time lap. The exact time of operation is unknown, and the runtime period is longer compared to the reality.
- The power consumption measured for a particular public light switchboard varies in case of faults on the power lines where the light sources temporarily (sometimes permanently) switch between the switchboard or the backup power supply. This can change the number of light sources connected to the given switchboard during operation.

The main disadvantage of the remote monitoring system is its initial cost, consisting of the cost of the technology, the assembly and commissioning, of which the cost of assembly and commissioning of the system may come up to more than 50% of the total acquisition costs. With technology advances these costs won’t represent the major part and therefore will no longer be an obstacle in changing to an automated consumption monitoring.

A key parameter for sustainability of the monitoring system will always be the operating costs. If long-term operation of the system is being considered, special attention needs to be paid to these costs. Different technology solutions represent different operating costs and the most appropriate solution needs to be considered in each situation based on the number and location of switchboards that fall within the remote monitoring system, and surrounding conditions such as any existing developed areas, the presence of high-rise points, the terrain, or available signal coverage.

3.3.3 Remote monitoring and control systems

The PLS surveillance system with remote monitoring elements allows for high-level management, which may include, in addition to the PL, further municipal assets such as architectonic luminaires and festive lighting, city information and camera systems, traffic light control, parking lot vacancy information updates and surveillance etc.

Public lighting has an immense unused potential not only from the economical point of view but from technical point of view as well. Large invoices for energy consumption and outdated technologies (luminaires) are the two main reasons why a municipality decides to start modernization process or reconstruction of the PLS. The decision to start the process should, however, be based on more holistic approach, such as the importance to use available tools and software with which public lighting can be monitored, analyzed and controlled. Different approaches can be used:

- Implementing and frequently updating GIS database of lighting infrastructure,
- Implementing smart metering systems,
- Implementing control and management systems (Smart City solutions).

3.3.4 Implementing and frequently updating GIS database of lighting infrastructure

GIS database provides simple overview of current state of public lighting. This concept uses data about public lighting infrastructure and software which is used for different types of analyses and for monitoring of current state of public lighting. Data are collected through a field survey, while software is used as a platform for user friendly access to the data.

GIS database for public lighting covers elements of a lighting infrastructure (substations, control boxes, lighting poles, luminaires etc.) and power supply routes in space. Additionally, in GIS database following parameters can be included:

- GPS coordinates of poles (luminaires),
- Type of poles (wood, concrete, steel),
- Pole height (luminaires),
- Type of the installed luminaire with all technical data (manufacturer, type and number of light sources per luminaire, number of luminaires, installed power per source, luminaire...),
- Reconstruction (date, company, cost of work…),
- Style, type of management of public lighting,
- Regimes of work (time when ON/OFF),
- Tariff model and electricity prices,
- Invoices for energy consumption,
- Cable routes (underground, above ground),
- Type of cables (manufacturer, cross section…),
- The number of substation output lines.

3.3.5 Implementing smart metering systems

A smart metering system consists of a hardware which is connected through different communication technologies with a software. A hardware are meters which are measuring energy consumption, while a software is used as a tool for different analyses and monitoring the energy consumption.

Different concepts of smart metering systems in public lighting can be implemented:

a) A Concept where smart meters are installed and placed on the power lines from substations or control boxes. By using this concept, the general energy consumption can be measured for all loads on the power line. Energy consumption of each luminaire is then calculated according to the parameters of each individual lamp.

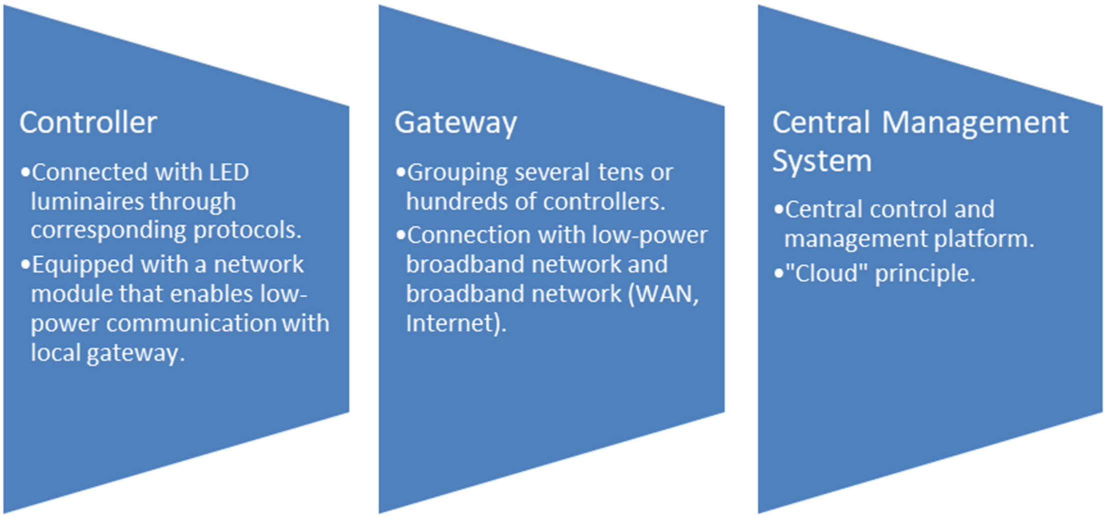
b) A Concept where smart meters are installed inside of a luminaire. In such case energy consumption of each individual luminaire can be measured more precisely/ with precision. This kind of a concept is usually used as part of a Smart City solution.

Implementing control and management systems

A Control and management system for public lightning consist of two main components: a hardware infrastructure and a software platform. Both components are communicating with each other through different communication technologies, standards and protocols. The system is based on modular upgrade of each luminaire (luminaire controller) which then enables remote regulation of light intensity.

Depending on number of elements (luminaires) that need to be connected and the type of communication between elements (luminaires) and Central Management System, two different concepts of system can be implemented:

a) One, where the hardware components consist of luminaire controllers and local gateways. Luminaire controllers communicate with local gateways. Basic role of local gateways is to group several luminaire controllers and communicate with Central Management System platform. Communication between luminaire controllers and gateways is based on one of the Low Power Wide Area Network (LP-WAN) technologies whose primary specialty is being low-energy and using optimal bandwidth. Communication between gateways and Central Management System is based on either local wideband wireless or on wired network by the common Internet protocols.



Controller

- Connected with LED luminaires through corresponding protocols.
- Equipped with a network module that enables low-power communication with local gateway.

Gateway

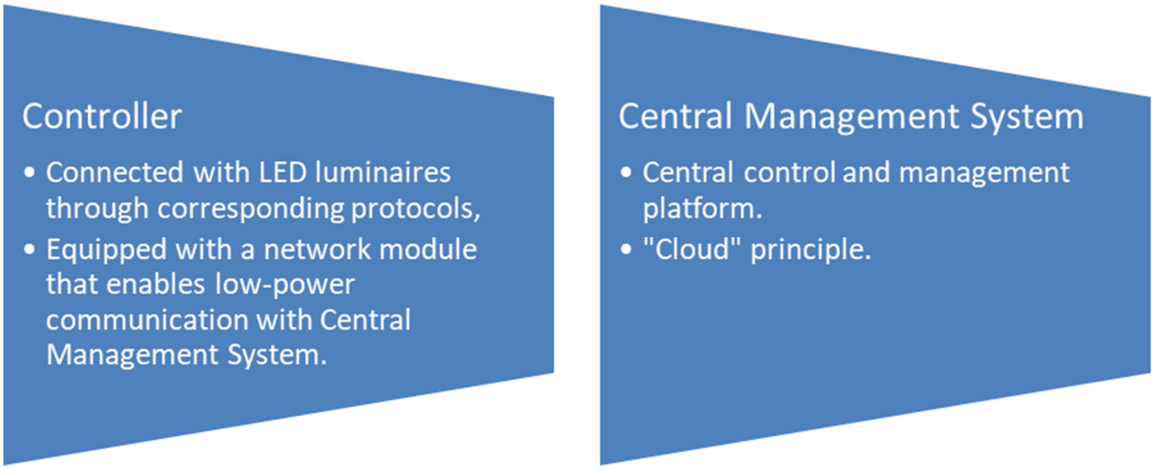
- Grouping several tens or hundreds of controllers.
- Connection with low-power broadband network and broadband network (WAN, Internet).

Central Management System

- Central control and management platform.
- "Cloud" principle.

Image 1. *Concept using gateway*

b) Two, a concept which uses only luminaire controllers ashardware components. Luminaire controllers are directly communicating with Central Management System through Internet and corresponding protocols. Gateways are not needed in this concept.



Controller

- Connected with LED luminaires through corresponding protocols,
- Equipped with a network module that enables low-power communication with Central Management System.

Central Management System

- Central control and management platform.
- "Cloud" principle.

Image 2. *Concept without gateway*

Control and management system of public lighting provides easy quality control and management and analysis of public lighting parameters. This kind of system can be implemented as a part of Smart City solution or as a separate solution.

Types of communication

Most systems for remote metering, monitoring, and energy data management are a combination of a basic hardware, a data transmission and a data processing and visualization software.

There are large quantities of technical devices for measuring consumption on the market. For the actual remote data transmission, however, the Internet is used in majority of the cases, with exception of the HDO type or of protected data which are transmitted in other ways. Before the data gets on internet, or its interface, their transmission can be secured by cable or wirelessly by radio transmission using GSM or wi-fi.

What is the most appropriate kind of system in this case always depends on the marginal conditions and above all, on the requirements that the user has for the system, see the data monitoring concept above.

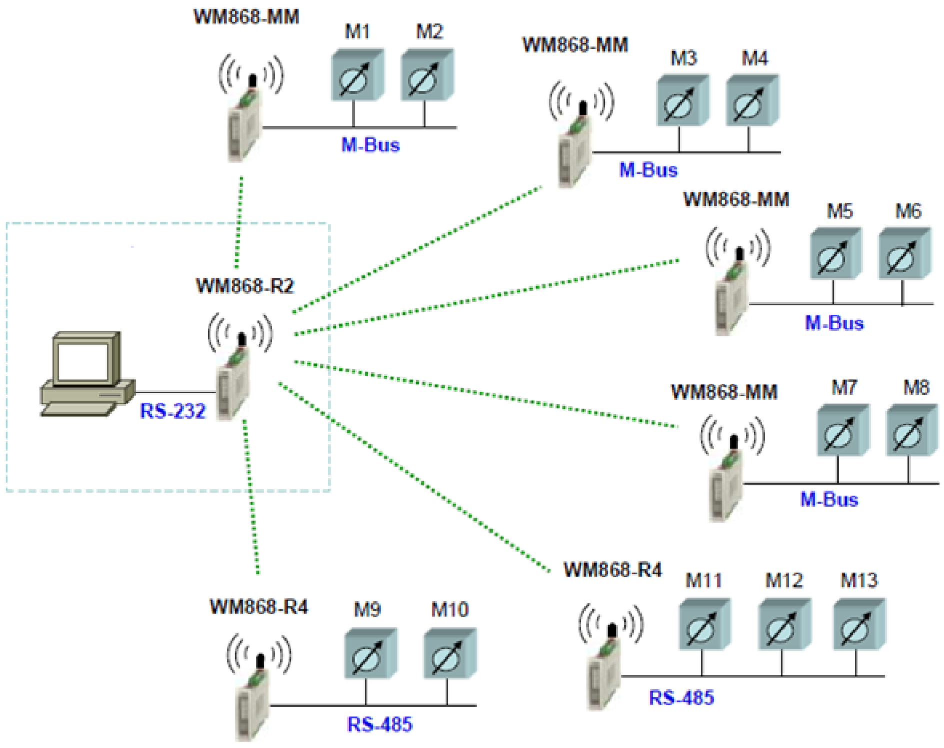
Below are described 3 basic communication systems using i) a radio network, ii) GSM communication, iii) IoT

Radio network

The advantage of our own radio network is the independence from external suppliers, however a good network maintenance service contract is necessary. The advantage is also in simple installation (as in case of IoT use), or likewise the radio systems which can be combined with both other solutions - IoT and GSM.

One of the systems for transmission of measured data, and potentially of the controlling devices is a WACO system (Wireless Automatic Collector). This radio technology for remote meter readings works within the free band of 868 MHz, or possibly of 169 MHz. With WACO modules, all M-BUS, RS-485, or indoor and outdoor pulses can be read.

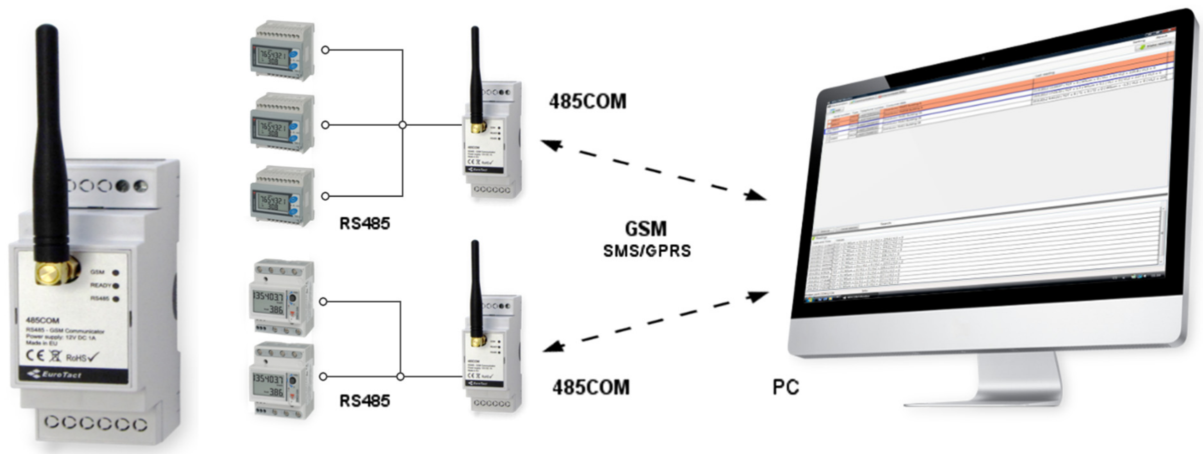
Figure 1: Ideové Illustrative WACO Infrastructure Scheme (radio system used by SOFTLINK); Note, m-bus is the communication protocol of certain HW devices, i.e. it is an internal HW quality.



GSM communication

One of the systems for transmission of measured data and potentially of the controlling devices, is a radio-based transmission system. This radio technology for remote meter readings works in the free band of 868 MHz or 169 MHz. With help of gateway and communication modules, all M-BUS, RS-485, or indoor and outdoor pulses can be read on the same basis.

Figure 2: Illustrative photo of GSM communicator for remote data reading (source: http://eurotact.com/)

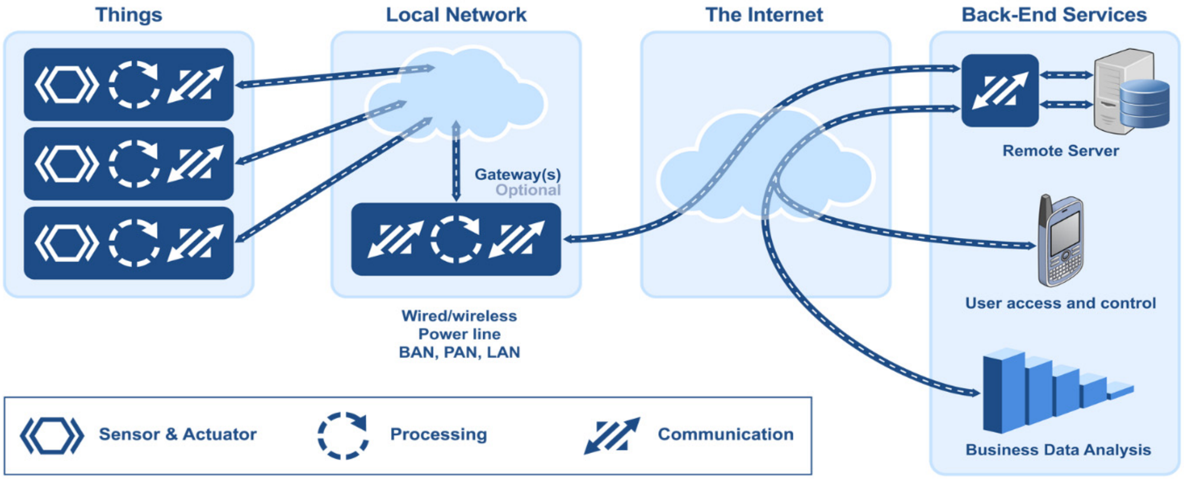


The advantage of GSM solutions is high reliability and availability – of the components, signal coverage, etc. The operator charges (data tariff) and relatively higher acquisition cost (more devices) can become a disadvantage.

Smart networks, Internet of Things

The so-called smart networks are also based on radio data transmission; in the energy sector, data may be specifically transmitted over power lines, however this method is not generally usable. A common standard "guideline" for data transmission should be the so-called Internet of Things (IoT). Several competing concepts are being developed in the Czech Republic, especially the LORA and SigfOx networks. The necessary basis for any communication is also the 868 MHz band. With regards to the availability of multiple networks, it is possible that service prices (licenses), will become acceptable also for a wider use of sensors and other devices within the field of energy management.

Figure 3: Illustrative scheme for Securing Communication via the Internet of Things (zdroj: https://www.micrium.com/iot/devices/)



Critical usage criteria will be both, signal coverage and strength, as well as license fees for network connections. Terminal devices (sensors, meters, counters) and other related technical facilities are already available or will be available on the market in sufficient variety and at a reasonable cost, considering their current technological accessibility. Operating costs will thus play a key role in terms of ensuring the long-term functionality, service conditions, etc.

Generally speaking, developing IoT brings wide range of possibilities and opportunities, yet it always depends on a set goal and on a defined purpose. In addition to the monitoring of energy and water consumption, IoT allows for an easy access to the meteorological data, to the indoor environment quality data, and the data about interconnection with building security systems, etc.

All the stated communication models simultaneously allow for additional monitoring of other variables directly related to energy management, such as, environmental parameters that may have influence on dynamic lighting control for example: precipitation, humidity and temperature.

3.3.6 Examples of the implementation of control and management systems

Worldwide suppliers of smart solutions deliver comprehensive SmartLighting systems, including the remote monitoring and software for dynamic control of public lighting. The delivery covers a full range of infrastructure, from luminaires to control software, with data collection, storage and evaluation services, that are made available to the owner or the administrator in a cloud storage. These are mostly closed systems including data storage and management - that is, the owner of the lighting system usually has no access to the raw data.

When running DynamicLight on an open platform basis, the city must ensure IT support for data collection, management and evaluation. The necessary services to ensure SmartLighting traffic management can be purchased from different providers.

The world's leading manufacturers of lighting and control systems (Osram, Philips, Schreder, iGuzzini, Thorn, Siemens, ABB, Tridonic ...) offer comprehensive solutions for the SmartLighting application area, ready to be incorporated into the SmartCity concept.

Philips City Touch

Philips City Touch is a secure, connected lighting management platform that provides full visibility and control of city’s street lighting from a centralized dashboard, allowing to securely monitor light points, set schedules and adjust light levels on demand. The system has web application which provides a complete view of connected street lights, enabling to manage workflows and deploy maintenance crews only when and where needed. System data gives real-time insights into energy use and cost.

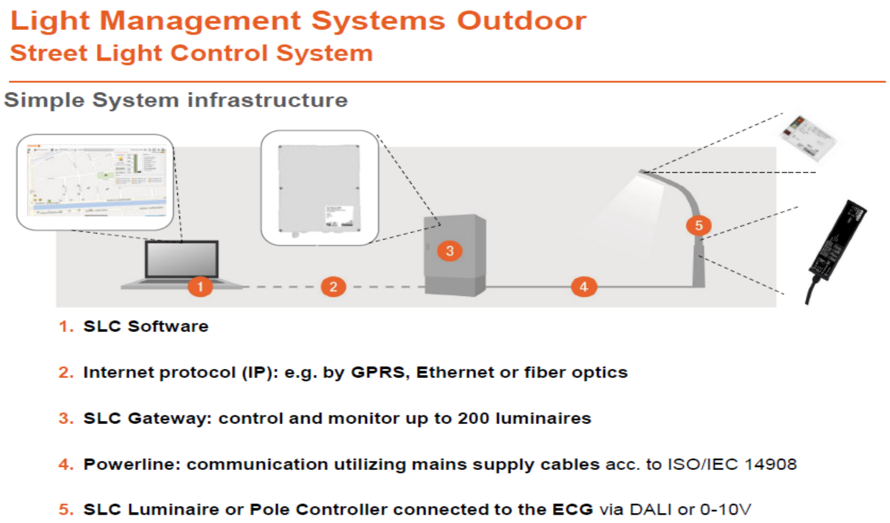
Schreder Owlet

Schreder Owlet is an autonomous Network Dimming system which enables luminaires to communicate together in a wireless network to provide dynamic profile dimming. This system can be enhanced with motion detection sensors.

When motion is detected, the detection scenario supplants the dimming scenario to provide safety and comfort for users. The sensors can be centralized or decentralized. Each luminaire is fitted with a control unit and can be managed independently. It is a remote-control system for monitoring, metering and managing a lighting network. It is a unique combination of state-of-the-art technology and an easy-to-use web interface. It can control each luminaire at any given time, from anywhere in the world. Based on Open Standards, it can interact with larger smart city platforms to exchange data or interoperate with neighboring systems.

iGuzzini Light management systems

Through this system it is possible to control either each lamp, or groups of lamps, and modulate the light intensity to adapt it moment by moment as needed. OSRAM SLC is a hybrid, open and standard light management system using a wireless mesh network based on the ZigBee standard and DALI (digital addressable lighting interface) technologies to manage any building size or type. The Street Light Control software is the central interface, where all the information is gathered and made available to the user. The entire system is represented clearly and can thus be easily controlled, administered and analyzed simply from a central location.

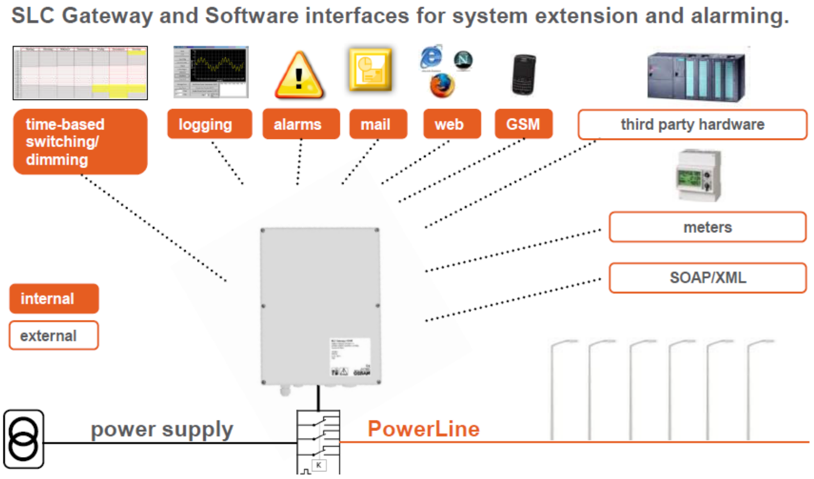


Light Management Systems Outdoor
Street Light Control System

Simple System infrastructure

1. **SLC Software**
2. **Internet protocol (IP): e.g. by GPRS, Ethernet or fiber optics**
3. **SLC Gateway: control and monitor up to 200 luminaires**
4. **Powerline: communication utilizing mains supply cables** acc. to ISO/IEC 14908
5. **SLC Luminaire or Pole Controller connected to the ECG** via DALI or 0-10V

Figure 4 Osram SLC System [OSRAM – Street Light Control – Innovative light-control brochure]



SLC Gateway and Software interfaces for system extension and alarming.

Figure 5 Extension of the light control system [OSRAM – Street Light Control – Innovative light-control brochure]

GE LightGrid

In the GE LightGrid., the lighting data for every fixture is accessible through a Web-based interface that can be hosted remotely. Protected by a high level of security encryption, our central management server offers secure login for all users. Municipalities can implement smarter energy-saving strategies through more precise on/off and dimming schedules, particularly during a middle-of-the-night operation in low-traffic areas.

Figure 6 LightGrid creates the wireless mesh network that puts complete control [GE-LightGrid-Wireless-Lighting-Control-Systems-Brochure]

3.3.7 Monitoring parameters useful for proper and efficient operation of public lighting

Monitoring of the parameters and possession of the information on public lighting infrastructure is crucial to create different types of analysis and to become familiar with lighting system behavior. Based on system behavior and different types of analysis, it's possible to detect good and bad features of the system, based –on which, the final decision for modernization and reconstruction of public lighting could be made. Different types of analysis can be made given the following parameters:

a) GPS coordinates of substations and control boxes,

b) Power supply installation route (from substations or control boxes to poles or luminaires),

c) Type of power supply installation,

d) Date and time of the first power supply laying/ installation,

e) Detailed list of interventions (repairs or replacement of installation),

f) GPS coordinates of poles and luminaires,

g) Type and height of poles,

h) Date and time of installing poles,

i) Detailed list of repairs or replacements,

j) Detailed technical data of luminaires (manufacturer, type and number of light sources per luminaire, number of luminaires, installed power per light source, type of casing etc.),

k) Date and time of the first installation of luminaires,

l) Detailed list of interventions (repairs or replacement of luminaire),

m) Detailed information on working schedules (switching ON/OFF, regulation of light intensity etc.),

n) Sensor status (if applicable),

o) Type of management,

p) Energy consumption,

q) Tariff models and prices of electricity,

r) Invoices for energy consumption,

s) Measurement results (if applicable),

t) Date and time of software malfunction,

u) Detailed technical information on software malfunction,

v) Date and time of malfunction of the hardware component (local controller, gateway),

w) Detailed technical information on malfunction of hardware components (local controller, gateway),

x) Detailed list of interventions (hardware, software),

y) Date and time of software upgrades.

3.3.8 Evaluation of monitored parameters Hodnocení monitorovaných parametrů

As mentioned above, monitoring of given parameters lacks sense without their regular evaluation. Technically speaking, we distinguish two types of evaluation – cost analysis and technical evaluation.

3.3.9 Cost analysis

An important part of public lighting monitoring is the costs analysis associated with the operation of the PLS. Operating expenses relate to a certain time (year) of operation and repeat with certain regularity throughout the life of the facility. They are determined by the sum of operating expenses (consumed electricity) and maintenance. The specific annual operating expenses are related to one light spot - the pole, or to one kilometer of illuminated communication.

Below are few basic economic indicators which should be evaluated annually based on the data obtained from the remote monitoring.

- Annual expenses on consumed electric energy

$$C_E = N * P_c * t_r * C_{el} + C_{sp}$$

Where N – number of luminaires/ počet svítidel soustavy

P_c– power of the luminaire

t_r– annual operation time

C_{el} – cost of electricity

C_{sp}– regular annual payments to the distributer of electricity

- Annual expenses on planned individual & batch device replacement (drivers and sensors)
    - Batch replacement

$$C_D = \frac{N}{T_d} * (C_{sd} + C_d)$$

Where/ Kde $\mathrm{T_d}$ – period of batch replacement

$\mathrm{C_{sd}}$ – cost of replaced device

C_d – cost of work

- Individual replacement of drivers and sensors

$$\mathrm{C_D} = N * \frac{k_d}{100} * (\mathrm{C_{sd}} + \mathrm{C}_d)$$

Where/ Kde k_d– portion (%) of replaced devices

- Annual expenses on luminaire cleaning

$$\mathrm{C_C} = \frac{\mathrm{N}}{\mathrm{T_c}} * \mathrm{C_c}$$

Where/ Kde $\mathrm{C_c}$ – expenses on luminaire cleaning (including work)

T_c – period of cleaning

- Total annual expenses on system operation

$$\mathrm{C_C} = \mathrm{C_E} + \mathrm{C_D} + \mathrm{C_C} + \mathrm{C_R} + \mathrm{C_B} + \mathrm{C_X}$$

Where/ Kde $\mathrm{C_R}$ – annual expenses on repair of lighting system *

$\mathrm{C_B}$ – annual expenses on maintenance of lighting system*

$\mathrm{C_X}$ – fixed expenses on annual service charge (dispatching operations, data management, data depository rental (cloud)

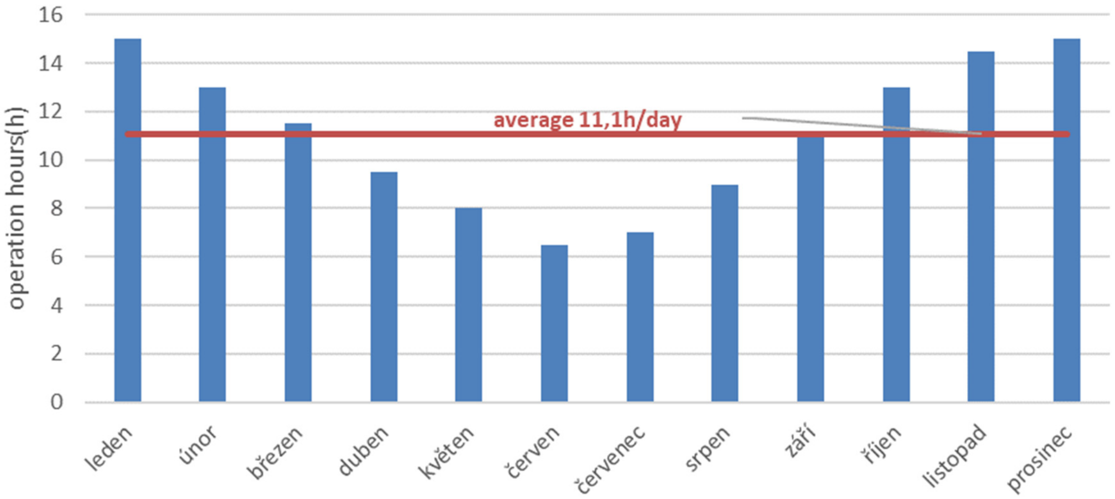
* x% of system purchase cost ($\mathrm{C_R}$ *a* $\mathrm{C_B}$*might be joined o*r the costs are fixed)

3.3.9.1 Methodology for evaluation of the energy consumption

The methodology for evaluation of the power consumption and the subsequent timely detection of any fault condition in the public lighting system can be automated by using remote meter readings. It is necessary to know the programmed power consumption levels for the individual outlets or the supply point, to ensure correct function of the methodology. For this purpose, the public lighting passport is updated regularly.

Consumption is evaluated on a basis of hourly readings and averaged in ten-day periods. Average values from 10 consecutive days are evaluated, each time from a reading at a specific hour, that is, for each month 3 consumption values are calculated for an hourly interval to eliminate short-term fluctuations (e.g. a blackout of few light sources).

Figure 7: PL ooperation for each individual month, an evaluation from ten-day averages (source: own)



Errors causing the difference between theoretical and measured consumption:

- Higher voltage drops on the switchboard outlets and higher losses on ballasts
    - Excessive voltage drops in the PL wiring due to an incorrect dimensioning, or a degradation caused by aging (occurrence of stray currents due to failure of insulation properties)
    - Losses on the choke vary according to its aging
    - Increased active power losses due to non-functional power factor compensation (compensation condenser in the luminaires is out of order)
    - Increase in active power losses due to increased transient resistance in the pole terminal block etc.
- The power consumption of the luminaire is calculated based on the known power of the installed light source, and the current losses on the choke (ballast) in the power line
    - The power consumption of the lamps varies depending on the number of hours in service.
- Remote reading is performed over one-hour period
- The activation and deactivation of the PL is detected within one-hour lap - the exact time of PL operation is unknown and thus the figure used for calculation is longer compared to the reality (does not apply to the cases when the PL is activated by astronomical clock)
- For some types of remote meter reading the consumption figure may be rounded to the full kWh
- In case of faults on the public lighting wiring, the lighting points temporarily (sometimes permanently) switch between the switchboards (connected to another outlet (or backup) of the supply point, which can change the number of light sources connected to the switchboard.

Detection of fault states in the PLS is based on a comparison method. A prerequisite of the same operating conditions is used, i.e. that within the monitored period the number and the input of installed resources does not change.

A comparison of consumption with long-term average helps to refine the method. The consumption for the same period, that is, the day of the year can be compared immediately. In order to get to this state, the measurements have to be made over a long-term period – several years.

In the methodology of evaluation, the comparison of a ten-day average figures is only performed when the PL is to be, with high certainty, operational throughout the year. Comparison is done with one-hour laps from 23:00 to 4:00. If there is any regulation in place, the regulation schedule and levels (%) must be known.

Figure 8: A ppossible output from remote reading of supply point electricity consumption (between 23h and 4h), for a measuring period of approx. 3 months.

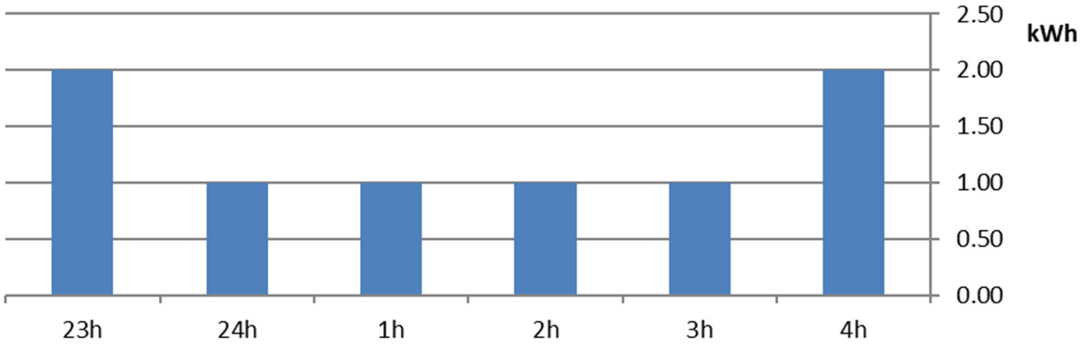
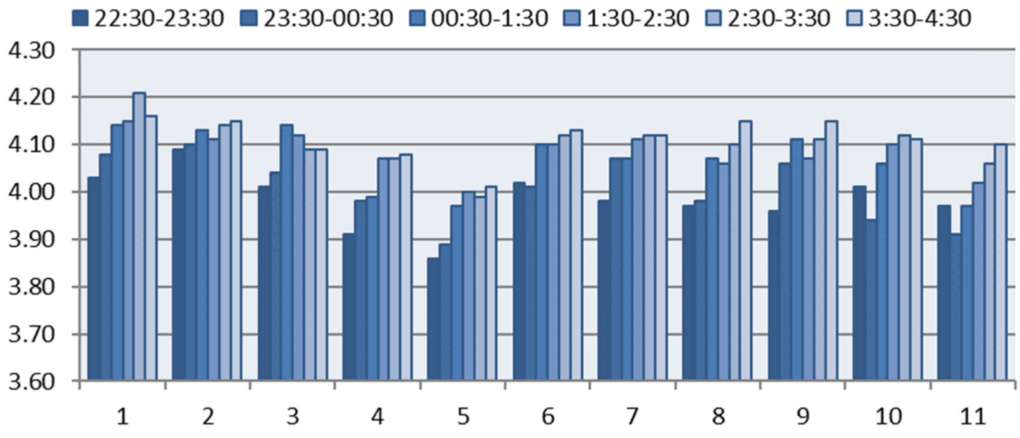


Figure 9: An output of the supply point electricity consumption (between 23h and 4h) for a period of 11 decades - in accordance to the above described methodology.



3.3.10 Technical evaluation/ Technické hodnocení

The main criterion for technical evaluation is compliance with the set of technical standards EN 13 201, applicable to public lighting. Other technical parameters which are not included in the standard are - the aspect of a technical solution, the possibilities of implementation and the expansion by other application areas from the SmartCity concept.

For technical evaluation in terms of quality of lighting, the following indicators (among others) can be used: the Correlated Color Temperature (CCT), the luminous flux utilization factor, the energy efficiency and the limitation of disturbing light.

- Correlated Color Temperature (CCT)

The alternative chromatic temperature gives information about a color tone the light emits, it depends on its light source spectral composition. In case of LED light sources, it is possible to choose from several (standardly produced) chromatic temperatures. From warm white (2700K) to cool white light (above 4000K).

- Utility factor of a luminous flux, η_E.

$\eta_E = D\cdot * B * E_{av} / \Phi_S$

where D – the pitch between two poles (the length of the control field) (m)

B – the width of the communication (the width of the control field) (m)

E_{av} – average illuminance measured in a control field

Φ_S – luminous flux of the light source (lm)

- The energetical efficiency of illumination expresses the power to achieve illuminance of 1 lux.

$\eta_W = P_T/E_{av}$

where P_T – total power consumption of the luminaire (W)

E_{av} – average illuminance measured in a control field (lx)

- Disturbing light

Disturbing light is a useless light, whose directional properties or quantity make it annoying, and which causes visual discomfort. Disturbing light increases the brightness of a night sky and can be a source of light pollution. The specification of the amount of luminous flux radiated to the upper half of the luminaire, related to the consumed electrical energy in the desired time horizon is used for the purpose of evaluating the disturbing light reduction.

3.4. CASE STUDY: TEST IMPLEMENTATION ROSTOCK

The Hanseatic City of Rostock is owner of the street lighting and responsible for the illumination of the city. Because of the increasing luminaire stock, it is more and more important to identify energy saving potentials to reduce the costs while improving the quality. Therefore, the Hanseatic City of Rostock was searching for sensor-based technologies to realize an adaptive lighting solution.

An adaptive lighting solution can only be realized with sensors which react to their environment. At the test implementation in the Hanseatic City of Rostock, the applicability of sensors for motion detection and classification of users was investigated.

For this, a park path with 5 LED luminaires was equipped with radar and infrared sensors, which are dimming automatically according to the presence of users. The sensors were installed on the bottom of the luminaire heads. An integrated control unit connects luminaires and sensors as well as the neighbouring luminaires. For this the controller uses the 2.4 GHz radio network with self-organizing meshing. An installed gateway collects all information send by the single controllers. The data from all gateway modules is combined in a cloud and provided for operating in a web application. The test implementation can thus be monitored, controlled and managed by any computer with an internet access.

Figure 3.7: Luminaires of test implementation

The crucial parameters of the investigation were the adaptability of illuminance, the economic feasibility as well as the user acceptance.

Due to the required minimum speed of 4 km/h of the radar sensors, the test was for this case not successful. Therefor the investigations were focussed on infrared sensors. As the infrared sensors are not suitable for use in motorized traffic, the rapid development of radar sensors continues to be tracked and tested further.

The infrared sensors work very reliable. Currently, if nobody is using the path, the luminaires are dimmed to 20 %. If somebody is detected by the infrared sensor, the luminaires go on high power. Due to the short test area, just one luminaire in advance is on high illumination level, if a user is crossing the detection range. That’s enough for both, pedestrians and cyclists. Because in the test area more elderly pedestrians are predominantly using the path, the follow-up time after leaving the detection range was set to 30 s. Depending on the users, this can be further reduced.

A first evaluation has shown that the use of adaptive lighting control allows savings of up to 50% compared to classic lighting solutions.

The previous feedback from the residents has shown that they are satisfied with the illumination. Initial objections of feeling disturbed by the constant up and down of the illumination were not confirmed. On the contrary, it is barely noticeable.

Apart from the functionality of the radar sensors, the test results are very positive in this application case. In the next step, the Hanseatic City of Rostock will implement a larger pilot plant with 28 lights along a combined foot and cycle path through green area. The further results of the investigation are basically for the planning of the adaptive lighting concept of the future cycling network of the city.

Figure 3.8: Test implementation at park path „Kringelgraben“ in Rostock

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