Demonstration Projects
Eastern Partnership

STREET LIGHTING GUIDEBOOK

Theory and Practice

TABLE OF CONTENTS

LIST OF ABBREVIATIONS AND ACRONYMS

AC	–	alternating current
CB	–	certification body
CCT	–	correlated color temperature
CIE	–	International Commission on Illumination (Commission Internationale de l´Eclairage)
CLO	–	constant light output
CRI	–	color rendering index
DC	–	direct current
ECU	–	electronic control unit
EEPCA	–	European Electrical Products Certification Association
EMC	–	electromagnetic compatibility
ENEC	–	European Norms Electrical Certification
ErP	–	Energy-related-Products-Directive
ETL	–	Electrical Testing Laboratories
IEC	–	International Electrotechnical Commission
IECEE	–	IEC System of Conformity Assessment Schemes for Electrotechical Equipment and Components
ILAC	–	International Laboratory Accreditation Cooperation
IR	–	infrared
ISO	–	international Standards Organization
HID	–	high intensity discharge (lamp)
HPMV	–	high-pressure mercury vapor (lamp)
HPS	–	high-pressure sodium (lamp)
LED	–	light-emitting diode
LLF	–	light loss factor
LPS	–	low-pressure sodium (lamp)
LVD	–	Low Voltage Directive
MF	–	maintenance factor
MH	–	metal halide (lamp)
UV	–	ultraviolet
PF	–	power factor
PLC	–	power line communication
RF	–	radiofrequency
RoHS	–	Restriction of Hazardous Substances
SPD	–	surge protection device
UGR	–	unified glare rating
ULR	–	upward light ratio

1 INTRODUCTION

Energy efficient street lighting is becoming an increasingly popular energy efficient measure pursued by municipalities. With the advancement of technological development, the energy efficient lights are widely available and their prices keep coming down.

This publication is designed for those that are interested in street lighting in general and the implementation of the street lighting projects in particular. It was meant to cover all key issues related to street lighting, in one place, with a sufficient level of details.

Street lighting can be a complex subject so it is always a challenge to find the balance between theory and practice. In this guidebook the theory has been reduced to the minimum necessary to understand the concept of light and streetlight design principles without trivializing the issues.

The guidebook is divided into chapters and annexes. The chapters address the basic theory and principles while the annexes contain supplemental information, practical advice and templates for collecting data.

Some information in the chapters and annexes may initially be too difficult to follow-it can be skipped and returned to later when the reader finds it useful to expand his knowledge. On the flip side, if the reader requires more in-depth information then the bibliography contained in the annexes offers useful publications and links to informative websites.

Chapters 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 13, and Annexes 3, 4, 5, 6 were prepared by Linda Zeltina; Chapters 10, 12, and Annexes 1, 2, 3, 4, 7, were prepared by Ruslan Solomakha. The technical editing and the overall guidebook preparation were done by Leszek Kasprowicz.

The authors would be grateful for constructive comments regarding the content of this publication.

2 THEORY OF LIGHT

2.1. Foreword

Defining the lighting terms is accompanied by certain difficulties. Very often a thorough understanding of theoretical fundamentals is required for complete comprehension of these terms. However, the description of lighting terms in this section is organized in such a way, that the first described terms simplify the understanding of the following terms. Also, useful references are given to the reader throughout the text in case he needs additional information.

The theory of light starts with the terms of two quantitative sciences based on a statistical model of the human visual response to light under carefully controlled conditions [1]:

- Photometry, which is based on the general capability of the human eye to sense light
- Colorimetry, which is based on the capability of the eye to distinguish different color light

2.2. Terms of Photometry and Colorimetry

Electromagnetic spectrum –the entire distribution of electromagnetic radiation according to frequency or wavelength, starting from long radio waves and ending with short X-rays and gamma rays [2], as shown in Fig. 2.1 [3].

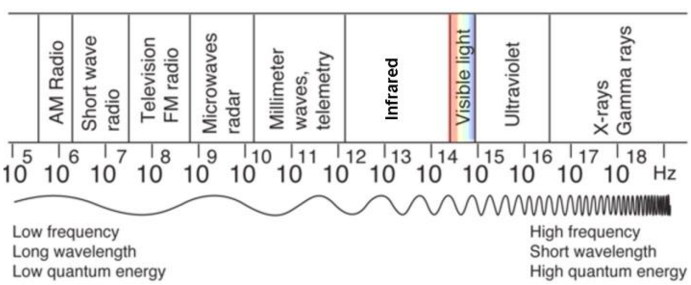


Fig. 2.1. Electromagnetic spectrum

Light – a physical phenomenon that can be described in several ways, but in lighting it is most commonly considered as a beam of rays (when talking about optics and light distribution), and as electromagnetic waves (when talking about photometric and colorimetric parameters of light source). Light is the visible part of electromagnetic spectrum as shown in Fig. 2.1 [3].

Wavelength – for electromagnetic waves the wavelength λ is expressed in nanometers (nm), and is equal to c/f , where f is the frequency, or the number of oscillations of electromagnetic field per second, and c is the propagation speed of electromagnetic wave, which is equal to 299,792,458 m/s, or the speed of light.

2.2.1 Terms of Photometry

Sensitivity of the human eye-human visual system responds to the light in the electromagnetic spectrum with wavelengths ranging from 380 to 770 nm, as shown in Fig. 2.1. We see light of different wavelengths as a continuum of colors ranging through the visible spectrum: 650 nm is red, 540 nm is green, 450 nm is blue, and so on [1]. Also, due to the specifics of the human eye depending on luminance level it has different vision regimes:

- photopic vision at high ambient light level; during daylight an eye is capable to distinguish colors, and,
- scotopic vision at low ambient light level; during night an eye is capable to distinguish different gray levels.

Sensitivity of the eye at photopic and scotopic vision regimes among whole visible range of spectra is shown in Fig. 2.2 [4]. Photopic vision is usually considered for the purposes of lighting applications. The curve of photopic vision is often denoted as *V(λ)* function-the base for all photometry quantities (in some information sources also called luminous efficiency function). Over time, the *V(λ)* function was slightly modified (green solid and dotted curves in Fig. 2.2).

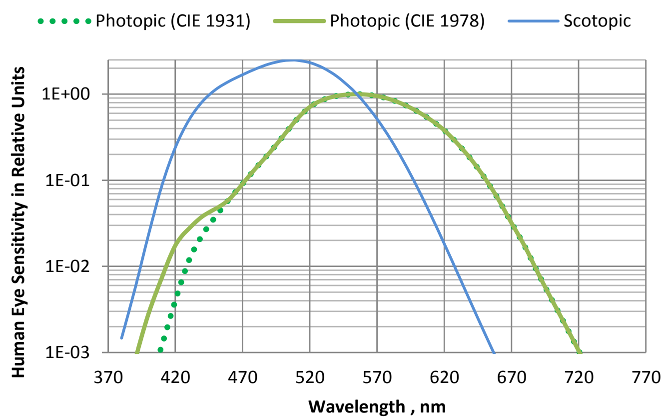


Fig. 2.2 Sensitivity of the human eye at photopic and scotopic vision regimes (normalized with respect to the maximum luminous efficacy factor for the photopic vision $K_m = 683\ lm/W$) [5], [6].

Solid angle – it is the solid angle denoted as *Ω,* and measured in steradians [sr], equal to the spherical surface area, denoted as *A*, divided by the square of the radius, denoted as *r.* A sphere contains *4π* steradians [8]. A concept of solid angle is given in Fig. 2.3.

(a) (b)

Fig. 2.3 Concept of solid angle: removed from the sphere (a) one steradian cone (b) with a solid angle [8].

Lumen – the standard unit for the luminous flux of a light source. It is a SI derived unit based on the candela. It can be defined as the luminous flux emitted into unit solid angle (1 sr), by a point source having a luminous intensity of 1 candela. The lumen is then equal to *cd·sr* [7].

Illuminance – denoted as E_v, it is a measure of photometric flux per unit area, or visible flux density. Illuminance is typically expressed in **lux** (lumens per square meter) [8]. The relationship between candela, solid angle and illuminance is shown in Fig. 2.4.

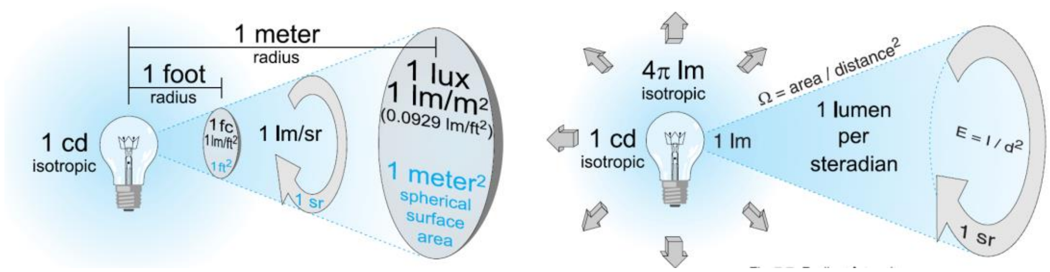


Fig. 2.4 Description of the relationship between luminous intensity I_v and illuminance E_v [8].

Luminance – denoted as L_v, it is the illuminance per unit solid angle, measured in $lm/m^2/sr$. In other words, luminance is the density of visible radiation in a given direction. For lambertian surfaces the relationship between luminance and illuminance can be expressed by the equation: $L_v = E_v/\pi$ [9].

Lambertian surface –it provides uniform diffusion of the incident radiation such that its luminance is the same in all directions from which it can be measured [8].

Luminous flux – for light source it is the total amount of produced light (total flux output), denoted as Φ_v. It is measured in lumens (lm).

Luminous intensity – denoted as I_v, it is the fundamental SI quantity for photometry and is measured in **candelas**. It is the base unit in light measurement, and is defined as follows: 1 candela light source emits 1 lumen per steradian in all directions (isotropically). So, 1 steradian has a projected area of 1 square meter at a distance of 1 meter. Therefore, 1 candela (1 lm/sr) light source will similarly produce 1 lumen per square meter at the distance of 1 meter [8].

Luminous efficacy – it is the ratio of the visible radiated energy of the light source to the whole radiated energy, including radiation in infrared and ultraviolet range of spectra of the light source.

Luminous efficiency – it is the ratio of visible radiated energy of the light source to the electrical power P_{el} applied to this source [4], [5]. The units of both of these quantities (luminous efficacy and luminous efficiency), are lumens per Watt (lm/W). These terms are often used erroneously or incorrectly. The same term "luminous efficiency" is often used to characterize the light source (LED, for instance), and to characterize the whole luminaire. Luminous efficiency of the whole luminaire includes losses in the optics and the driver. Therefore, it is always important to clarify which term and which light source configuration are used for comparison.

Inverse Square Law – the illuminance Ev of a surface decreases in inverse proportion to the square of the distance d from the surface: Ev = Iv/d2 [9]. This law is further explained in

Fig. 2.5:

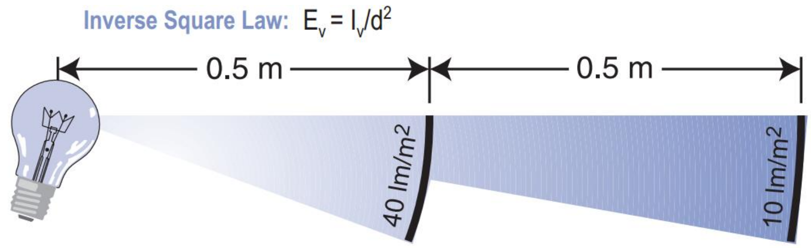


Fig. 2.5 Description of Inverse Square Law [9].

2.2.2 Terms of Colorimetry

Color temperature – denoted as T, it is a simple parameter describing color hue of white light. Blackbody radiator, an ideal black body, has become a standard for the representation of color hue of white light. Depending on temperature expressed in Kelvin degrees (K), the radiation of blackbody radiator, perceived by human eye, appears in different colors: red hue at lower temperatures and blue hue at higher temperatures. The dependency of light color on the blackbody temperature can be shown as a curve on chromaticity diagram (Fig. 2.7 a). This curve is called Planckian locus or blackbody locus.

Correlated color temperature - denoted as T_c, it is the temperature of a blackbody radiator whose color is closest to the color of the measured white light source. In outdoor lighting the standard color temperature for streets is equal to 4,000 K (neutral white). There are some places where warm light (3,000 K), is preferable; for instance, in parks. The 5,000 K color temperature is usually used for crosswalk lighting to create a contrast among neutral light colors.

Color rendering index – denoted as CRI, is defined as the measure of the degree of color shift of an object when illuminated by a light source as compared to when illuminated by a reference source of comparable color temperature. Color rendering index compares how a light source shifts the location of eight specified pastel colors, as defined by the CIE, as compared to the same colors lit by a reference source of the same color temperature. A 100 is the maximum possible CRI value; it is not a percentage though). A CRI value is obtained by subtracting average differences from 100 [10].

Color matching functions – there are standard observer colorimetric functions: red $\bar{x}(\lambda)$, green $\bar{y}(\lambda)$, and blue $\bar{z}(\lambda)$, as presented in Fig. 2.6.

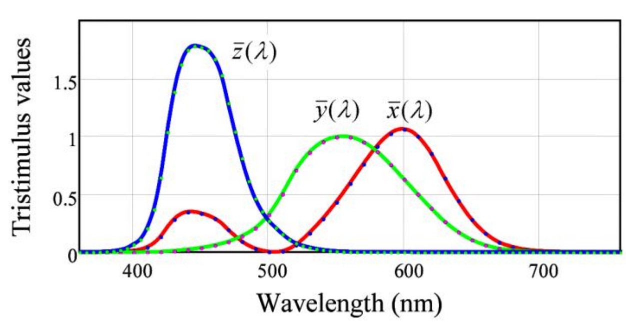


Fig. 2.6 Colorimetric function values of standard observer color matching functions (CIE 1931) [6].

Chromaticity diagram is used to get convenient representation of colors. It is a two-dimensional projection of three-dimensional space of colorimetric functions, and should be used with great care [11]. Samples of chromaticity diagrams are given in Fig. 2.7.

David MacAdam was the first who drew attention to the phenomena that small region in the chromaticity diagram appears identical to particular observer. He found that the size and orientation of such regions, called MacAdam ellipses, on the standard CIE 1931 (x, y) chromaticity diagram varied widely depending on test color and the geometric distance between two points does not scale linearly with the color difference [4], [13] (Fig. 2.7 b). To solve this problem, in 1960 the CIE introduced (u, v) and in 1976 the (u´, v´) uniform chromaticity coordinates (Fig. 2.7 c).

One step ellipse is approximately equal to Δu'v' = 0.001 of coordinate difference. Different step MacAdam ellipses are used for definition of chromaticity regions of light sources. The standard requirement for LED street lighting is that the color of light sources in lighting system should fall in 5-step MacAdam ellipse to appear the same. For LED indoor lighting 3-step MacAdam ellipses are used. Earlier requirements were less stringent; for instance, 7-step MacAdam ellipses were used to define the chromaticity regions for compact fluorescent lamps (CFL) as shown in Fig. 2.7 (d)

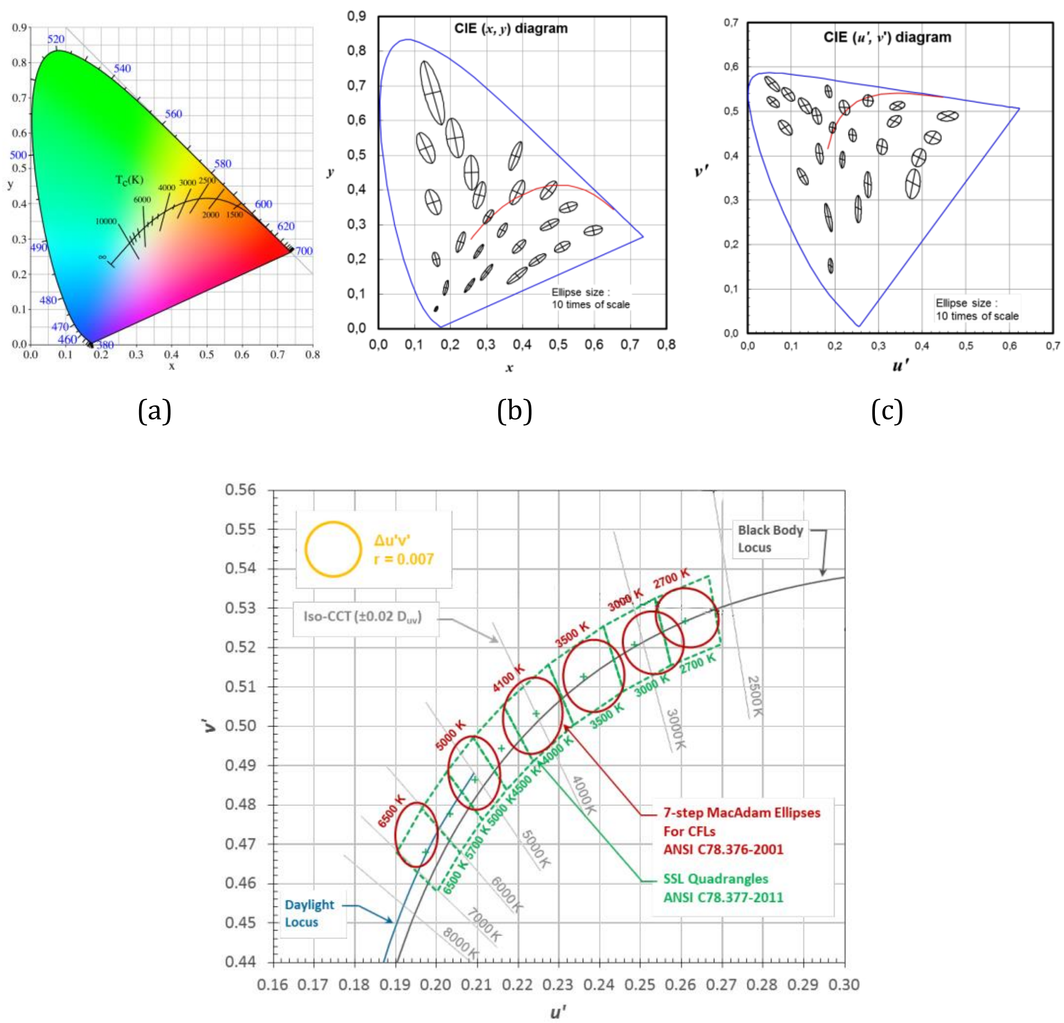


Fig. 2.7 **Chromaticity diagram and Plancian locus (a); MacAdam ellipses: (b) CIE 1931 (x,y); (c) CIE 1976 (u´,v´); (d) chromaticity diagram with 7 step MacAdams ellipses [12], [13].**

2.3. Luminaire

LED – light-emitting diode or semiconductor light source.

High-power LED – a single LED with power higher than 0.5 W. Typical construction of a high-power LED is shown in Fig. 2.8**.**

LED chip – the "heart" of the LED, sometimes called a "LED die". It is shown in Fig. 2.8.

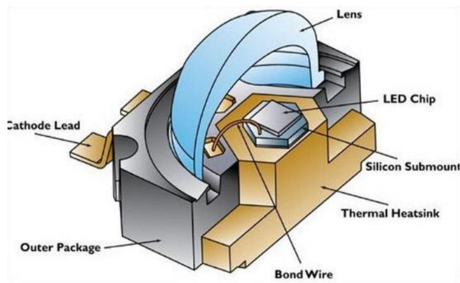


Fig. 2.8 Typical construction of a high-power LED [14].

COB – stands for chip-on-board. It is a special technology of LED packaging for LED light engine. Multi LED chips are packaged together as one lighting module. When it lights up, it looks like a lighting panel [15].

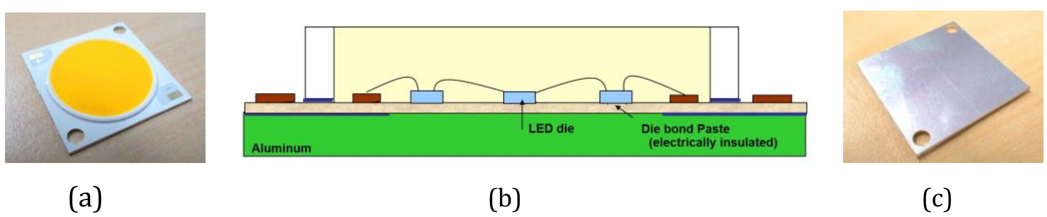
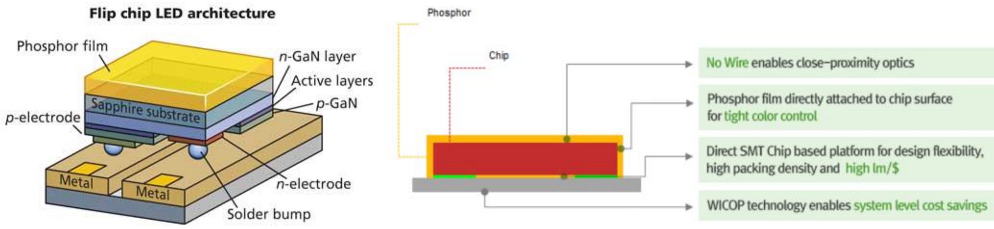


Fig. 2.9 Construction of chip-on-board LEDs: (a) top view; (b) construction; (c) bottom view.

Flip-chip LED – it is a new technology where the LED chip is placed upside down when compared with the present day LED production; this way it provides direct electrical connection (Fig. 2.10). The majority of the current market LED products are using gold wires to provide electrical connections (Fig. 2.8).

PCB – printed circuit board; it is a mechanical fixture of electrical components (also LEDs), which at the same time provides electrical connections between these parts by conductive copper circuits. PCB is a base of LED module or LED engine. Different types and materials of PCBs are possible. The most common for LED modules are metal core printed circuit boards MCPCB, where the core of the board is usually made of an aluminum plate, FR-4 PCBs glass-reinforced epoxy laminate, and CEM-3 PCBs composite epoxy materials.

CSP – stands for Chip Scale Package. These are fully functional LED packages that are equal to or slightly larger than the size of a LED chip. The CSP technology allows directly attaching the LED chip to the printed circuit board (PCB) (Fig. 2.10).



(a) (b)

Fig. 2.10 New compact LED package technologies: (a) Flip-chip [16]; (b) CSP [17].

LED module – it is a unit containing one or more LEDs which is supplied as a light source. It may contain additional components, such as lenses, resistors or ESD protection devices, but does not include the LED driver [18]. Several LED module samples are presented in Fig. 2.11 (a) and (b).

LED engine – it is a combination of one or more LED modules with a LED driver, also known as electronic control gear, or ECG. Sample LED engine is shown in Fig. 2.11 (c) [18].

(a) (b) (c)

Fig. 2.11 Samples of LED modules (a) [19] and (b) [20], and (c) LED engine [21].

Lenses – a secondary optics of a luminaire. Depending on the requirements it provides necessary light distribution by light beam refractions. Usually, the luminaires are designed in such a way that the lenses can be easily replaced (Fig. 2.13 a).

Reflectors – a secondary optics of a luminaire. Depending on requirements it provides necessary light distribution by light beam reflections (Fig. 2.13 b).

Diffusers – optical components used to evenly distribute light from a source while eliminating bright spots. A perfected diffuser should create uniformly bright surface where the radiance is independent of an angle, as shown in Fig. 2.13 (c) [22].

(a) (b) (c)

Fig. 2.12 Samples of LED luminaire secondary optics: (a) lenses [23]; (b) reflector [24]; (c) diffuser.

Heatsink – the part of a luminaire that dissipates heat from the LEDs. In case of street luminaires the body of the luminaire usually plays role of the heatsink. In this case the type of the luminaire body plays significant role on the effective heat dissipation. Large aluminum casted parts may serve as a very effective heatsink. The effectiveness of a heatsink depends on its surface, therefore very often the LED luminaire bodies are equipped with fins. Attention should be paid to the distance between the fins. Dirt and fallen leaves can fill the spaces between the fins and significantly decrease the radiator's heat dissipation capability, increase the temperature of the LED modules, and consequently reduce service life of the luminaire.

Ballast – the device needed for proper operation of the lamp. The original ballasts were inductors or autotransformers, which provided current limiting function for discharge lamps. Modern ballasts are electronic devices with additional functionality, like dimming function. The terms "electronic ballast", "electronic control unit", and "LED driver" are often used interchangeably.

Electronic control unit (ECU) –also commonly known as a **LED driver**, it is an electronic unit placed between the power supply and one or more LED modules to provide the module(s) with an appropriate voltage or current. It may consist of one or more separate parts, and may offer additional functionalities, such as dimming, power-factor correction, or radio interference suppression [18].

LED Driver – see electronic control unit (ECU).

Constant Light Output (CLO) – it is a function of an ECU or luminaire controller, which provides compensation for luminaire's lumen depreciation during the service life.

Ignitor – a device for ignition of discharge lamps. It usually provides high voltage pulse to provide electric breakdown of gas filling between the electrodes of the lamp.

Illuminance sensor – it is a visible light sensor, based on photoresistor, phototransistor, or photodiode. The spectral response of these sensors is close to that of the human eye.

Motion sensor – the most common are passive infrared (PIR) sensors. More advanced are radar technology sensors.

Surge Protection Device (SPD) – a device which provides protection of luminaire electronic components against severe voltage surge that can be caused by natural phenomena, like lightning. For street luminaires it is a good practice to choose SPDs with 10 kV and 10 kA surge resistance capabilities.

2.4. Dimming interfaces[1]

1 – 10 V dimming interface – an analog dimming interface. Requires additional wires. Dimming is performed without feedback from the luminaires.

DALI – digital dimming interface that also requires additional wires. Additional information about the state of the luminaire can be transmitted over DALI interface.

DMX512 interface –Digital Multiplex, it is a standard for digital communication networks that is commonly used to control stage lighting and effects. Sometimes it is used for architectural and decorative lighting applications

[1] Most often dimming interfaces are used for communication between the internal devices of a luminaire; for instance, between LED driver and luminaire controller.

2.5. Communication protocols[2] and luminaire controller

Power line communication (PLC) – it is a communication technology that enables sending data over existing power cables. This means that through power cables connected to an electronic device one can both power it up and at the same time control/retrieve data from it in a half-duplex manner [25].

RF communication – means wireless communication. The most common frequencies for lighting applications are very high (VHF: 30–300 MHz), and ultrahigh (UHF: 300 MHz–3 GHz), frequencies.

ZigBee –a mesh network specification for low-power wireless local area networks (WLANs) that cover a large area. ZigBee was designed to provide high data throughput in applications where the duty cycle is low and low power consumption is of an important consideration. Many devices that use ZigBee are powered by batteries. It operates at a frequency of 2.4 GHz [26].

Luminaire controller – a device which controls ECUs via DALI or 1–10V dimming interface, provides monitoring of luminaire's operating parameters and other required functions as it has digital and analog inputs for sensors. It supports communication and provides data transfer between the luminaire and central server.

2.6. Additional properties of the ECU for consideration

Flickering – light intensity fluctuations caused by voltage or current fluctuations, or by abnormal operation of ECU.

Power factor (PF) – it is a parameter which indicates how effectively electrical power consumer (in our case LED driver), utilizes AC power line. The possible power factor values lie in the range between 0 and 1. For instance, it would be possible to connect to the same AC line (with the same losses in the line), twice as many luminaires with PF = 0.9 than luminaires with PF = 0.45.

Power factor is closely related to harmonic currents; the limits and precise values of harmonic currents for electrical equipment are defined in IEC 1000-3-2 (EN 61000-3-2). The usual market requirement for power factor is PF ≥ 0.9. Electric retail companies may impose a penalty for customers operating electric devices with low power factor.

2.7. Measurements in outdoor lighting and DIALux calculations

Adaptive lighting – controlled changes in luminance or illuminance in relation to traffic volume, time, weather, or other parameters [27].

Goniophotometer – a device that is generally used to measure luminous intensity distribution of luminaires.

Maintenance factor (MF) –it is defined as the ratio of illuminance produced by a lighting system after a certain period of time to the illuminance produced by a brand new system. This period of time is often equal to the lifetime of the light source, particularly with regards to the LEDs. A lighting installation should be designed with an overall maintenance factor calculated for the selected lighting equipment, environment, and specified maintenance schedule [28]. The following documents are useful in calculating maintenance period for the LED luminaires:

---

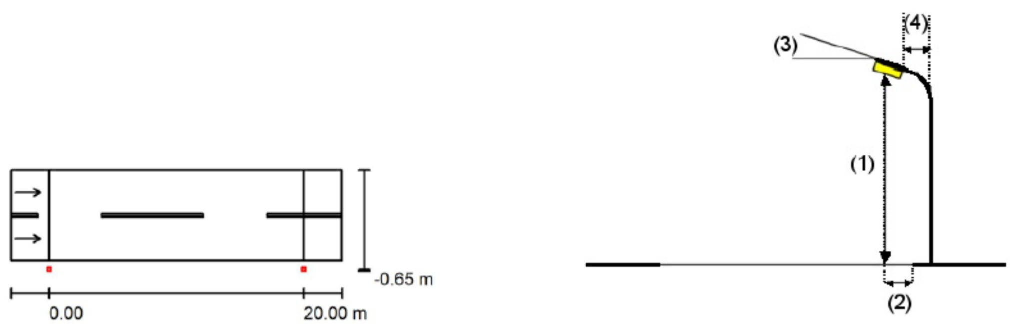
[2] Communication protocols are mainly used for communication between the separate luminaires or luminaire and segment controller.

- IESNA LM-80-08: Measuring Maintenance of LED Light Sources
- IESNA TM-21-11: Projecting Long Term Lumen Maintenance of LED Light Sources
- IESNA LM-82-12: Characterization of LED Light Engines and LED Lamps for Electrical and Photometric Properties as Function of Temperature

Lumen Depreciation - it is the luminous flux loss over time; it complements lumen maintenance [29].

Light Loss Factor (LLF) – in general, it is any multiplier used to recalculate initial candlepower or lumen values. The most common LLFs are Lamp Lumen Deprecation (LLD), Lamp Dirt Depreciation (LDD), and Ballast Factor (BF). Despite the name, it is possible for the LLF to be greater than 1, which means that the luminaire is emitting more light than it's originally tested light output (in the LED luminaire can be implemented as a function). Light Loss Factors multiply each other. Usually, the term LLF is used to denote multiplication of several loss factors [30], [31], [32].

Lighting pole - it is a structure designed to support single or multiple luminaires [33]. Some common terms related to the placement of a luminaire on the pole are given in Fig. 2.13.



(a) (b)

Fig. 2.13 Street lighting in DIALux: (a) top view; (b) front view. Definition of terms: (1) mounting height; (2) overhanging; (3) boom angle; (4) boom length.

Light Distribution Curves –luminaire and lamp manufacturers provide candlepower, or luminous intensity, distribution curves for their fixtures. The curves provide the designer with important information about the way the light is distributed from the fixture and how that light reaches a surface [34]. Although the final distribution strongly depends on luminaire's mounting position, namely height and angle, and while sometimes it is difficult to predict luminous intensity from the curve, it gives a good initial assessment of the luminaire. A sample light distribution curve is presented in Fig. 2.14.

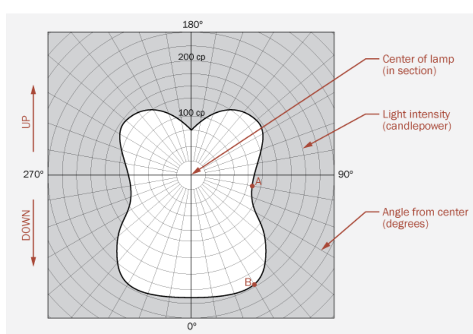


Fig. 2.14 Sample of light distribution curve [34].

Luxmeter –a device for measuring illuminance in the field.

Reflection factor or **reflection coefficient** – a measure of surface's ability to reflect light. Outdoor surfaces have significantly different reflection factor values during dry and wet weather conditions.

Glare – harsh uncomfortable feeling of the observer caused by areas of high brightness right next to areas of low brightness or direct bright light from the source.

Unified Glare Rating (UGR) – it is the measure of the glare in a given environment; basically it is the logarithm of the glare of all visible lamps, divided by the background luminance [35]. The UGR values are in the range of 10–30. Larger UGR values mean greater probability of a glare.

Upward Light Ratio (ULR) – it is the maximum permitted percentage of luminaire flux from the entire installation that goes directly towards the sky [36].

3 TYPES OF LIGHTS AND THEIR COMPONENTS USED IN STREET LIGHTING APPLICATIONS

3.1. LED lighting technology

A comparison of different lighting technologies gives a good insight in the growing popularity and prevalence of LEDs. The light-emitting diode (LED) is a light source which uses semiconductors and, most commonly, electroluminescence to create white light. Although the luminous efficiency of white LEDs is slowly approaching the theoretical maximum of over 300 lm/W, the technology continues to develop and is moving towards the improvement of price/performance ratio. The advantages and drawbacks of the LEDs are summarized in Table 3.1.

Table 3.1. Advantages and disadvantages of the LEDs

Advantages	Disadvantages
• High-quality lighting • Long life • Energy efficient: total luminous efficiency of luminaire >100 lm/W • Low maintenance costs • Convenient dimming 2–100% • No flickering* • Appropriate for smart lighting systems • Appropriate for either small or big areas • Solid state light source–resistant to vibrations	• Higher requirements on thermal management system of luminaire (to provide long life) • High initial costs • Electronic components inside the luminaire are more sensitive to voltage spikes. Additional protective devices may be required

* depends on the type of the LED driver

There are many different types of LEDs and LED packages but, in general, these are low voltage and low wattage devices. Therefore, to provide required amount of light (lumens), the LED modules with several LEDs are usually used (Fig. 2.11.).

The LEDs use direct current (DC). Therefore, they cannot be connected directly to the AC power grid, the most common power grid for outdoor lighting systems; a LED driver is required for proper operation. The LED driver may also provide additional functions. Common configuration of a LED street luminaire is shown in Fig. 3.1.

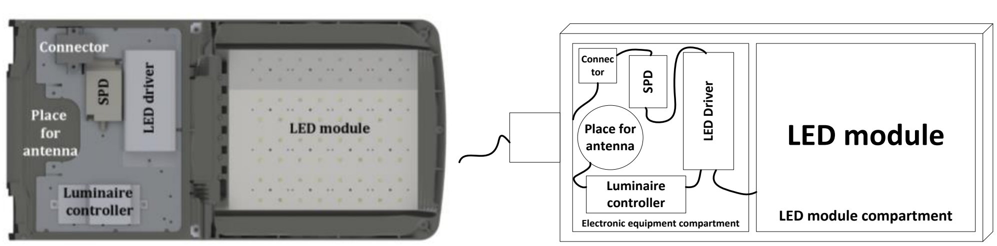


Fig. 3.1. Location of components in a LED luminaire-common configuration.

3.2. Conventional lighting technologies

The summary of different lighting technologies and lamps is given in Table 3.2

Table 3.2. Comparison of different lamps [37]

Type	Power [W]	Efficacy [lm/W]	Color Rendering Index	Service life [hours]
Incandescent (120V)	10–1,500	8–23	100	≈1,000
Tungsten halogen (120V)	5–2,000	10–35	100	1,700–2,500
Fluorescent (low-power units)	4–5	35–50	50–95	5,000–15,000
Fluorescent (higher-power linear)	70–125	75–100	50–95	5,000–15,000
Fluorescent (electronic ballast)	10–60	75–100	50–95	7,000–30,000
LPS	18–180	100–200	5	14,000–18,000
HPMV	45–1,000	20–50	16	8,000–10,000
HPS	50–1,000	60–130	20–25	24,000
MH	20–1,8000	70–110	60–95	2,000–30,000
Induction lamp	23–85	47–71	80	100,000
Sulfur lamp	1,425	95	79	20,000
High power LED (white)	0.1–100*	90–240**	60–97	25,000–150,000

* For single casing.
** For commercial LEDs over 300 lm/W efficacy can be achieved in the lab [38].

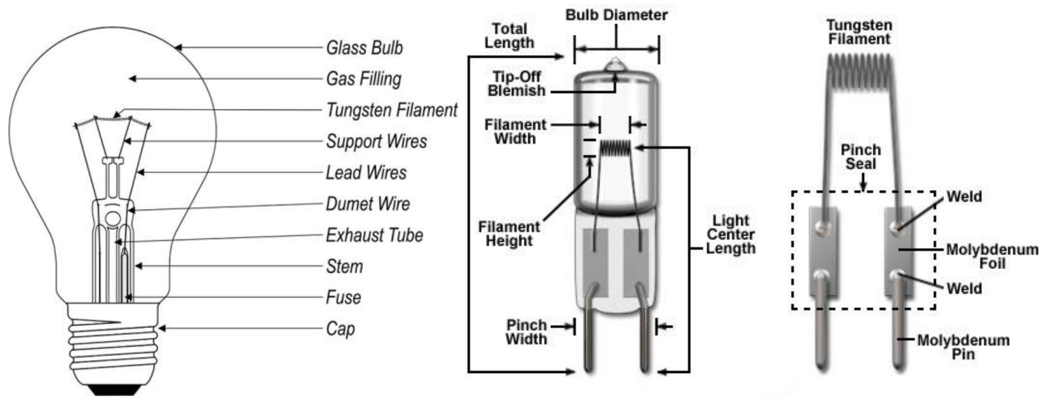
3.2.1 Incandescent lamps

The overall luminous efficacy and efficiency of an incandescent lamp is rather low; greater part of the emission of a blackbody (tungsten filament is regarded as blackbody), is in the infrared rather than visible range of electromagnetic waves. Depending on the operation temperature the efficacy varies from 8 lm/W to 23 lm/W for 120 V incandescent filament lamps. The efficacy also depends on the voltage they are designed for; 220–240 V lamps are approximately 20% less efficient when compared to 120 V lamps and they also have a longer service life. The most common cause for a failure is the evaporation of tungsten from the filament [37]. Incandescent lamps can be used as design elements and for decorative lighting. However, the so called “LED filament bulbs” are more often used nowadays in these applications.

The construction of incandescent lamp is shown in Fig. 3.2 (a).

3.2.2 Tungsten halogen lamps

The tungsten evaporation rates can be reduced and the efficacy can be increased by adding the halogen to the gas filling. The halogens participate in chemical transport cycle when halides are formed during tungsten diffusion process and concentrate at the filament, thus allowing higher operation temperatures (3,450 K). However, tungsten halogen lamps cannot be dimmed since the reduced temperature breaks the halogen cycle [37]. Furthermore, the sale of incandescent filament lamps has been banned and the halogen lamps will be phased out in the near future (except special applications) [39], [40]. Due to excellent color rendering index (CRI) and improved efficiency, when compared to traditional incandescent bulbs, halogen lamps are often used in exhibition halls, showrooms, showcases, and other places where precise color mapping is required. Due to low efficiency filament lamps are not appropriate for street lighting. The construction of a halogen lamp is shown in Fig. 3.2. (b).



(a) (b)

Fig. 3.2. Filament lamps: (a) incandescent lamp [41]; (b) halogen lamp [42].

3.2.3 Fluorescent lamps

Light can also be generated during the electrical discharge process in a gas. To obtain visible light noble gases are usually used: neon, argon, krypton, or xenon. Often noble gases are used with elemental vapors of metals and nonmetals–mercury, sodium and sulfur. In fluorescent lamps the main part of light emission is ultraviolet (UV), but the visible light is produced by photoluminescence in a tube wall coating phosphor. Thus, there are two energy conversions in fluorescent lamps to obtain visible light: electricity conversion to UV radiation and then UV conversion to visible light. Low-pressure (for fluorescent lamps pressure in tube is approximately 30 times less than normal atmospheric pressure), and high-pressure (pressure up to 30 times more than normal atmospheric pressure) discharge lamps are available. Low-pressure discharge is used in fluorescent lamps where the effective discharge emitter are mercury vapors and in low-pressure sodium lamps. The light output of the fluorescent lamp is highly affected by the ambient temperature, making them less appropriate for outdoor lighting applications.

3.2.4 Low-pressure sodium (LPS) lamps

Low-pressure sodium (LPS) lamps are very efficient but they have significant drawbacks: extremely poor color rendering and long warm-up time. This is because all the produced light is in a very narrow spectrum range near the peak of human eye sensitivity. The correlated color temperature of LPS is equal to 1,800 K [43]. The LPS lamp is the most common low-pressure lamp used for high lumen outdoor lighting applications. The light is produced during low intensity, low voltage, discharge process in a linear or U-shaped tube filled with neon gas and a small amount of sodium. This means that a relatively long tube is required for high-power devices. The U-shaped tube is usually placed in another glass bulb for better thermal stability and additional protection. The LPS lamp is also called SOX lamp (SO for sodium) [44]. The construction of a LPS lamp is shown in Fig. 3.3.

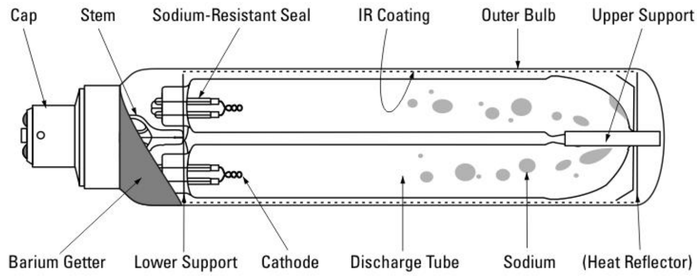


Fig. 3.3. LPS lamp [41].

As any discharge-type lamp, the LPS lamp requires warm-up time to achieve nominal luminous output (5 to 10 minutes), but it restarts immediately after brownout. It should also be noted, that lumen output of LPS lamps doesn't drop with time [44]. The use of LPS lamps is very limited due to poor CRI. Fluorescent lamps, another type of low pressure discharge lamps, achieve very high CRI values but are less appropriate for outdoor use. However, induction lamps (electrodeless modification of fluorescent lamp), are sometimes used for street lighting applications.

Color rendering of high-pressure discharge (high-intensity discharge–HID) lamps is better in comparison with LPS but they are less efficient. The most common HID lamps are high-pressure sodium (HPS), high-pressure mercury vapor (HPMV), and metal halide (MH) lamps.

3.2.5 High-pressure or high intensity discharge (HID) lamps

The principle of HID lamps operation differs from that of LPS lamps but they share similar features [45]:

- The HID lamp consists of an arc tube filled with gas (the type of gas depends on HID lamp type). Two main electrodes, usually tungsten, are placed inside the tube made of quartz to withstand the arc-produced heat. Usually, the HID lamps have outer glass bulb for protection and better thermal stability of the arc tube. The ballast is required for the HID lamp to control the current.
- Because of high pressure inside the arc tube the high voltage is required to start the current flow between the electrodes. After the ignition, when the current starts to flow between the electrodes, the applied voltage is reduced.
- The arc inside the tube vaporizes mercury, sodium, metal salts (depending on lamp type), and produces intense light.
- During the HID lamp operation the gas inside the tube is ionized and acts as a conductor.
- Most of the HID lamps require short warm-up time after the ignition before the nominal brightness is reached.
- Most of the HID lamps cannot be turned on instantly after being turn off when the lamp is still hot.

There are three main types of the HID lamps: high-pressure sodium (HPS), high-pressure mercury vapor (HPMV), and metal halide (MH) lamps. The construction of these lamps is shown in Fig. 3.4.

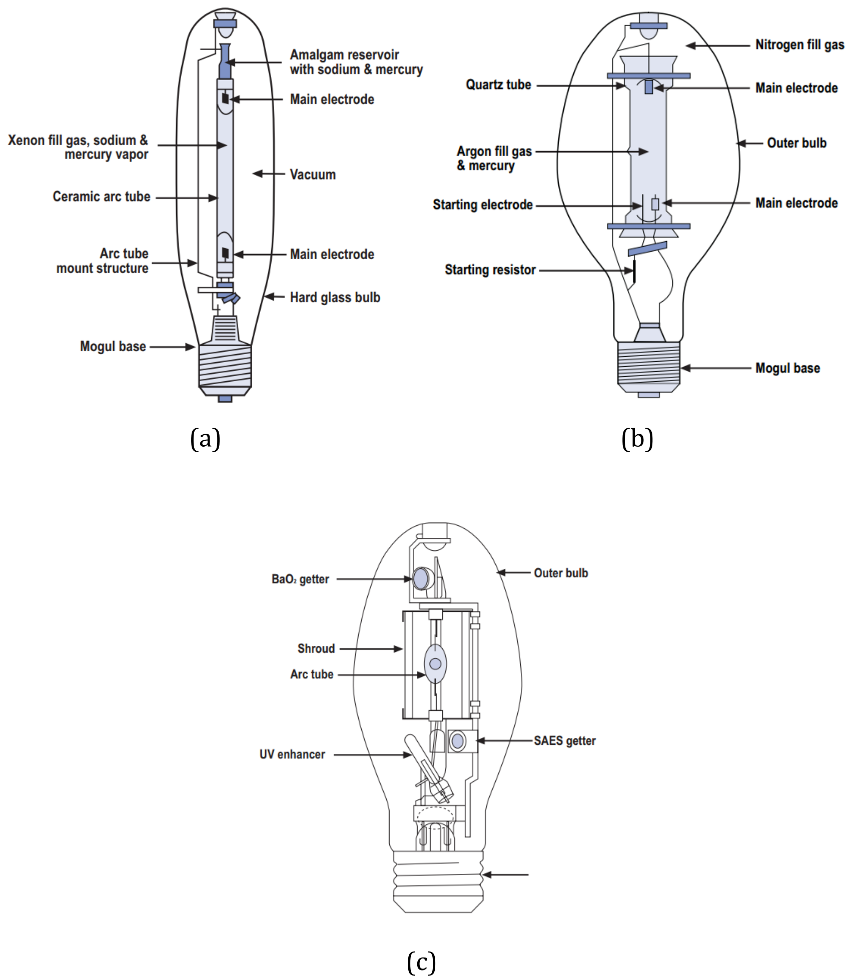


Fig. 3.4. Construction of high-intensity discharge lamps: (a) HPS lamp; (b) HPMV lamp; (c) MH lamp [46].

Several technical parameters of the HID lamps were presented in Table 3.2. Their advantages and disadvantages have been summarized in Table 3.3.

Table 3.3. Advantages and disadvantages of HID lamps [45]

Type	Advantages	Disadvantages
HPS	• High efficiency • Long life span • Compact size • Reliability • Good lumen maintenance • Improved color rendering of white and deluxe HPS lamps • Can be installed horizontally and vertically (when compared to LPS lamps)	• Low color rendering index • Specific ballast requirements • Not as efficient as LPS lamps • Can cycle towards the end of life • Contain toxic mercury • 15-20 minute warm-up time and few minutes restart time needed • Limited usage due to poor color rendering
HPMV	• Up to 24,000 hours lifetime • 2–4 times higher efficacy when compared	• Contain toxic mercury • Poor color rendering when compared to

	to incandescent bulbs • Low price • Improved models have better color rendering than HPS and LPS lamps	induction and LED lamps • Cannot maintain constant luminous flux throughout the lifetime • Short warm-up time and 4–8 minute restart time • Problems with durability and safety
MH	• High efficiency • Excellent color rendering • Large variety of color temperatures • Large variety of wattages and shapes	• Expensive • Can cycle and rupture at the end of life • Shorter life span than other HID lamps • Higher lumen depreciation • Contain toxic mercury • Require 10 minute warm-up time and 5–10 minute restart time

The lifetime of discharge lamps can be improved by elimination of electrodes. Induction and sulfur lamps are electrodeless discharge lamps. The lifetime of induction lamps is approximately 3 to 5 times longer in comparison to other discharge lamps.

The LEDs have the efficiency comparable to LPS lamps (and it is still increasing), their lifetime is comparable to induction lamps, and color rendering is comparable to fluorescent and metal halide lamps. Therefore, at the moment, the LED technology is the most efficient and the most promising among described artificial light sources.

3.2.6 Induction or electrodeless lamps

Induction lamps create light by using an electromagnetic field to excite mercury particles mixed with an inert gas, like argon or krypton. The mercury creates an UV light and the layer of phosphor on the inside of the bulb or the tube converts it into visible light. This is a type of a fluorescent light. Unlike a standard fluorescent light it does not use electrodes in the tube [43]. The principle of induction lamp operation is shown in Fig. 3.5. The advantages and disadvantages of induction lamps are summarized in Table 3.4.

Table 3.4. Advantages and disadvantages of induction lamps [43].

Type	Advantages	Disadvantages
Induction lamp	• Longer life: no electrodes, sealed tube • Energy efficient: >80 lm/W • No flickering • Dimmable 30% to 100% • Appropriate for either small or big areas	• Bulky design, large tubes for high power devices • Partly old technology • Expensive • Radio interference problems caused by electronic ballast and magnetic coil

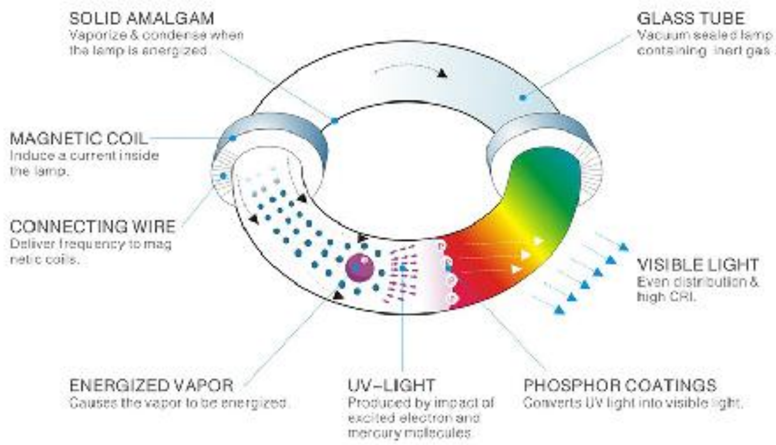


Fig. 3.5. Principle of operation of an induction lamp [47].

3.3. Considerations on the ballasts of discharge lamps

Any type of the discharge lamp requires the ignition device and the ballast for proper operation. There may be different ignition approaches, operation voltages, and currents that are used for different discharge lamps but the lamps cannot operate directly with the grid without these devices. Often, both functions are combined into one device. There are two types of ballasts:

- Traditional, made of magnetic components, like inductors and autotransformers, to provide high voltage for ignition and for current limitation when lamp is ignited, and capacitors for stabilization;
- Modern, that use electronic ballast.

Electronic ballasts are usually more expensive but provide several benefits over the traditional ballasts; they allow utilizing lamps with:

- higher efficiency;
- higher power factor;
- longer service life;
- offer dimming function, although in rather limited range for discharge lamps.

These features make electronic ballasts an ideal choice in modern lighting applications.

4 ADDITIONAL STREET LIGHTING EQUIPMENT

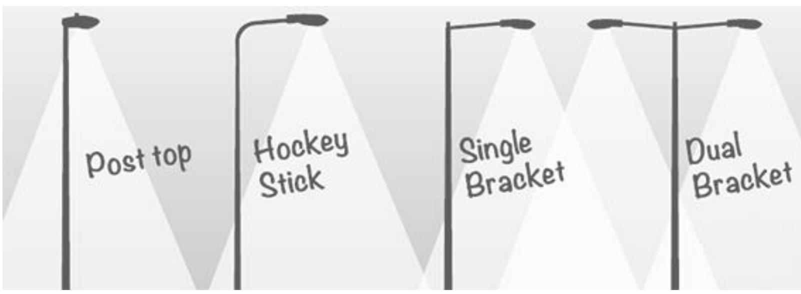
4.1. Poles

There are different types of lighting poles; they differ in form, construction, length, weight and wind load resistance. In principle, there are two major types of poles:

- different dimension and configuration standard poles;
- custom design poles.

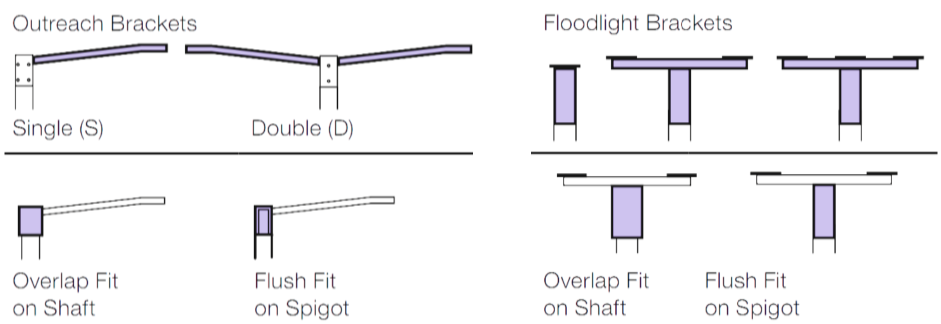
The samples of both types are shown in Fig. 4.1. (a) and (b).

Lighting pole manufacturers usually offer different standard form luminaire fastening constructions called brackets or consoles. Different standard forms of brackets are shown in Fig. 4.1. (c); they can also offer custom made brackets [48], [49].



(a)

(b)



(c)

Fig. 4.1. Pole types: (a) different configurations of standard poles [50]; (b) custom design poles; (c) samples of different brackets and bracket mountings [49].

Selection of poles may depend on many conditions and requirements. In general, this process may be reduced to two approaches:

1) Cost effective selection–choose the least expensive offer that fulfils all necessary standards and calculations:
    a. Pole parameters–height, console length, bracket type, length, etc.,–have to provide necessary illumination level in accordance with lighting standard EN 13201;
    b. Poles have to bear a CE mark and be designed, manufactured, and tested in accordance with the EN standards, including EN 40–Lighting columns;

c. Poles have to comply with real technical specifications with defined parameters, such as maximum allowable wind load (wind load map of Europe is given in Annex 5), and the maximum allowable weight of luminaire; and,
d. Poles are selected in accordance with safety requirements[3].

2) Aesthetic selection:

a. Poles have to fulfil aesthetic requirements and be in harmony with the environment, where they are intended to be installed (park, old city, or modern town, etc.); and,
b. Poles have to fulfil all of the requirements that were defined for cost effective selection.

4.1.1 Passive safety poles

Passive safety poles are designed, manufactured, and tested in accordance with standard EN 12767[4]. These poles are intended to increase the level of road safety for car drivers and pedestrians.

According to EN 12767, passive safety poles are classified as follows [51]:

1) NE or No Energy
   - The car loses minimal speed in the impact:
     - 70 km/h rating–exit speed is between 30 km/h and 70 km/h in a 70 km/h test
     - 100 km/h rating–exit speed is between 70 km/h and 100 km/h in a 100 km/h test

2) LE or Low Energy
   - The car loses some considerable speed in the impact:
     - 70 km/h rating–exit speed is between 5 km/h and 30 km/h in a 70 km/h test
     - 100 km/h rating–exit speed is between 50 km/h and 70 km/h in a 100 km/h impact

3) HE or High Energy
   - The car is significantly arrested or slowed in the impact:
     - 70 km/h rating–exit speed is less than 4 km/h (and the car may be totally halted)
     - 100 km/h rating–exit speed is 50 km/h or less
     - Most HE poles use their length to achieve the necessary retardation by bending round and flattening under the vehicle thus bringing it to a relatively gradual halt. The poles remain embedded in the ground and do not shear or break free. The ability to halt or almost halt a vehicle at medium speeds make them very suitable for use in towns to safeguard pedestrians.

Another aspect to consider is the type of pole's foundation. Possible types of pole foundations are shown in Fig. 4.2.

[3] **Important! Please, refer to local resources, normative acts and recommendations, when choosing and using safety poles! They differ from country to country**.

[4] Passive safety of support structures for road equipment. Requirements, classification and test methods.

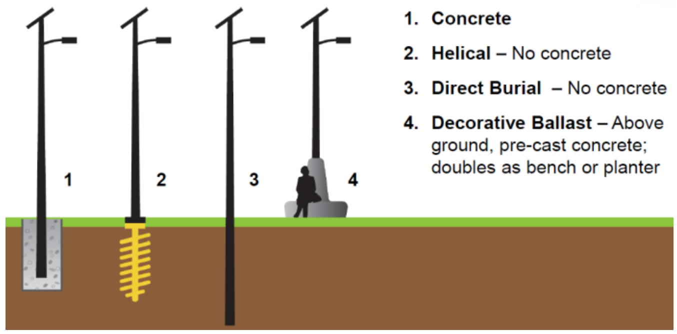


Fig. 4.2. Pole foundation types [52].

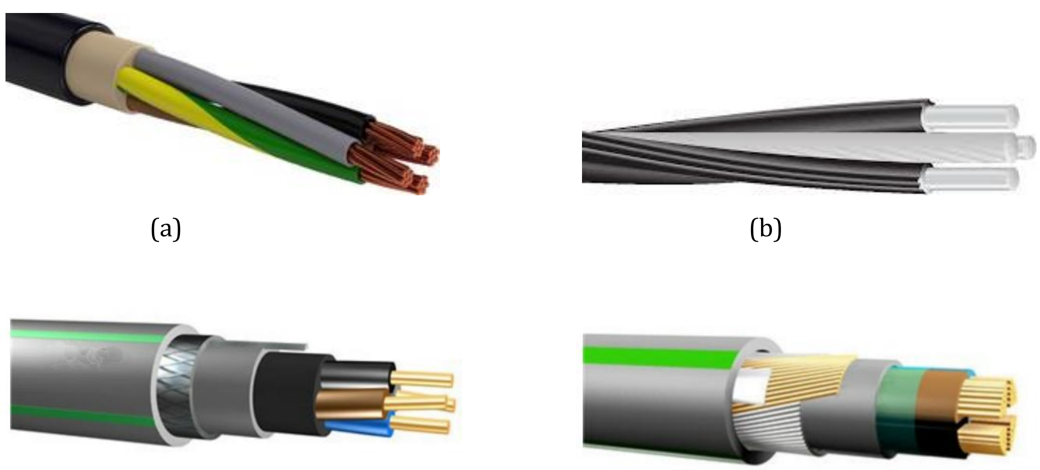
The most common are concrete and direct burial without concrete. However, for passive safety poles the type of foundation is strictly regulated. Please, refer to local resources, normative acts, and recommendations for details.

During the installation lighting poles usually are equipped with miniature circuit breakers (MCB), with the ability to instantaneously trip currents 3 to 10 times higher than nominal current I_n (MCB type B or C).

4.2. Wiring

Special attention should be paid to the wiring as repair work related to troubleshooting may be very expensive, especially for underground lines (restoration works of asphalt pavement, landscaping, etc.).

There are many different types of cables depending on the project, system configuration (IEC 61140 protection classes), or environmental conditions. The most common cables for street lighting systems are armored 3 or 4 core power cables (Fig. 4.3.).



(a) (b)

(c) (d)

Fig. 4.3. Different cable types and conductor types: (a) NYY-J type cable; (b) AMKA type cable; (c) solid conductor; (d) stranded conductor.

The cable conductor cross-section area should be selected in accordance with calculated electrical load, cable length, inrush current, and should take into account environmental conditions so that cable temperature stays within allowable range as defined by the manufacturer and given in cable technical specification datasheet. The greater the conductor area, the greater the electrical load can be connected–more luminaires and higher luminaire wattage. The cable must withstand environmental conditions–temperature, humidity, UV radiation, etc. Flame retardant materials must be used as insulator. Usually, cable manufacturers produce several types of cables specially designed for lighting systems. The most common cable type for underground lines is NYY-J, while for overhead lines the most common type is AMKA.

To determine smoke concentration and gases emitted during cables combustion the cables are graded and approved in accordance with standards EN 60754 and EN 61034-2.

4.3. Control boxes

The configuration of control boxes can be very different (Fig. 4.4 (a) and (b)). Usually, at least one control box is installed on each segment of the lighting system to provide control functions. There are also other possible configurations where one box provides control of multiple segments. Depending on the configuration, the control box may consist of many different elements: bus bars, connectors, protective elements (circuit breakers, surge protection devices, arresters), contactors, and control equipment (astronomical timer, segment controller, communication module, metering equipment, relays). However, from the power savings and control possibilities point of view the most versatile configuration is offered by lamps equipped with ECUs and control boxes with segment controllers.

(a)

(b)

Fig. 4.4 Examples of control box configurations: (a) control box with modern control equipment – controllers, communication modules, contactors; (b) old system, upgraded with segment controller

Make sure that for outdoor installations the control boxes, or existing junction boxes, are waterproof- they should be manufactured and tested according to local normative acts and recommendations.

4.4. Metering equipment

For energy accounting and statistics control boxes are often equipped with metering equipment (Fig. 4.5 (a) and (b)). In case of traditional luminaires the metering equipment also provides an effective feedback by monitoring the electrical power consumption. For example, there is a known power consumption for a given lighting system segment under normal operating conditions. When at least one lamp fails, the consumption drops. In this way the failure on the segment can be detected.

Very often metering equipment, communication module, relays and contactors are combined into one device, a segment controller, which provides all this functionality.

(a)

(b)

Fig. 4.5 Examples of power metering devices: (a) some power meters as separate devices; (b) devices installed in a control box, provides measuring, control (switch on/off function), and communication functions.

4.5. Data transmission from control boxes to server

There are several communication protocols how to transmit data from control boxes to monitoring center (server):

- **PLC (Power Line Communication)**–transmits data over the existing power line wires and does not require additional wires. Best suitable for communication between luminaire controller, sensors and segment controller. It is less suitable for communication between segment controllers and monitoring center or server (high transmission distances and isolation transformers).
- **GSM (Global System for Mobile) communication**–the data is transferred using mobile phone provider services. The most significant disadvantage is slow data transfer.
- **Wireless RF (Radio Frequency) communication**–one of possible wireless communication protocols (discussed in next section). Although the most advantageous communication type, its suffers from potential problems with communication in areas with high electromagnetic interference.

5 CONTROL OF STREET LIGHTING SYSTEMS

5.1. General description of control and management system for street lighting

There are many possible luminaire configurations. A general block diagram of the luminaire which supports remote monitoring and/or lighting management systems is given in Fig. 5.1.

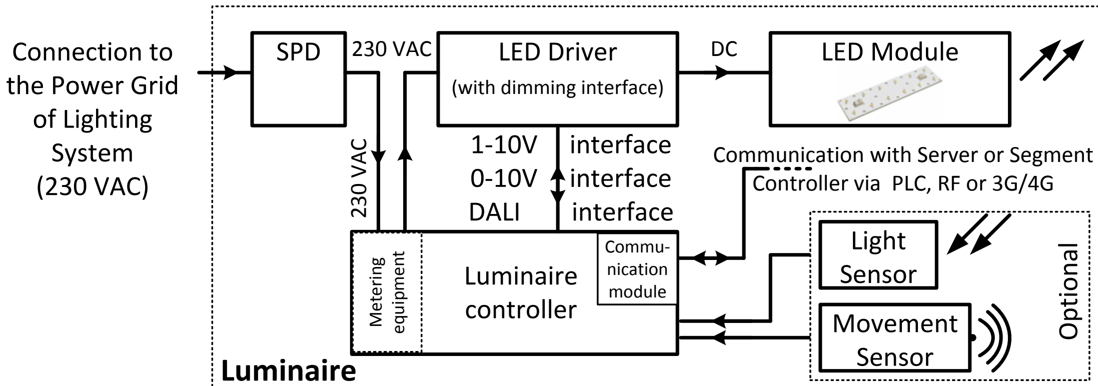


Fig. 5.1. Block diagram for common configuration of luminaire which supports remote monitoring and/or lighting management systems.

The main function of the luminaire controller is to provide communication between the luminaire and the segment controller – translating the segment controller commands to the driver into understandable commands/control signals. As described before, PLC, RF or 3G/4G communication interfaces can be used for data transfer between the luminaires and segment controller although 3G/4G is less suitable due to expensive equipment and possible maintenance problems. Optionally, different kind of sensors can be connected to the luminaire controller to establish autonomous management system of the segment or provide system improvement with different feedbacks and monitoring of environmental conditions. Those sensors can be installed as separate nodes, as shown in Annex 6. The luminaire controller can also be equipped with metering equipment.

Depending on the LED driver configuration there are several light intensity management (dimming) interfaces:

- **1-10 V dimming** – analog signal interface with no feedback from the driver. The dimming may range from the minimum of 10% to the maximum of 100%. The output status is not guaranteed when the dimming signal is less than 1V; so, if application requirement is to completely turn the driver off then additional switch at AC mains of the driver is required [53].
- **0-10 V dimming** – analog signal interface with no feedback from driver. The maximum level is still 100% but the minimum level for DC 0-10 V is 5.7% in case the dimming signal is given at 0.57 V. In case the dimmer is giving voltage lower than 0.57 V the LED driver will cut off the output current resulting in no light output from the LED module [53].
- **DALI (Digital Addressable Lighting Interface) dimming** – digital signal interface specially developed for lighting applications. DALI network consists of a controller and one or more lighting devices, like electrical ballasts, LED drivers, and dimmers, that have DALI interfaces. The controller can monitor and control each light by means of a bi-directional

data exchange. DALI requires a single pair of wires to form the bus for communication to all devices on a single DALI network.

Theoretically, these interfaces for dimming can be used directly without luminaire controllers by being connected by wires to segment controller. In practice, this results in many difficulties and drawbacks such as control signal disturbances, unreliable performance, and need for additional wires, which is critical for outdoor lighting applications.

Modern LED drivers usually support pre-programmed functions and parameters such as:

- **Maximum and minimum current values.** In general, maximum and minimum current values are determined by driver hardware. However, minimum and maximum current values can be adjusted according to the requirements of each specific LED module connected to the driver.
- **Thermal protection.** By connecting an external temperature sensor to the specific port of the driver, a very easy and cost-efficient temperature protection of the LED module can be realized. As an example, a NTC (negative temperature coefficient resistor), can be mounted on the LED module. This function can be enabled or disabled.
- **Constant Light Output (CLO) function.** It is a system to compensate for the depreciation of luminous flux and to avoid excess lighting at the beginning of the installation's service life. Without remote management this simply means increasing the initial power upon installation in order to make up for luminous depreciation [54].
- **Midnight function.** Additional energy savings can be achieved for outdoor and street lighting by dimming the lighting at quiet times during the night. This can be pre-programmed in LED drivers, which support this function.
- **Astronomic dimming.** It allows an autonomous dimming without the need for an additional control line. The dimming profile, defined in the reference schedule, is referenced to the annual average middle of the night, which is calculated based on the theoretical sunrise and sunset times.
- **Operating mode and dimming type.** Usually, there are several operating/dimming options to select. Operating/dimming possibilities depends on driver type. For instance, one of the following options can be selected:
    - No dimming
    - Astronomic dimming
    - Astronomic dimming plus movement detection
    - Standard DALI dimming
    - Specific DALI dimming

Configuration of these driver functions and parameters can be implemented via DALI interface using special programmer provided by the LED driver manufacturer.

6 NORMS, STANDARDS, CERTIFICATIONS AND REGULATIONS

6.1. Introduction

Why Standardization and Regulations? From an industry perspective, standards and regulations provide a platform for consistent language with regard to definitions, test methods, laboratory accreditation, and for product design, manufacturing, and testing.

From a governmental perspective, regulations help ensure public safety, provide consumer protection, regulate energy consumption, and monitor environmental issues.

Standards are voluntary while regulations are mandatory [55].

6.2. CE marking

The CE marking tells that manufacturer claims the conformity of manufactured products to all the relevant European safety standards. CE marking is mandatory for certain products, which must comply with safety standards, and are sold within the European Economic Area (EEA)-28 EU member states-as well as three of the four member states of the European Free Trade Association (EFTA)-Iceland, Liechtenstein, and Norway-since 1985. At the same time, it is forbidden to affix the CE marking to other products. For LED lamps, luminaires, floodlights, etc., the CE marking is obligatory as these products must conform to the European safety standards, the most important of them being EN 60598, which covers electrical, thermal, and mechanical safety [56], [57], [58], [59].

The LED products for general lighting purposes must comply under CE marking with the following directives:

- Low Voltage Directive (LVD) - 2006/95/EC (2014/35/EU from April 20, 2016)
- Electro-Magnetic Compatibility (EMC) Directive - 2004/108/EC (2014/30/EU from April 20, 2016)
- Restriction of Hazardous Substances (RoHS) Directive - 2011/65/EC
- The Eco-Design Directive ErP and relevant regulations - 2009/125/EC [60].

For the LED products in general lighting applications the route for the CE marking is through **self-certification**, as shown in the diagram in Fig. 6.1. It means that the manufacturers should declare conformance when they are confident, and confidence requires some level of due diligence, that the product meets the requirements [60].

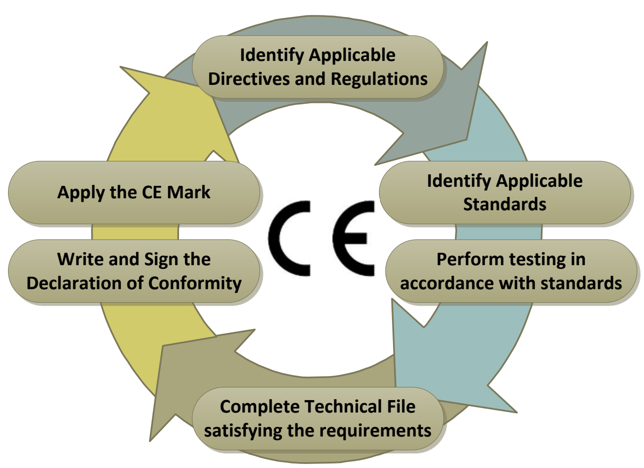


Fig. 6.1. CE marking process [60].

So, the CE marking does not indicate that a product has been approved as safe by the EU or by another authority! Neither it indicates the origin of the product [60]!

6.2.1 Declaration of conformity

The declaration of conformity is the legal document, which is signed by the company directors when there is sufficient information contained in the technical file[5] to back up the assertion of compliance in the normal route for applying the CE marking through self-certification [60].

6.3. Accredited tests

There is no legal requirement that only accredited laboratories provide the test reports for technical file. However, manufacturers must be sure that their technical file can demonstrate their products conformity to the relevant requirements of the European directives and regulations. Use of test reports from ISO/IEC 17025-accredited testing laboratories could greatly facilitate this task, making manufacturer (therefore also the consumer!), completely confident in the quality of the product, by getting test reports from third party (independent and impartial verdict) [60].

There are three main widely adopted schemes of accredited tests which are used in Europe:

- IECEE[6] CB scheme (http://iecee.org), which offers:
  - Third party services (independency and impartiality)
  - Certification by a single Certification Body (CB)–one test (based on IEC International Standards), and one certification (to show the conformity), in order to obtain one or more national certification marks as appropriate (the visual symbol for proof of conformity), or simply for third party documentation of product conformity
  - Worldwide recognition and acceptance
  - CB Test Certificate and a CB Test Report can be used as a basis for issuing certification marks–the ETL Listed Marks for the U.S. and Canada, or the S Mark for Europe (Fig. 6.2 a) [61], [62].
- ILAC[7] signatories (http://ilac.org/ilac-mra-and-signatories/), i.e. global network of accredited conformity assessment bodies, namely calibration laboratories, testing laboratories, medical testing laboratories, and inspection facilities, that can be relied on to provide accurate data and results. It offers:
  - Third party services (independency and impartiality)
  - International confidence and acceptance of accredited testing and inspection reports
  - Additional level of confidence to the general public and consumers purchasing testing and calibration services on their samples, instruments or products
  - Worldwide acceptance [63].

---

[5] Technical documentation contains certain information to demonstrate the conformity of the product to the requirements of the directives.

[6] The IEC System of Conformity Assessment Schemes for Electrotechnical Equipment and Components.

[7] ILAC is the international organization for accreditation bodies operating in accordance with ISO/IEC 17011 and involved in the accreditation of conformity assessment bodies, including calibration laboratories (ISO/IEC 17025), testing laboratories (ISO/IEC 17025), medical testing laboratories (ISO 15189), and inspection bodies (ISO/IEC 17020).

- ENEC[8] scheme run by EEPCA (http://www.eepca.eu/page.php?p=2), an European mark for electrical products which demonstrates compliance with European Standards (EN), mainly related to safety. It offers:
    - Third party testing and certification
    - Annual factory inspection
    - Ongoing product and production monitoring
    - Certification mark on the products (Fig. 6.2 b), which indicates high quality [64].

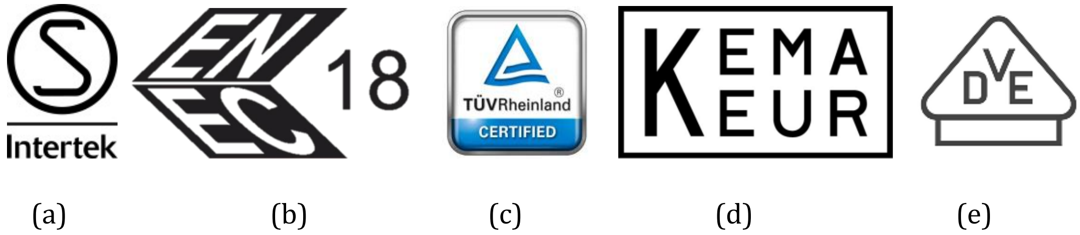


Fig. 6.2. Third party testing marks: (a) S Mark by Intertek; (b) ENEC mark[9]; (c) TUV Rheinland mark; (d) KEMA-KEUR mark by Dekra; (e) VDE mark.

Additionally, big certification bodies, such as TÜV Rheinland, Dekra, and VDE, may offer their own certification marks (as shown in Fig. 6.2 c, d, e). The CE markings awarded by these reputable bodies indicate the conformity to all relevant standards and highest quality levels of the products. This includes control of the manufacturing facilities, product inspections and the regular production monitoring by those bodies [65], [66], [67].

6.4. Relevant standards for outdoor lighting

European conformance is generally proven through reference to European Standards (EN) which generally apply across all European countries. However, in the absence of the EN standards other internationally recognized standards may be used, providing that they are relevant to the European market. Some typical standardization bodies which are important for lighting products are IEC, CIE, and IESNA. There are many standards to be complied with and they depend very critically on the type of the product, i.e. module, lamp, driver, or luminaire, and the application of the product (e. g. recessed lighting, portable, or street lighting) [60]. Several EU standards applicable to outdoor lighting are summarized in Table 6.1.

---

[8] Abbreviation for European Norms Electrical Certification.

[9] Apart from the mark itself, there are also two digit numbers that indicate which certification body has issued the ENEC certification.

Table 6.1. Applicable standards associated with outdoor lighting (EU)

Standard	Name	Comment
Luminaire standards, mechanical tests and endurance tests, corrosion tests, RoHS		
IEC PAS 62722-1:2014	Luminaire performance - Part 1: General requirements	
IEC PAS 62722-2-1	Luminaire performance - Part 2-1: Particular requirements for LED luminaires	
EN 60598-1	Luminaires. General requirements and tests	In particular, thermal endurance tests in accordance with this standard
EN 60598-2-3	Luminaires. Particular requirements. Luminaires for road and street lighting	
EN 60598-2-5	Luminaires. Particular requirements. Floodlights	
EN 62262	Degrees of protection provided by enclosures for electrical equipment against external mechanical impacts.	Mechanical impact tests - IK code. This standard supersedes EN 50102 standard
EN 60529	Degrees of protection provided by enclosures	IP code
EN 60068	Environmental testing. Tests. Test Fc. Vibration (sinusoidal).	
EN 60068-2-27	Environmental testing. Tests. Test Ea and guidance: Shock	
ISO 9227	Corrosion tests in artificial atmospheres – Salt spray tests	
EN 50581	Technical documentation for the assessment of electrical and electronic products with respect to the restriction of hazardous substances	RoHS
EMC standards		
EN 55015	Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment	EMC Emissions
EN 61547	Equipment for general lighting purposes. EMC immunity requirements.	EMC Immunity
EN 61000-3-2	Electromagnetic compatibility (EMC). Limits. Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)	EMC Limits for harmonic current emissions
EN 61000-3-3	Electromagnetic compatibility (EMC). Limits. Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤ 16 A per phase and not subject to conditional connection	EMC Limits for voltage fluctuations and flicker
Standards associated with LED drivers		
EN 61347-1	Lamp control gear. General and safety requirements	

EN 61347-2-13	Lamp control gear. Particular requirements for DC or AC supplied electronic control gear for LED modules	
EN 62493	Assessment of lighting equipment related to human exposure to electromagnetic field	Electro Magnetic Fields Safety – Lighting Equipment
EN 62384	DC or AC supplied electronic control gear for LED modules. Performance requirements	

LED module and photobiological safety standards		
EN 62031	LED modules for general lighting. Safety specifications	
IEC/EN 62471	Photobiological safety of lamps and lamp systems	
IEC TR 62778	Application of IEC 62471 for the assessment of blue light hazard to light sources and luminaires	
Photometry		
EN 13032-1	Light and lighting. Measurement and presentation of photometric data of lamps and luminaires. Measurement and file format.	
IES-LM-80	Measuring Lumen Maintenance of LED Light Sources	LM-80
IES-TM-21	Projecting Long Term Lumen Maintenance of LED Light Sources	TM-21
Light planning standards		
CEN/TR 13201-1	Road lighting. Guidelines on selection of lighting classes	
EN 13201-2	Road lighting. Performance requirements	
EN 13201-3	Road lighting. Calculation of performance	
EN 13201-4	Road lighting. Methods of measuring lighting performance	
EN 13201-5	Road lighting. Energy performance indicators	

As mentioned previously, CE mark shows the conformity only to the most critical safety EU directives and standards. The highest quality products conform to all application-specific standards.

6.5. EU and International standardization bodies which are important for lighting products

CELMA–Federation of National Manufacturers Associations for Luminaires and Electrotechnical components in the European Union. CELMA, along with European Lamp Companies Federation (ELC), provides standards and guides for LED lighting in Europe [68].

CIE–International Commission on Illumination (Commission Internationale de l'Eclairage)**.** It is devoted to worldwide cooperation and the exchange of information on all matters relating to the science and art of light and lighting, color and vision, photobiology and image technology [69].

ISO–International Organization for Standardization. It is an independent, non-governmental international organization with a membership of 163 national standardization bodies.

Zhaga–it is an industry-wide consortium aiming to standardize specifications for interfaces between LED luminaires and light engines. The aim is to permit interchangeability between products made by different manufacturers. Zhaga defines test procedures for luminaires and LED light engines so that the luminaire will accept the LED engine [70].

PAS–Publicly Available Standard. While it is not a formal EN standard, it is an industry-agreed way of presenting data and procedures [71].

6.6. US standards bodies which are important for lighting products

ANSI–American National Standard Institute. It stablishes definitions of solid state lighting devices and components. It also provides a common terminology (Standard Organization) [72].

IESNA–Illuminating Engineering Society of North America. It provides procedures for reproducible measurements of photometry, color and electrical characteristics of solid state lighting products (Professional Association) [72].

NEMA–National Electrical Manufacturers Association. It is a Trade Association [72].

UL–Underwriters Laboratories. It writes safety standards for LED products including drivers, controllers, arrays, packages and modules (Standard Organization) [72].

6.7. Sample system certification and standards for organizations

ISO 9000 series standards, in particular ISO 9001 – Quality management systems – Requirements. It can help organizations achieve standards of quality that are recognized and respected throughout the world. The quality policy is understood and followed at all levels and by all employees. Each employee is given measurable objectives to work towards. Applies to product (luminaire) manufacturer [73].

ISO 14000 series standards, in particular ISO 14001 – Environmental management systems – Requirements with guidance for use. This family of standards is related to environmental management that exists to help organizations:

(a) minimize how their operations (processes, etc.) negatively affect the environment (i.e., cause adverse changes to air, water, or land);

(b) comply with applicable laws, regulations, and other environmentally oriented requirements; and,

(c) continually improve in the above. Applies to product (luminaire) manufacturer [74].

ISO/IEC 17025 – General requirements for the competence of testing and calibration laboratories. In most of major countries, ISO/IEC 17025 is the standard for which most labs must hold accreditation in order to be deemed technically competent. In many cases, suppliers and regulatory authorities will not accept test or calibration results from a lab that is not accredited. It usually applies to independent laboratories [75].

7 STREET LIGHTING DESIGN

7.1. Street classes

The European street lighting class system operates with two main types of streets (roads):

1) Streets/roads for motorized vehicles of medium to high speed, where the lighting requirements meet the need of the drivers for visual conditions
2) Streets/roads/areas for pedestrians and bicyclists with low traffic intensity and lower driving speed of the vehicles.

Lighting class selection process is described in European standard CEN/TR 13201-1.[10]

The following lighting classes are defined in this standard:

- Lighting classes which are intended for drivers of motorized vehicles on traffic routes of medium to high driving speeds:
  - **ME**-series: luminance of the road surface of the carriageway for the dry road surface condition
  - **MEW**-series: for the dry and wet road surface condition
- **CE**-series: lighting classes which are intended for drivers of motorized vehicles and other road users, on conflict areas such as shopping streets, road intersections of some complexity, roundabouts, or queuing areas.
- Lighting classes which are intended for pedestrians and bicyclists on footways, bicycle lanes, emergency lanes and other road areas lying separately or along the carriageways of traffic routes, and for residential roads, pedestrian streets, parking places, or schoolyards.
  - **A-**series: hemispherical illuminance
  - **S-**series: horizontal illuminance
  - **ES-**series classes are intended as additional classes for pedestrian areas for the purposes of reducing crime and suppressing feelings of insecurity (semi-cylindrical illuminance)
  - **EV-**series classes are intended as additional classes in situations where vertical surfaces need to be seen, such as interchange areas.

In some situations it can be necessary to restrict disability glare from installations where the threshold increment (TI) cannot be calculated.

- **G**-series classes are intendent to meet appropriate requirements for restriction of disability glare and/or the control of obtrusive light.
- **D**-series classes are intendent to meet appropriate requirements for restriction of discomfort glare [76].

All the minimum requirements of the classes discussed above are given and summarized in the tables of European standard CEN/TR 13201-2. Refer to this standard for detailed lighting class requirements.

[10] Road lighting–Part 1: Guidelines on selection of lighting classes.

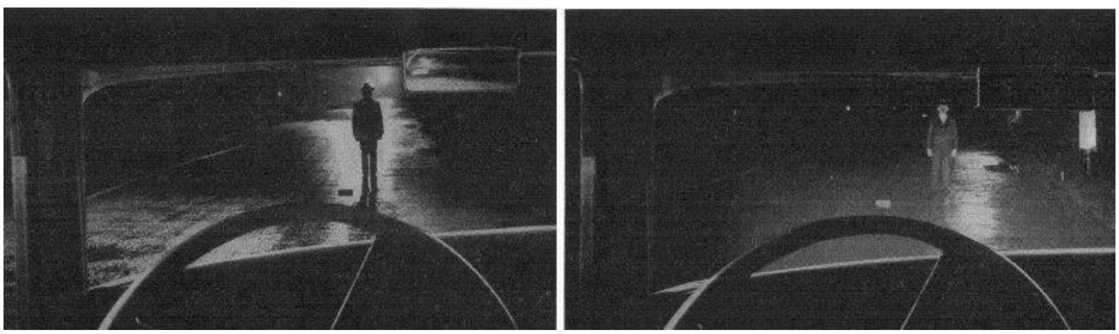
7.2. Illumination of pedestrian crossings

For pedestrian crossings the lighting should be organized so as to provide good pedestrian contrast against the background. At the relatively low lighting levels common in road lighting, color vision is poor and visual detection is made possible due the difference in luminance between an object and its background [77].

Two contrast situations are possible:

1) positive contrast with objects brighter than their background; and,
2) negative contrast with objects darker than their background.

When a sufficiently high road surface luminance level can be provided it is possible to position the normal road lighting luminaires in a way to provide good negative contrast with the pedestrians visible as dark silhouettes against a bright background (Fig. 7.1 a) [78].



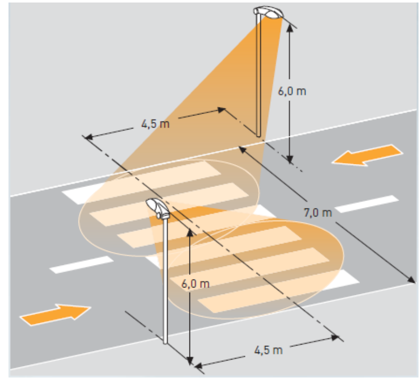
(a) (b)

Fig. 7.1. Example with contrast situations: (a) negative contrast (dark silhouette); (b) positive contrast.

With positive contrast, as shown in Fig. 7.2, the intention is to directly illuminate pedestrians on or at the crossing and to draw the attention of the drivers to their presence at the crossing, as shown in Fig. 7.2 a. The type of the additional luminaires and their positions and orientations relative to the crossing area should be considered to achieve positive contrast and not to cause undue glare to drivers.

One solution is to mount luminaires a short distance before the crossing in the direction of approaching motorized traffic, and direct the light onto the side of pedestrians facing the drivers of this traffic (Fig. 7.2 b). Usually, higher contrast of pedestrian crossings can be achieved by different light color temperatures, as shown in Fig. 7.2 a. Luminaires with asymmetric light output are suitable, causing less glare to drivers [76].

(a)



(b)

Fig. 7.2. Illumination of pedestrian crossings: (a) draw the attention of drivers of motorized vehicles to the presence of the crossing with higher illumination level and different light color temperatures [79]; (b) luminaire position to achieve pedestrian positive contrast and minimize driver glare [80].

The illuminance, when measured on a vertical plane, should be significantly higher than the horizontal illuminance produced by road lighting on the carriageway of the road. Zones at either end of the road crossing, where pedestrians wait to enter the crossing, should receive adequate illumination. The light transition between zones should be sharp. Lighting confined to a narrow band around the crossing area produces a dramatic effect assisting in raising attention as shown in Fig. 7.2 a [76].

To increase the contrast and attract drivers attention the LED pedestrian crossing luminaires are often equipped with cool white LEDs. For instance, if road luminaires are equipped with neutral white (4,000 K) light sources, then pedestrian crossing luminaires can be cool white (6,000 K-7,000 K) for better contrast.

7.3. Illumination of intersections

Conflict areas on traffic routes are those where:

- different vehicle streams intersect;
- there is a change in road geometry (e.g. reduced number of lanes);
- the same road network is used by a mixture of motorized traffic and other types of traffic (pedestrians, cyclists, etc.); and,
- road intersections of some complexity, roundabouts, queuing areas, etc., exist

For the lighting of conflict areas European Standard CEN/TR 13201 uses weighting values to determine the lighting class of the conflict area (CE0–CE5) [76], [81]. Selection of lighting classes is summarized in Table 7.1 and According to Table 7.1 lighting situations for sets D1 and D2 are used for intersection lighting. The main users in these lighting situation sets are motorized traffic and pedestrians; typical speed of main users ranges from 5 to 30 km/h. In set D1 slow moving vehicles and cyclists are excluded. In set D2 slow moving vehicles and cyclists are allowed.

Table 7.2.

Table 7.1. Recommended lighting classes for conflict areas[11] [81].

Geometric measures for traffic calming[12]	Crime risk	Facial recognition	Difficulty of navigational task	Pedestrians traffic flow					
				Normal			High		
				←	o	→	←	o	→
No	Normal	Unnecessary	Normal	CE5	CE5	CE4	CE5	CE4	CE3
			Higher than normal	CE5	CE4	CE3	CE4	CE3	CE2
		Necessary	Normal	CE4	CE4	CE4	CE4	CE4	CE3
			Higher than normal	CE4	CE4	CE3	CE4	CE3	CE2
	Higher than normal		Normal	CE4	CE4	CE3	CE4	CE3	CE3
			Higher than normal	CE4	CE3	CE2	CE3	CE2	CE2
Yes				Choice as above, but select ≤ 4 only at areas of traffic calming					

According to Table 7.1 lighting situations for sets D1 and D2 are used for intersection lighting. The main users in these lighting situation sets are motorized traffic and pedestrians; typical speed of main users ranges from 5 to 30 km/h. In set D1 slow moving vehicles and cyclists are excluded. In set D2 slow moving vehicles and cyclists are allowed.

Table 7.2. Recommended selection from range [81].

Ambient luminance		
Low	Medium	High
←	o	→

The selection of lighting classes in street lighting applications can be a complicated task. However, in standard situations a selection tool can be used. In DIALux there is Illumination Class Wizard, which can help the user to select lighting class in a question-answer manner.

[11] All the tables in this guidebook are given for example purposes only. Please, refer to the latest relevant standards for up-to-date information.

[12] Physical design and other measures to improve safety for motorists, pedestrians and cyclists. There are many strategies for traffic calming, including narrowed roads and speed bumps.

8 OTHER NIGHT TIME ILLUMINATION APPLICATIONS

8.1. City zones and corresponding requirements for night time illumination

In road lighting the main users are drivers of motorized vehicles. The main zone of their "visual interest" is road surface and the nearest surrounding-horizontal surfaces. According to standard EN 13201, in general, ME (Motorway) classes are applicable to roads, and the following lighting classes are applicable to different city zones (pedestrian areas, cycle paths, roads, as well as boulevards and entertainment areas):

- CE – conflict area classes
- S – slow traffic classes
- ES – semi-cylindrical for facial recognition

The requirements for horizontal illuminance for CE and S lighting classes are summarized in Table 8.1 and

Table 8.2. The choice of S classes depends on number of cyclists and the need for recognition of faces (mainly in problem areas) [82].

Table 8.1 Requirements for horizontal illuminance for CE lighting classes [82].

Class (in decreasing complexity of traffic)	E_h, lx	U_h, lx
CE1	30	0.4
CE2	20	0.4
CE3	15	0.4
CE4	10	0.4
CE5	7.5	0.4

Table 8.2. Requirements for horizontal illuminance for S lighting classes [82].

Class	E_h, lx	E_{min}, lx	U_h, lx
S1	15	5	0.3
S2	10	3	0.3
S3	7.5	1.5	0.2
S4	5	1	0.2
S5	3	0.6	0.2
S6	2	0.6	0.3
S7	Orientation lighting	–	–

In city lighting in many areas the main users are pedestrians. The studies [83] show that the primary zone of their “visual interest” lies in the 40° viewing zone (defined as a cone 20° above and below a horizontal line extended out from the eyes), as shown in Fig. 8.1. For pedestrians in a typical urban environment this viewing zone will include the principal vertical surfaces around them–walls, trees, monuments, and other people. Therefore, care should be taken to ensure these vertical surfaces are illuminated [84].

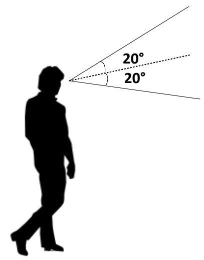


Fig. 8.1 Primary zone of visual interest of a pedestrian.

The difference between an object or a surface which is about twice as bright as the adjacent area is barely noticeable, whereas a luminance ratio of 5:1 appears significantly different and a ratio of more than 10:1 in apparent brightness is emphatic.

In narrow streets or streets with a lot of obstacles luminaires are hung on cables strung between opposite buildings. The same requirements exist for these luminaires as for the luminaires that are mounted directly onto posts. In situations where it is preferable not to place lampposts in the street, wall–mounted luminaires offer a solution. Such lamps are part of building facade, so the particular attention should be paid to the mounting method and concealment of electric wires.

8.2. Illumination of buildings, monuments, and other standalone objects

Several lights on the same post provide various possibilities. They can be placed around the post and light up the surroundings in different directions. In some cases it is possible to light up an object–a monument or a wall or its section–from the group of lights attached to a single post. However, this approach has drawbacks–the wall becomes 'flatter'. There are many aspects to take into account with building lighting:

- To make a tall building appear relatively uniformly lit when seen from the standpoint of a person the highest part of building must be illuminated more intensively than the bottom, as the person perceives wall reflected light, not direct light.
- Lights must be placed so that there are light and dark sections. Such combination allows an object to lit in the best possible way.
- High contrast in lighting of separate parts of the building results in an unpleasant appearance; the recommended ratio between dark and light parts is 1:10.
- Certain uniformity in the object that is to be illuminated is generally desirable as too great contrasts fragment the architecture. The further the lights are placed from the wall the more uniform the effect. However, this has drawbacks–the wall becomes 'flatter' and the likelihood that the surroundings will be disturbed increases.
- Flat walls of buildings without projecting or recessed parts can be lit in an interesting way by an asymmetrical arrangement of floodlights or sometimes by a small difference in the color of the light. The differences in brightness do not have to be large to be perceived by

the viewers as long as there is sufficient contrast with the surroundings; the eye in this case is adjusting to night vision.

- Lighting of a detailed facade with many recessed and projecting sections sometimes results in strong shadows. To avoid this, the shadow areas can be softened with additional direct light from a different angle [82].

Reflective facades cause specific problems. People want to see reflections and at the same time they do not want to be blinded by them. To prevent blinding effect in such a case the lighting from above is preferable.

Recommendations for the illumination of buildings are usually given in luminance values, which are related to the reflected light (Table 8.3) [82]:

$$L = \frac{E \times \rho}{\pi} \quad \text{or} \quad E = \frac{\pi \times L}{\rho}, \tag{8.1}$$

where L is luminance (cd/m^2), E is illuminance (lux), and ρ is reflectance.

Table 8.3. Recommended luminance values for buildings [82].

Situation	L (cd/m^2)
Freestanding building or statue	3.2 – 6.5
Building in a street or on a square:	
• in dark surroundings	6.5 – 10
• in well-lit surroundings	10-13

The required illuminance E depends also on the brightness of the surface and on the light levels in the surrounding area. The reflectance for some building material is given in Table 8.4. It makes no sense to illuminate a dark wall; to achieve some effect reflectance must be equal to or greater than 0.2.

Table 8.4. Reflectance of different building materials [82].

Material	Condition	Reflectance
yellow brick	new	0.3-0.4
red brick	new	0.15-0.25
brick	dirty	0.05-0.1
white marble	clean	0.6-0.65
granite	clean	0.1-0.15
concrete	light	0.4-0.5
concrete	dark	0.2-0.3
concrete	dirty	0.05-0.1
plasterwork (pale yellow)	new	0.35-0.55

Using equation 8.2 and the information from Table 8.3 and Table 8.4 the required illuminance *E* for a building in a street or on a square can be found. For some materials this is summarized in Table 8.5.

Table 8.5. Illuminance values for different building materials [82].

Material	Dark surroundings	Light surrounding
white marble	35	55
light concrete	50	80
yellow brick (new)	70	105
dark concrete	100	160
granite (clean)	200	310

A variety of lamps are available on the market. There are two main factors to take into account during the selection process:

- color of the light, which must fit in with the light of the surroundings
- color rendering, which must produce the best possible appearance of the illuminated surfaces and details. If it is necessary to emphasize the color of the facade then good color rendering is of primary importance [82].

8.3. Parks and recreational areas

It is necessary to pay particular attention to the illumination of town parks. In parks the visitor needs to know what happens around him, also at night time. There must be a good view of the pathways and cycle paths. The feeling of being safe is also important. The transition from the well-lit street to the park must be naturally tuned to the adaptation of the human eye and not be abrupt [82].

Trees and bushes are often illuminated in the parks for peaceful mood. The choice of lamp for this application is also tricky. For example, deciduous trees need a different light source than coniferous trees. Trees and wooded areas absorb quite a lot of light from illumination. However, not everything has to be illuminated. Trees with interesting shapes can just be left in the dark to create silhouette thus making scene more attractive [82].

Fountains create liveliness and make the surroundings look particularly cheerful. Illuminated fountains (in particular with colored light) look best on dark background. Large open areas such as boulevards and squares are appropriate. It is best to place light source under water, just under the jet of water, which leads to beautiful effects. External light weakens effect of fountain illumination [82].

Advances of modern lighting technologies, such as dimming possibility or even full color control, gives opportunity to make temporary changes in architecture, monuments, and standalone objects, to create a mood or during special occasions without doing anything with objects themselves. Sometimes color may be used to achieve unusual effect or to create special concept. It can help to ensure that daytime harmony of the site may be experienced also at night [82].

8.4. Choice of the Lighting Solution for City Zones

As described above there are a lot of aspects to take into account in buildings, monuments, , parks, fountains, and other city lighting zones. There are always several possible solutions; the result is a choice. In case of city zones, it is necessary not only to fulfill standard requirements but also aesthetic appearance. Thus, the implementation of successful lighting project for an object to a great extent depends on the experience and professional skills of lighting designer.

8.5. Light pollution

Light pollution is a by-product of outdoor lighting, especially when luminaires with inappropriate light distribution curve are used (application inefficient luminaires), and when they are lit to excessive levels. Very often we only need a little light to see each other, at least when all the light sources are in harmony. It is often possible to do more with less light; more light is not always better, particularly when it increases contrasts. Illumination is not necessary everywhere; after all, the idea is that we should still be able to see the stars in the sky [82].

A light pollution world map during 2006 is shown in Fig. 8.2. The main objective for the reduction of light pollution is the use of application-efficient luminaires, light only what is actually needed, when it is needed, and only to the necessary level.

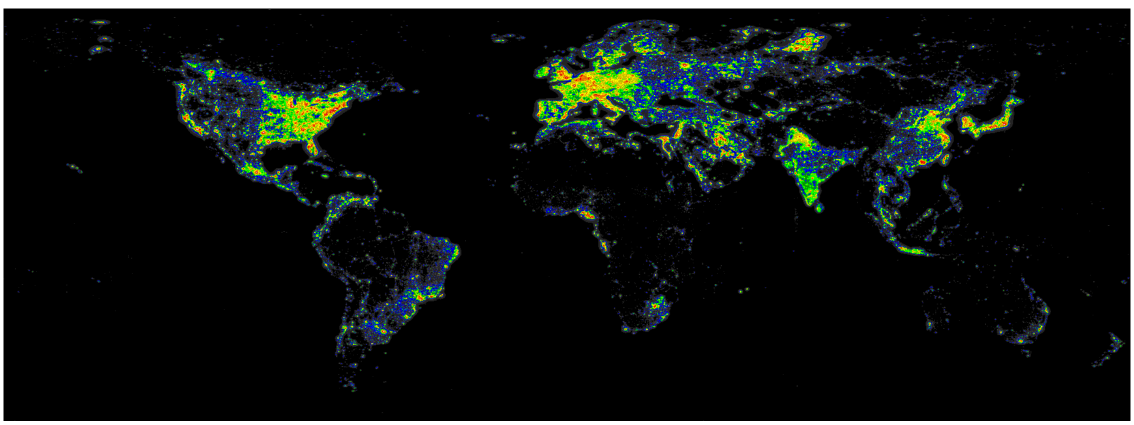


Fig. 8.2 Light pollution world map (2006) [85].

Light pollution components and graphical description is given in Fig. 8.3. It includes the following components:

- Glare – excessive brightness that causes visual discomfort
- Sky glow – brightening of the night sky over inhabited areas
- Light trespass – light falling where it is not intended or needed
- Clutter – bright, confusing and excessive groupings of light sources

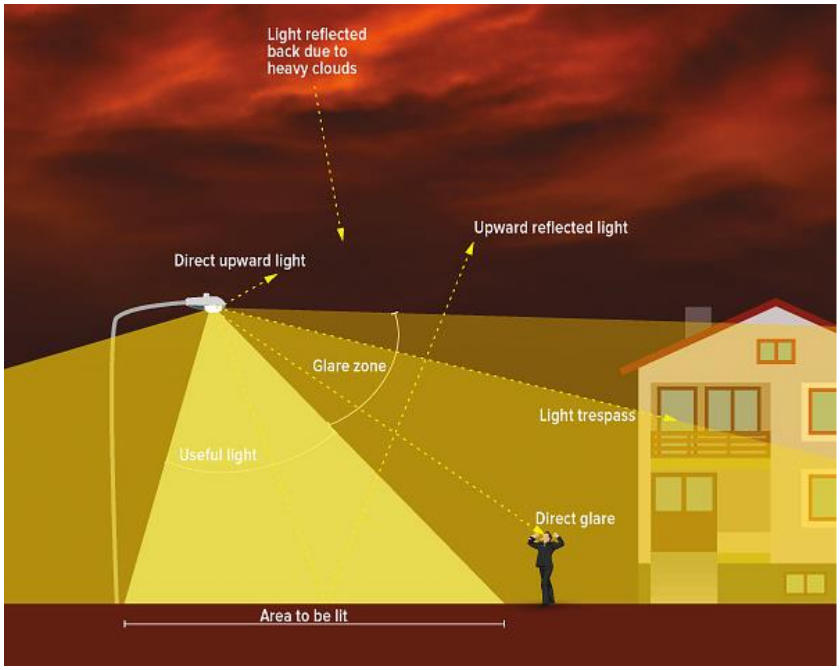


Fig. 8.3. Example of useful light and light pollution from a typical outdoor luminaire [86].

To reduce the light pollution effect the Illuminating Engineering Society of North America (IESNA) has adopted the concept of environmental zones as described in Table 8.6, and recommended their use in developing new outdoor lighting (IESNA 1999). Application of environmental zones is first envisioned for the protection of natural park preserves and astronomical observatories. [36].

Table 8.6. Light environmental zones as adopted by IESNA [36].

Environmental zone	Description
E1	Areas with intrinsically dark landscapes National parks or residential areas with strict limits on light trespass Roads usually unlit
E2	Areas of low ambient brightness Outer urban or rural residential areas
E3	Areas of medium ambient brightness Urban residential areas
E4	Areas of high ambient brightness Urban areas, residential and commercial with high levels of night time activity

The IESNA gives recommendations for pre-curfew and post-curfew light levels to limit light trespass (IESNA 1999). Pre-curfew is from dusk until 11:00 p.m. local time, when the area being illuminated is more likely to be in use. Post-curfew is from 11:00 p.m. to 7:00 a.m. local time. Recommended lighting levels are higher during pre-curfew time. The Institution of Lighting Engineers (ILE) provides guidelines on obtrusive light limits for sky glow, light trespass, and glare in exterior lighting installations (ILE 2000) [36]. These limits are summarized in Table 8.7,

Table 8.8, and

Table 8.9.

Table 8.7. Limits on sky glow for different environmental zones [36]

Environmental zone	Sky glow ULR[13] (max %)
E1	0.0
E2	2.5
E3	5.0
E4	15

Table 8.8. Limits on light trespass for different environmental zones [36].

Environmental zone	Light into windows, vertical illuminance (lux)	
	Before curfew	After curfew
E1	2	1[14]
E2	5	1
E3	10	2
E4	25	5

Table 8.9. Limits on glare for different environmental zones [36].

Environmental zone	Source intensity (kilocandela)	
	Before curfew	After curfew
E1	0	0.0
E2	20	0.5
E3	30	1.0
E4	30	2.5

[13] ULR is the Upward Light Ratio of the installation and is the maximum permitted percentage of luminaire flux for the total installation that goes directly into the sky.

[14] Acceptable from public road lighting installations only.

9 MODERNIZATION OF STREET LIGHTING SYSTEMS-PRACTICAL SOLUTIONS

9.1. System modernization strategies

First of all, the modernization level should be considered. These levels may be distinguished as follows:

- Replacement of old luminaires with new LED luminaires (without dimming function)
- Replacing of old luminaires with new LED luminaires (with dimming function)
- Replacing of old luminaires with new LED luminaires (Smart lighting solution)

One important point to consider is the time in which the project will cover its costs. It directly depends on the price of electricity. Thus the approximate pay off time in the EU countries is 5 to 7 years[15] when upgrading from sodium lamps to the LED lamps (lighting system without dimming function), 3 to 5 years when upgrading from sodium lamps to the LED lamps with dimming function, and approximately the same pay off time when upgrading to Smart lighting systems[16]. In Nordic countries (Scandinavian and Baltic countries), the pay off period is even shorter due to higher electricity price. In the CIS[17] countries, where the price of electricity is noticeably less in comparison with the EU countries, the pay off period is longer (up to 12 years).

So, lighting system pay off time should be kept in mind throughout the consideration of all the parameters during the implementation of new lighting system or renovation project. The higher the payoff time the higher attention should be paid to the quality of the system elements and equipment. Also, particular attention should be paid to the scheduled system element inspections and maintenance–scheduled cleaning of luminaires, painting of metal parts of columns and brackets, or cable insulation measurements. The higher the pay off period the more critical are maintenance procedures.

It should be taken into account that the repair works of some lighting system elements when the system is put in operation may be costly or hard to complete. If it is decided to use the elements of the existing equipment such as existing columns, brackets, cables, and switchboards, they should operate correctly at least during the pay off period. If some lighting system configurations require additional wires for communication[18] then the old system cables should definitely be replaced by the new ones. It should be kept in mind that faulty existing equipment may cause failure of new LED luminaires.

The decision to use the existing equipment strongly depends on the pay off period and modernization level. The relevant municipal service company must reach a verdict on the capability of individual old system elements for further use during the pay off period of the new lighting system by making inspection of the existing equipment and performing related measurements.

[15] Often the existing street lighting system does not fultfill lighting standard requirements in accordance with the specified lighting standard. However, during implementation of renovation project the standard requirements must be fulfiled. Higher illumination levels or even additional luminaires may be required. This also may increase the payoff time. Also, the safety associated with sufficient light level in accordance with specified lighting class should be considered as the first priority.

[16] In the EU countries where electricity price is quite high.

[17] Commonwealth of Independent States.

[18] For instance, additional DALI communication cables, which is not a common solution in new street lighting systems; wireless communication is more prevalent.

Another aspect to keep in mind with the existing columns and brackets is that in most cases there will be limited choice among the standard LED luminaires to provide uniform light distribution and only custom luminaire configurations will be suitable.

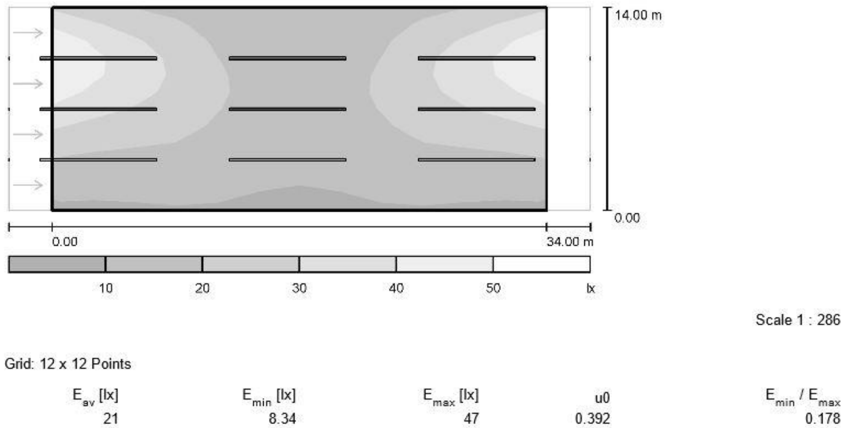
Usually, old type street luminaires were equipped with discharge lamp ballasted by capacitor, inductor or transformer – the elements with inherent capability to withstand against the voltage surges caused by other connected electric equipment or by lightning. The LED luminaires with all the internal electronic components are extremely sensitive to the voltage surges. Usually, separate electronic parts of luminaires have their own surge protection. However, the experience has shown that such protection is often not sufficient. Therefore, a good practice is to install additional surge protection device in each luminaire with the capability to withstand at least 10 kA and 10 kV surges.

A really significant role in the successful project implementation plays light planning. Often luminaire's efficiency is considered as the most critical parameter when comparing the lighting system renovation projects associated with the reduction of the CO_2 emission. Luminaire efficiency is good for fast estimation of quality of the LED module and whole luminaire. For the same luminaire housing and internal component layout higher lm/W at the same wattage means less heat, less stress on internal components, thus potentially longer service life. The efficiency of luminaire can always be improved by increasing the number of LED per luminaire, which in turn increases the price of the end product.

However, all efforts to increase luminous efficiency can be reduced to zero by the wrong choice of luminaire optics. The uniform light distribution is definitely a more critical parameter over the efficiency of the luminaire as the minimal required illumination level and better uniformity can be achieved with proper optics even at the lower total system power values and, consequently, lower electrical power consumption and electricity bills!.

The samples are given in Fig. 9.1 and Fig. 9.2.

a)



b)

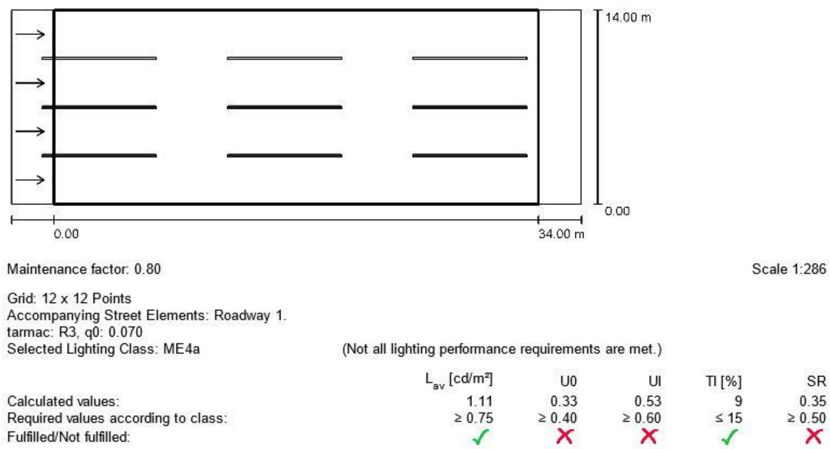


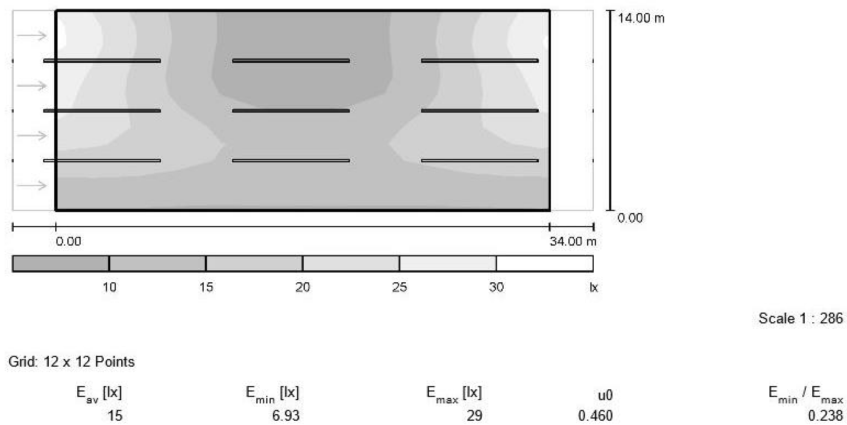
Fig. 9.1. Partial report from DIALux road lighting project (with 168 W LED luminaires and optics type A): (a) surface illuminance map; (b) report on the compliance with the lighting performance requirements.

In Fig. 9.1 the partial report of lighting system configuration with 168 W LED luminaires and type A optics is given. Surface illuminance map is given in Fig. 9.1 (a) for better visual perception of the light distribution on the road for the given configuration. The evaluation of lighting parameters in accordance with given lighting class is shown in Fig. 9.1 (b). Below is given a brief description of these parameters:

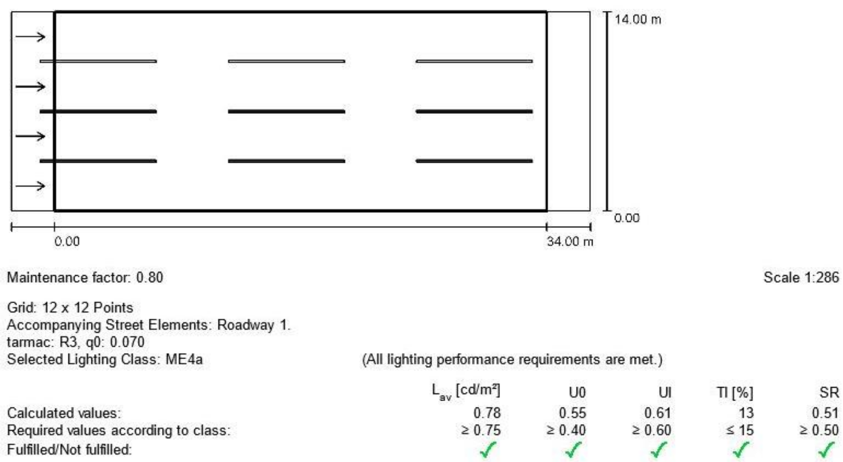
- L_{av} – average road surface luminance
- U_0 – uniformity of surface E_{min}/E_{av}
- U_l – uniformity of surface E_{min}/E_{max}
- TI – threshold increment-the percentage increment of the detection threshold caused by disability glare in road lighting
- SR – uniformity of calculated surface E_{min}/E_{av}

As it can be seen from this figure that there are problems with uniformity and the requirements are not fulfilled.

In Fig. 9.12 the partial report of lighting system configuration with 137 W LED luminaires and type B optics is given. Although the power of luminaires is approximately by 18 % lower in comparison with the previously described system configuration, the appropriate optics gives opportunity to fulfil the requirements in accordance with the given lighting class.



a)



b)

Fig. 9.2. Partial report from the same as in Fig. 9.1 DIALux road lighting project (with 137 W LED luminaires and optics type B): (a) surface illuminance map; (b) report on the compliance with the lighting performance requirements.

As a conclusion for this it can be said that the proper optics choice can bring more benefits than higher luminaire wattage or efficacy.

So, particular attention should be paid to street/road light planning, especially uniformity given as a value in the light planning project report. The closer this value is to 1 the more uniform distribution.

Actually, all the considerations described above lead to the main conclusion, that for proper estimation of the efficiency of the lighting system the parameter of whole system should be considered, not only the parameters of a single luminaire. So, the most critical parameter is total system electrical power consumption. The most effective lighting system consumes the least amount of electrical power when fulfilling all the lighting requirements.

9.2. Luminaire properties and features to pay attention to

1. Conformance to the norms, directives, and specific standards. Presence of the certification marks.
2. Materials and separate construction elements – capable of withstanding the environmental conditions (inherent resistance to corrosion and UV radiation); bolts, nuts and screws with stainless coating or made from stainless material.
3. The heatsink construction – cast aluminum housing, which at the same time plays the heatsink role, is one of the best possible options.
4. Fastening construction – convenient attachment to the pole (bracket/console)
5. Luminaire angle change mechanism – convenient change in small increments
6. Protection levels against ingress of dust and water (IP code), and impact resistance (IK code)
7. Painting quality – absence of cracks and scratches for maximum corrosion resistance
8. Operation temperature range – corresponds to the specific region requirements
9. Adequate surge protection level – capability to withstand at least 10 kA and 10 kV surges

9.3. Use of existing equipment

The use of existing equipment should be carefully estimated for each particular case, part of lighting system, and equipment being in use. For instance, different types of lighting columns are exposed to different defects as shown in Table 9.1.

It is difficult to estimate depreciation level of the columns; the expert opinion is usually necessary for the final decision. The same situation is with the rest of the equipment in lighting system.

Table 9.1. Significant defects for different lighting column types [80].

Significant defects	Types of lighting column					
	Tubular steel	Sheet steel	Aluminum	Concrete	Composite	Cast iron
Corrosion up to 300mm above ground level			x			
Corrosion from the bottom of the door to just below ground level	x	x				x
Corrosion of the root of planted columns	x	x	x			x
Corrosion at the door opening	x	x	x			
Cracking at the door opening	x	x	x		x	x
Internal corrosion of overlap joints	x	x				
Cracking below ground						x
Cracking at welded joints	x	x	x			
Failure of adhesives			x		x	
Corrosion of pre-stressing wires of pre-stressed columns				x		
Corrosion of the reinforcement and cracking of the concrete at the base and around the door opening				x		
Corrosion of reinforcement and cracking of concrete at or on the bracket/shaft joint				x		
Impact damage and vandalism	x	x	x	x	x	x
De-lamination					x	
Effects of UV					x	

10 ECONOMICS OF STREET LIGHTING PROJECTS

10.1. Energy audit

Detailed energy audit for street lighting is to assess its EE potential in the municipalities, and to identify potential investments which may be needed to rehabilitate and optimize the lighting system, including replacement of lighting equipment, and associated infrastructure.

The energy audit will help determine the following:

1. Energy-saving potential
2. Energy efficiency indicators
3. Energy efficiency measures needed to increase the energy efficiency of the lighting system.

To analyze the rationale for the activities proposed in the energy audit it is necessary to evaluate the results of calculation of the economic efficiency of street lighting system modernization.

Economic efficiency of street lighting projects is determined by the following main factors:

- Switching lighting on/off, based on the real level of natural illumination, taking into account the current length of daylight and weather conditions
- Economical mode of partial illumination during night time hours due to smooth dimming of the LED street lights output
- Saving on the "Luminaire running time" by reducing the total burning time
- Savings on organizational and technical measures: accident prevention, savings on maintenance, extending service life of equipment (lamps, wires), etc.

When evaluating the economic data of energy audit, special attention should be paid to comparing the options for technical, organizational and financial solutions being developed for each energy-saving measure.

Each measure proposed by the audit should contain the following data:

1. Analysis of the existing lighting system
2. Definition of goals and objectives of installation of energy-efficient lights
3. Description of plausible scenarios
4. Rationale and choice of technical solutions
5. Description of the technical solutions and characteristics of the selected equipment
6. Evaluation of the costs

The feasibility analysis of pole acquisition, fixtures replacement as well as potential rebate and/or financing programs should be considered by the auditor. This can be done in three phases:

Phase I - Identification and analysis of individual poles characteristics:

1. Conduct a full inventory of the light poles, including their location. Comments on age or condition of the pole(s)/lamp(s) should be included.
2. Identify the type of light fixture on each pole and estimated energy/maintenance cost for each type of pole/fixtures.

Phase II – Estimation of financial feasibility

1. Calculate expected cost of acquisition of qualified poles and show any cost savings vs. current arrangement.
2. Calculate cost/benefit ratio of bulb replacement of existing lamps.
3. Compare operation and maintenance costs of existing light fixtures against the LED lights.

Phase Ill - Recommendations

With the above feasibility analysis completed, the auditor should provide recommendations on the next course of action.

10.2. Evaluation of options

Basic principles for evaluating the effectiveness of the street lighting modernization project are:

1. Review the project throughout its life cycle, from conducting an audit of the lighting system to the conclusion of the project.
2. Define the conditions for comparing different activities.
3. Define an effective measure when comparing alternative options to meet project objectives.
4. Account for future costs associated with the development and implementation of the project.
5. Determine the effectiveness of activities at various stages of project preparation and implementation.

Each measure should be evaluated through a basic feasibility study, which includes:

- setting the goal
- describing the current situation and the proposed organizational decision
- calculating the costs and revenues of the project, and
- conclusions on the implementation of the event.

Evaluation of the effectiveness of used funds allocated to the implementation of energy saving measures should be carried out on the basis of the following indicators:

- simple and integral payback period;
- pure discounted income/net present value (NPV). Net present value is the difference between the present value of cash inflows and the present value of cash outflows. It is used in capital budgeting to analyze the profitability of a projected investment or project. Net present value focuses on the total cost gained over the whole life of the project. Future benefits and costs are discounted at a compounded interest rate, typically 12% per year. Benefits, net of costs, are then summed across all years.
- internal rate of return (IRR). It is a metric used in capital budgeting measuring the profitability of potential investments. Internal Rate of Return is the rate of discount at which the NPV of the project is reduced to zero.[19]

[19] Some valuable discussion of the NPV and IRR metrics can be found at the following links:

http://www.investopedia.com/ask/answers/05/npv-irr.asp

http://www.investopedia.com/ask/answers/05/irrvsnpvcapitalbudgeting.asp

When evaluating the cost-effectiveness of replacing old fixtures with new LEDs, in addition to saving on the electricity bill, it is also necessary to take into account the savings associated with the increased average time of trouble-free operation of new fixtures. It is also necessary to take into account the costs associated with the disposal of old mercury and other lamps.

Below is the algorithm for calculating the efficiency of replacing luminaires:

1. Determine the active power consumed by the lamps.
2. For a lamp of the appropriate power determine the value of the light flux generated by this luminary.
3. Select suitable types of energy saving lamps to be installed in place of the existing lamps, based on the compliance with the criteria for supply voltage U, color temperature T, length of emitted electromagnetic waves λ, color rendering index Ra, average time of failure-free operation, and according to the requirements of DBN and SNIP, the degree of protection IP, the type of lamp cap and other conditions.
4. Select variety of energy saving lamps able to generate the same luminous flux. In the presence of several versions of lamps for installation, preference is given to a lamp with a greater nominal efficiency and greater average time of trouble-free operation.
5. For replacement purposes, a luminaire of the same type is selected with a reserve for the generated light flux.
6. Determine consumed active power for the selected lamp.
7. Calculate the average duration of the lamp's on-time per year.
8. Calculate monetary savings for all years in question and calculate a payback period.

10.2.1 Indicators for evaluating the efficiency of lamp replacement:

Type of lamp
Power [kW]
Total power [kW]
Reduction of power consumption [kW]
Luminous flux, [lm]
Average service life [h]
Price [EUR]
Cost [EUR]
Electricity consumption per year [kWh]
Annual energy saving [kWh]
Total annual savings [EUR]
Simple payback period [years]

To assess the economic effectiveness of the implementation of the proposed measure over a long period, inflation, the growth of tariffs for energy resources, payback period, NPV and IRR are taken into account.

10.2.2 LED street lighting projects

Modern, low energy consuming, efficient street lighting options revolve mainly around LED, fluorescent lamps and induction lighting. The LED lighting has emerged as the favored energy efficient street lighting technology due to energy savings of up to 80 per cent and savings on maintenance costs. More manufacturers have concentrated on LEDs, their efficiency, light output and increasing quality.

The general direction of reconstruction of lighting systems in the public sector is focused on the introduction of energy-efficient LED light sources and flexible individual control of light sources in hybrid lighting complexes. A typical municipal street lighting system will include a blend of lighting in the residential, commercial, and highway settings; the types of LED luminaires and bulbs may range from low-powered to high-powered.

The total project capital and development costs could vary. The LED project costs could be increased by poles replacement, application of dimming technology, installation costs, survey costs, and adviser and project team costs.

The audit report should forecast the inflation related to energy cost and savings over the project period (influenced by the forecasted LED life and the warranties obtained), and the long-term inflation related to maintaining achieved savings. Electricity costs for municipalities have more than doubled over the last 10 years so LED projects economic calculations should include long-term electricity increase. The increase in the costs of maintenance is likely to be achieved but will be influenced by financial ability of the local budget. The total LED project costs can therefore be substantial but so can be the forecasted savings.

Street lighting project costs can be largely offset by the future energy, replacement, and maintenance savings. Therefore, municipalities should not be put off by the initial capital costs and need to carefully evaluate each component over the life of the project.

10.3. TECHNICAL AND ECONOMIC INDICATORS OF STREET LIGHTING PROJECT COSTS

10.3.1 Indicators used in financial study of the project

Costs for lamps including replacement [EUR]
Street (cable lines) length [km]
Costs for cable lines replacement [EUR]
Number of replaced pillars [quantity]
Costs for pillars replacement [EUR]
Monitoring and control system [technical specification]
Costs for monitoring and control system [EUR]
Installed capacity [kW]
Annual Net Saving [EUR]

Savings [%]
Total costs excluding VAT [EUR]
Simple Payback Period [years]
Net NPV [EUR]
IRR [%]
Costs per lamp[EUR/lamp]
Costs per km [EUR/km]
Costs per installed lamp power [EUR/kW]
Costs for monitoring and control system [EUR]
Costs per pillar [EUR]

10.3.2 Savings

Retrofitted lighting systems can be a major source of energy savings. These savings can be so significant that lighting systems should be tread like an investment. The financial priorities and goals of the street lighting projects should correspond to the required financial indicators.

The relative savings in the projects amount, on average, to more than 50%. In general, the savings are higher in cases where incandescent light bulbs are replaced.

In many cases, savings were achieved not only by the LED technology but also due to other lighting energy efficiency measures, such as motion controls or time scheduling.

The manufacturers stress that besides evaluation of energy savings the quality of existing installation, as well as quality and age of the original installation, need to be assessed.

10.3.3 Calculating Financial Payback Periods

Given the continuous development in the LED technology and the unstable quality of different installations, the project analysis should specifically highlight the fact that the given installation has fulfilled the relevant norms and lighting standards. The payback period should vary from less than a 5 years to around 7 years, with the average of 4.5 years.

A preliminary analysis of a simple financial payback period of a retrofit/new project can be conducted using the following formula:

Simple Financial Payback = initial cost of the project/annual savings in energy and maintenance costs

In general, a simple financial payback under 3 to 5 years is considered favorable.

10.3.4 Pole spacing

The projects economic results would have been different with different pole systems and spacing, when the LEDs have to be installed in the existing system. The life-cycle costs of the whole installation are dominated by the costs of the poles. To put it simply, the pole spacing for LEDs needs to be more dense in order to comply with the standards, but it will create additional costs.

10.3.5 Conducting a Life Cycle Cost Analysis

A Life Cycle Cost Analysis (LCCA) is a calculation that provides the total cost of a lighting system over its lifetime, from purchase to disposal. The function of LCCA is to guide purchasing decisions by showing the actual value of a given lighting system from purchase to disposal, and conducting cost comparison based on all costs as opposed to initial investment costs alone.

A system requiring lower initial investment may use more energy (higher operating cost), require frequent luminaire cleaning (higher maintenance costs), and have a shorter lifespan (require frequent replacement). Conversely, a system requiring higher initial investment may cost significantly less over the course of its lifespan for opposite reasons.

10.3.6 Estimates of Financial Feasibility

The most immediate option available to the municipality is to explore the feasibility of upgrading light fixtures on city-owned network.

Assumptions (example) of upgrading existing fixtures to the LED technology.

Cost of Poles [EUR /pole]:
Project Finance Rate [%]:
Finance Period [yrs]:
Pole Replacement Reserve [per pole/month]:
Tariff Escalation Rate [%/yr]:
O&M, Repairs, Replacement Escalation Rate [%/yr]:
Discount Rate [%]:
HPS O&M Cost [EUR /pole/month]:
LED Retrofit O&M [EUR /pole/month]:

Results (example)

Cost of Poles [EUR]:
LED Installation Costs [EUR]
SCE Incentive Amount [EUR]:
Loan Amount [EUR]:
Positive Cash Flow Begins in Year:
Base Case PV [EUR]:
Proposed Case PV [EUR]:
20-year NPV Savings [EUR]:

Retrofitting city-owned lights from the HPS to the LED fixtures could result in lower energy costs for the municipality. The difference between the two types of lighting fixtures is that the HPS fixtures are low cost but have high energy consumption. Although the HPS fixtures are readily available they have a short service life. The LED fixtures consume less energy but can be expensive.

10.3.7 Estimated Energy Savings and Associated Costs

It should be noted that the total annual cost savings are based on economic analysis assuming municipal ownership of streetlights and the ability for municipalities to receive discounted volume pricing for LED fixtures. However, very often, only part of the estimated streetlight inventory may be under municipal ownership.

To estimate the energy savings potential for a municipal LED retrofit, all streetlights have to be first grouped into “bins” by the type of lamp technology and their wattage. In general, the detailed street lighting inventories show street light count, including lamp type and its nominal wattage. To account for ballast losses, these nominal wattages have to be converted to actual connected wattages using typical ballast loss conversion factors. Next, the auditor can apply an average percentage of wattage reduction per fixture to each bin depending on the size of the fixture. Finally, the estimated annual operating hours can be applied to determine the energy savings for each bin.

The savings for all bins can then be summed to develop the estimated annual savings.

The analysis may omit savings for existing incandescent, induction, and fluorescent fixtures when they represent a small percentage of the overall technology distribution and cannot be well grouped around common wattages.

Savings for advanced street lighting control system can be estimated by assuming that not all of existing street lights are appropriate for dimming controls. This assumption reflects the fact that there are both practical and aesthetic barriers to implementing dimming controls on all streetlights.

Economic analysis (example)

From	To	Count	Investment costs [UAH]	Electricity Savings [UAH]	O&M savings [UAH]	Pay back period [years]	NPV [UAH]	IRR [%]
HPM 250	Fixture LED 50							
HPS 250	Fixture LED 150 DKU							
HPS 150	Fixture LED 65 DKU							
HPS 70	Fixture LED 30							
CFL 65 W	Fixture LED 30							
CFL 50 W	Fixture LED 30							
CFL 30 W	LED Lamps 15							
CFL 26 W	LED Lamps 10							
CFL 14 W	LED Lamps 8							

10.3.8 Estimated Installation Costs

Similarly to the approach used in estimating energy savings, the costs for the LED retrofit are estimated assuming appropriate total installation costs (i.e., total fixture costs and installation works) for each wattage bin. Estimated installation costs can be estimated assuming installation costs per fixture.

10.3.9 Estimated Operation and Maintenance Cost Savings

Using a simplified approach, the annual operation and maintenance savings can be estimated per fixture based on typical replacement lamp costs, labor costs, and re-lamping frequency over the life of the LED fixtures when compared to the existing lights.

Savings (example)

Savings components	Existing situation		After implementation		Net savings	
	Quantity [kWh]	[UAH/ year]	Quantity [kWh]	[UAH/ year]	Quantity [kWh]	[UAH/ year]
Electricity use						
Maintenance costs						
Savings total						
Electricity Savings %						

10.3.10 Cost effectiveness-other benefits

In addition to street lighting projects being able to pay for itself with actual cost savings, there are a number of other benefits. They include:

- longer LED lifespan, which reduces the number of maintenance staff and fuel usage for transportation to the replacement sites;
- reduction of mercury and other hazardous chemical components that require special disposal procedures;
- improvement in illumination levels and lighting quality; and,
- reduction of light pollution and sky glow.

11 PROCUREMENT OF EQUIPMENT AND SERVICES

The procurement of equipment and services to a great extent depends on the technical project, which is developed on the base of inspection of the object and in accordance with the customer's requirements. In addition an assessment of further use of existing equipment may be considered. Bill of Quantity of necessary materials and works will be attached to the project during its development. However, quite often procurement of equipment and services is carried out through a competitive bidding. Then the parameters and requirements of this equipment should be clearly defined in procurement documentation, as the specific model of known manufacturer, or a brand cannot be given to be sure that all competitors have an equal footing. Sometimes, it is quite a tricky task as some components in common parlance are called by brand names. So, particular attention should be paid to the definition of parameter and technical specifications, while the datasheets of each component should be carefully studied and then defined in procurement documentation in order to receive proper equipment through competitive bidding.

For example, below in Table 11.1, a sample report from the project of replacement of street luminaires and modernization of separate lighting system elements is given. As can be seen from this table, a plenty of different components, materials, and work types are necessary to accomplish project.

In Table 11.2 there are summarized parameters of some components from Table 11.1. These parameters are appropriate for competitive bidding documentation. When preparing competitive bidding documentation, it is always worth consulting with project designer and experts.

It also should be noted that in case of smart lightning system the maintenance of IT part of the system can be procured as service. Then the payment will be charged, for example, like a subscription fee each year for each luminaire.

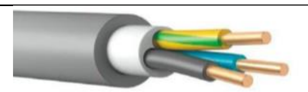
Table 11.1. Sample of report of replacement of street luminaires and modernization of separate lighting system elements.

No.	Materials, tasks	Unit	Qty	Total at entire volume	By category				
				EUR	Qty	Materials	Mech.	Salary	Total
						EUR	EUR	EUR	EUR
	Materials								
1	Cable with Al conductors AXMK 4x25	m	2400	6679.53	2400	6679.53	0.00	0.00	6679.53
2	Cable with Cu conductors NYM 3x1,5	m	460	227.77	460	227.77	0.00	0.00	227.77
3	Protective tubes DVK75	m	2300	1564.00	2300	1564.00	0.00	0.00	1564.00
4	Plastic tube for puncture PE80.PN10 110x8.1	m	30	202.84	30	202.84	0.00	0.00	202.84
5	Warning tape	m	2300	117.81	2300	117.81	0.00	0.00	117.81
6	Cable tips EPKT 0015	pcs.	226	910.68	226	910.68	0.00	0.00	910.68

7	Steel lightening pole with concrete base 8 PJ 60 HL 1; 6m.	pcs.	46	9406.25	46	9406.25	0.00	0.00	9406.25
8	Bracket P 10 60	pcs.	46	1655.68	46	1655.68	0.00	0.00	1655.68
9	LED Luminaire XXX with XXX control unit	pcs.	46	25657.22	46	25657.22	0.00	0.00	25657.22
10	Fuse, holder set for lighting pole SV 15.11	pcs.	46	662.11	46	662.11	0.00	0.00	662.11
11	XXX segment controller	pcs.	1	558.48	1	558.48	0.00	0.00	558.48
12	Miniature circuit breaker (MCB) 1P6A C	pcs.	46	196.36	46	196.36	0.00	0.00	196.36
13	JAB Ground Rod Clamps 5/8	pcs.	46	165.72	46	165.72	0.00	0.00	165.72
14	Ground Rod Cu d=5/8'' h=1,5m	pcs.	92	1311.66	92	1311.66	0.00	0.00	1311.66
15	Ground Rod Top d=5/8''	pcs.	46	344.80	46	344.80	0.00	0.00	344.80
16	Ground Rod Connector C60	pcs.	46	337.73	46	337.73	0.00	0.00	337.73
17	Accessories	sets	1	426.86	1	426.86	0.00	0.00	426.86
	Works								
1	Hole digging for puncture 3x1.5x1.5m	pcs.	6	110.98	6	0.00	8.54	102.45	110.98
2	Ground puncture with PE80.PN10 110x8.1 plastic tube	m	30	853.72	30	0.00	341.49	512.23	853.72
3	Trench digging and cable burial (hand work)	m	2300	1569.26	2300	0.00	327.26	1242.00	1569.26
4	Groundwork for cable	m	2300	672.26	2300	0.00	327.26	345.00	672.26
5	Burial of protective tubes DVK75	m	2300	1505.40	2300	0.00	327.26	1178.14	1505.40
6	Burial of AXMK 4x25 cable with protective tube in trench	m	2300	1523.26	2300	0.00	327.26	1196.00	1523.26
7	Final finish installation	pcs.	92	523.62	92	0.00	13.09	510.53	523.62
8	Application of protective tape MBN	m	2300	242.17	2300	0.00	163.63	78.54	242.17

9	Gigging holes for pole base 8 m	pcs.	46	680.70	46	0.00	327.26	353.44	680.70
10	Installation of lighting poles with base and console	pcs.	46	2683.54	46	0.00	327.26	2356.28	2683.54
11	Installation of XXX LED luminaire	pcs.	46	798.52	46	0.00	130.90	667.61	798.52
12	Installation of fuse, holder set SV 15.11	pcs.	46	674.16	46	0.00	6.55	667.61	674.16
13	Installation of XXX segment controller	pcs.	1	162.05	1	0.00	0.14	161.91	162.05
14	Installation of NYM 3x1,5 cables in lighting poles	m	460	418.89	460	0.00	65.45	353.44	418.89
15	Renewal of asphalt coating	m^2	30	754.27	30	555.00	4.27	195.00	754.27
16	Renewal of grass	m^2	50	754.27	50	110.00	7.11	225.00	342.11
17	Development of technical project (the customer provides topography)	set	1	342.11	1	0.00	0.00	1520.00	1520.00
18	Insulation resistance measurements	pcs.	184	1520.00	184	0.00	26.18	588.80	614.98
19	Execution of digital measurements	m	2300	614.98	2300	0.00	327.26	598.00	925.26
20	Ground resistance measurements	pcs.	46	925.26	46	0.00	6.55	183.08	189.63
	Total			67190.31		51090.53	3064.72	13035.06	67190.31

Table 11.2. Summarized parameters of some components from Table 11.1. (Appropriate for competitive bidding documentation).

1. AXMK cable	
Construction:	• Four conductor cable, XPLE insulation, filler layer, PVC sheath • Aluminum conductor solid, class 1, or stranded, Class 2 • 4x25 conductors
Use:	Fixed outdoor and underground installations.
Rated voltage:	U_0/U = 0.6/1 kV; U_m = 1.2 kV
Maximum permissible conductor temperature in continuous operation and in short circuit operation (max. 5 s)	+90 °C +250 °C
Minimum recommended temperature during laying	– 15 °C
Manufactured in accordance with	IEC 60502-1
2. NYM cable	
Construction:	• PVC insulation, inner covering from not vulcanized rubber compound, special PVC compound Sheath • Annealed copper solid class 1, or circular stranded conductor class 2 acc. to EN 60228 • 3x1,5 conductors
Use:	In poles. Outdoor usage is possible only if cable is protected against direct sunlight
Rated voltage:	U_0/U = 300/500 V; (2 kV test voltage)
Maximum permissible conductor temperature in continuous operation and in short circuit operation (max. 5 s)	+70 °C +160 °C
Minimum recommended temperature during installation	– 5 °C
Flame retardant in accordance with:	IEC 60332-1-2
9. LED luminaire	
Construction	• Die-cast aluminum body • Tool-less opening or closing • Vandal protected (IK09) • IP66 protection
Performance	• ≥110 lm/W system efficiency • ≥ 0.92 power factor • Ra ≥ 70 color rendering index (CRI) • 4000°K color • -40°C to +50°C working temperature • 220 to 240 VAC voltage power
Protection	Surge protection U_{oc} = 10kV, In = 5kA
Control	Radio frequency control unit (technical specifications below)

Lifetime, h	100,000
Guarantee, years	5
9.1. LED luminaire controller	
Construction	Dimensions fit luminaire
Environmental requirements	-40°C to +50°C working temperature
Communication performance	• RF communication Frequency - 868MHz • Dynamic mesh topology • Network size up to 350 nodes • Network depth up to 14 hops
Power	• Voltage: 230 VAC -15% to +10% • Frequency: 50/60 Hz • Peak over voltage 3000V • Power consumption <2W
Inputs and Outputs (at least)	• 1x Mains power • 1x Relay output • 1x Configurable control interface (DALI, 0-10V, PWM) • 1x Digital input • 1x SMA for external RF antenna

12 FINANCING OF STREET LIGHTING PROJECTS FOR MUNICIPALITIES

A high proportion of LED retrofit will be delivered through direct on-balance-sheet financing; the rationale for that being:

- LED conversion is more of a capital project than a long-term services contract. Streetlight conversion projects are significantly simpler than most infrastructure projects and involve reduced ongoing maintenance and inspection.
- Risk transfer (particularly on installation and long-term lamp life) should be achievable through appropriately structured contracts and warranties.
- Off-balance-sheet funding is more expensive and most local authorities will be able to accommodate the investment within their prudential borrowing limits using a "spend to save" philosophy.

In certain circumstances other financing options may be used:

- On smaller LED projects the municipality can draw funds from its own budget
- The municipality can use its own cash resources

When the municipality does not want to, or cannot, use external funding or increase its borrowing limit then an off-balance sheet solution using asset finance or an ESCO solution may be appropriate. Some manufacturers and third party providers are able to offer this financing option.

13 OPERATION OF STREET LIGHTING SYSTEM

13.1. Key aspects of street lighting operation

13.1.1 Warranty

There are some aspects to consider in the context of luminaire warranty. On the one hand, the LED street lighting luminaire manufacturers declare the lifetime of their products as long as 50,000 to 100,000 hours (at specified ambient operation temperature), which is several times more than traditional, discharge lamp-type, light sources used in street lighting. On the other hand, the LED luminaire manufacturers usually give 3 to 7 years warranty. So, why the warranty time and lifetime are so different (even during continuous 7 year operation there will be approximately 61,500 operation hours)? Why the manufacturer gives the warranty that is less than declared lifetime?

First of all, the LED luminaire is an electronic device; it is equipped with electronic driver, can be equipped with luminaire controller, and surge protection device. These are the most non-reliable nodes of the luminaire and these nodes to a greater extent determine the warranty period. The reliability of the remaining nodes (optical system, mechanical parts, and connections), should also be taken into account. The reliability and the warranty of the entire luminaire are calculated on the basis of statistics and probability theory, taking into account properties and predicted lifetimes of the individual components used in these nodes.

The lifetime of luminaire is based on the lifetime of the LEDs. It depends on many parameters, the main ones being the LED driving current and the LED junction temperature, while both are partially dependent on each other. The LED luminaire manufacturer can predict the lifetime of the LED using the data from LM-80 lumen maintenance report and TM-21 for this data extrapolation. As mentioned above, the reliability of the entire luminaire is not the same as the reliability of the LEDs.

13.1.2 Monitoring

The lighting system based on the LED luminaires does not require special monitoring measures. Besides that, dimmable LED luminaires are often capable of sending a fault signal to the server. Therefore, a lighting system operator can determine a faulty luminaire and promptly solve the problem. To a greater extent this applies to smart lightning system.

13.1.3 Maintenance

A street lighting installation is capable of operating continuously with high efficiency and delivering sufficient amount of light only when it is well maintained. However, even well maintained lighting systems experience some deterioration. Deterioration is caused by lamp failures, lamp-lumen deprecation (reduction of the produced light amount), and luminaire fouling.

The information about the lamp failures and lumen deprecation should be obtained from the luminaire manufacturer. It should be taken into account that environmental conditions and several other factors like ambient temperature, voltage fluctuations and surges, frequency of on/off switching, and burning position, may affect these parameters to a great extent.

Another serious reason for a light loss is the accumulation of dirt on the light emitting surface. Severity of the fouling depends on the type of luminaire, its IP code, and the level of pollution present in atmosphere. In the atmosphere with high pollution rate the deterioration due to pollution is the main deterioration factor. The total effect of various factors influencing the light deprecation of a street lighting system can reduce the lumen output by 15 to 40% at the end of the maintenance interval.

The maintenance factors for different IP code luminaires in different polluted environments in accordance with CIE 154:2003 are summarized in Table 13.1 [87]. However, some recent studies show that these maintenance factor values can be increased [88].

Table 13.1. Maintenance factors covering dirt accumulation on luminaires with different IP codes and polluted environments in accordance with CIE 154:2003 publication.

	Pollution category		
IP code	**Low**	**Medium**	**High**
1 year operation period			
IP2x	0.82	0.62	0.53
IP5x	0.92	0.9	0.89
IP6x	0.93	0.92	0.91
3 year operation period			
IP2x	0.78	0.53	0.42
IP5x	0.88	0.82	0.76
IP6x	0.9	0.87	0.83

So, there is such a parameter as maintenance factor (MF), which includes all of the described above light deterioration factors. It is used to determine initial luminance $L_{initial}$ (or luminous intensity $E_{initial}$), by dividing specified required luminance L_{spec} (or specified luminous intensity E_{spec}), by the maintenance factor (MF):

$$L_{initial} = L_{spec} / MF \tag{13.1.}$$

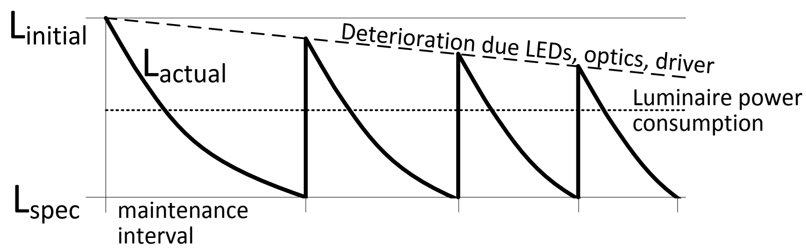
For the LED luminaires, the maintenance interval could be the period between the cleaning procedures. Traditionally, the initial lighting system luminance, or light intensity, is calculated using (13.1), so that it does not decrease below specified luminance at the end of maintenance period. If a system luminaire operates with the same power during its entire service life then each next maintenance interval becomes shorter due deterioration of the LEDs, optics, driver, etc., as shown in (b)

Fig. 13.1 a.

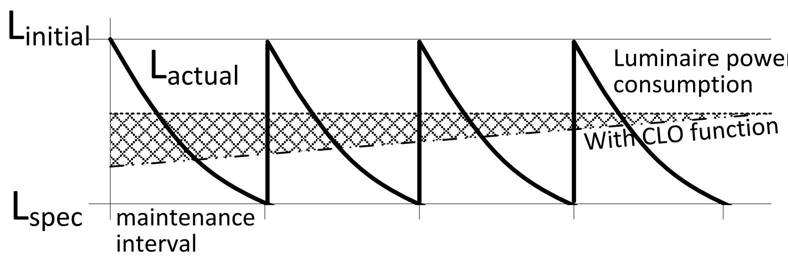
However, with the LED-based lighting systems and programmable LED drivers it is easy to implement constant light output function (CLO), this way reducing power consumption when commissioning the system and then continuously increasing power to compensate for deterioration of lighting system due to the LEDs, optics, and driver, as shown in (b)

Fig. 13.1 b. The cross-hatched area in (b)

Fig. 13.1 b shows possible level of savings.



(a)



(b)

Fig. 13.1. Maintenance intervals and possible savings for LED based street lighting systems: (a) system consumes constant power during service life; (b) system with constant light output feature – the cross-hatched area shows possible energy savings due to this feature.

13.2. Estimation of annual operating costs

Operation costs may include:

- Electricity bills – they depend on electricity rates and its consumption. The consumption, in turn, depends on the type of system: traditional, with dimming, with CLO function, or smart system. Therefore, the cost calculations will be completely different. For traditional systems operating at constant power consumption – only operation hours and electricity price are factors. For the systems with the dimming option – operation hours at full power, operation hours when dimmed, and electricity price are factors.
- Subscription fee – in case of smart lighting systems it may apply to the maintenance of server, web pages, etc.
- Monitoring costs – system monitoring costs.
- Maintenance costs (planned) – for instance, cleaning procedures. Planned maintenance costs on existing infrastructure should be planned by street lighting service company.
- Maintenance costs (unplanned) – due to abnormal failure of equipment or abnormal weather conditions. If insured, then the insurance annual costs should be included.

Table 13.2. Cost components to take into account for different street lighting system modernization levels

Cost components	Without dimming	With CLO	With dimming	Smart Lighting System
Electricity price	x		x	x
Operation hours at full power	x		x	x
Operation hours when dimmed			x	x
Continuous increase of power		x		
Planned maintenance costs	x	x	x	x
Subscription fees (server, webpages)				x
Monitoring costs (optional)	x	x	x	x
Unplanned maintenance costs (insurance)	x	x	x	x

ANNEXES

Annex 1 ENERGY AUDIT OF STREET LIGHTING PROJECTS

The first step in creating energy efficient street lighting is to conduct an energy audit. A quality energy audit of street lighting represents a basis for quality analysis of the current state in street lighting. It consists of the following: gathering basic information about the user, analysis of the available project documentation, description of the street lighting system with mapping of the existing installations, analysis of electricity bills, and the system conformity to the norms and standards of street lighting.

The purpose of energy audit is to assess the energy efficiency (EE) potential in street lighting in the municipalities and to identify potential energy efficiency investments which may cover the rehabilitation and optimization of the lighting system, including replacement of lighting equipment and associated infrastructure to enhance energy efficiency.

The second step is to create technical documentation. The main design is a subsequent step of an energy audit, where a lighting designer uses data gathered in the energy audit report and defines technical solutions for the EE potential of the lighting system.

The third, and the last step, is (re)construction work based on the main design and the energy audit report. The data on the present state of the street lighting system is usually drawn from the energy audit.

- **The condition of the lighting system**

This task involves the review of background information, data collection, site visits, and definition of a baseline and current situation.

The data to be collected and reviewed will involve a mixture of spot measurements, metered data, energy bills, and other historical data.

Table A1.1. Light sources

№	The street name	Lamps							
		Incandescent	Mercury						
			DRL			High pressure sodium			Vapour RVL
		150	125	250	400	70	100	150	40

Table A1.2. The main characteristics of the lamps providing external lighting

Lamps	Incandescent	DRL 250	DRL 125	HPS 100
Power consumption (incl. ballast) [W]				
Luminous flux [lm]				
Service life [hours]				

Table A1.3. Current situation

Existing lamps	Quantity pcs	Capacity [kW]	Annual electricity consumption [kWh]		Electricity cost [EUR]	Woking hours annual	Day hours	Night hours	Day tariff [EUR/kWh]	Night tariff [EUR/kWh]	Total electricity consumption [kWh]	Average [EUR/kWh]
			Night	Day								

Table A1.4. Analysis of contractual conditions for the electricity supply to street lighting and analysis of electricity consumption over the past two years.

2015	1	2	3	4	5	6	7	8	9	10	11	12	**Total**
Active power [kW]													
Reactive power [kW]													
The amount of payment for electricity [EUR]													
2016	1	2	3	4	5	6	7	8	9	10	11	12	**Total**
Active power [kW]													
Reactive power [kW]													
The amount of payment for electricity [EUR]													

Table A1.5. The measured power consumption and cost of electricity

		Electricity use	Tariff (day/night)	Payment for electricity
Year	Month	kWh	[EUR/kWh]	[EUR]
	January			
	February			
	March			
	April			
	May			
	June			
	July			
	August			
	September			
	October			
	November			
	December			
	Total			

Table A1.6. Electricity consumption for the needs of street lighting

Address of electricity metering point	Month/ year	Consumption by separate meters [kWh]											
		1	2	3	4	5	6	7	8	9	10	11	12
	2015												
	2016												

Table A1.7. Operating and maintenance costs of street lighting

№	Name of the works	Units	Amount annual [EUR]
1		Hours	
2		[EUR]	
	VAT 20%	[EUR]	
	Total	[EUR]	
Maintenance works		[hours]	

- **Compile a list of existing energy-consuming lighting equipment and power grids.**

It provides a brief description of the covered systems and facilities and overview of the existing conditions.

Table A1.8. Metering

№	Meter/functionality	Location	Valid from [year]	Name / Type	Serial Number	Conversion factor

Table A1.9. Lighting

№	Location	Number	Type of fixtures	Lamp type	Lamp power [W]

Table A1.10. Power lines

№	Location	Line type	Cable type	Length [m]

Table A1.11. Control cabinets

№	Location	Type	Type of control	Availability monitoring

- **Measurement of parameters of street lighting network equipment**

Details of electricity consumption by all facilities.

Table A1.12. Measurements of capacities and parameters of power supply

Transformer substation	Phase	Measured electrical indicators of the external lighting network						Measured load [kW]	Connected load [kW]	Usage [%]
		[A]	[V]	[cos φ]	[VA]	[VAR]	[W]			

- **Measurement of illumination and brightness of the street surface.**

Table A1.13. Analysis of the quality of street lighting for compliance with regulatory requirements.

Street	Standard value [lx]	Measured value [lx]	Notes

- **Perform simulation of lighting and illumination calculation model areas of street lighting system. Calculate the installed capacity before and after reconstruction.**

Software: DIALux, Lightscape, RELUX, Light-in-Night Road, WinElso-Light.

Table A1.14. Examples of lighting modelling and light calculation in DIALux program:

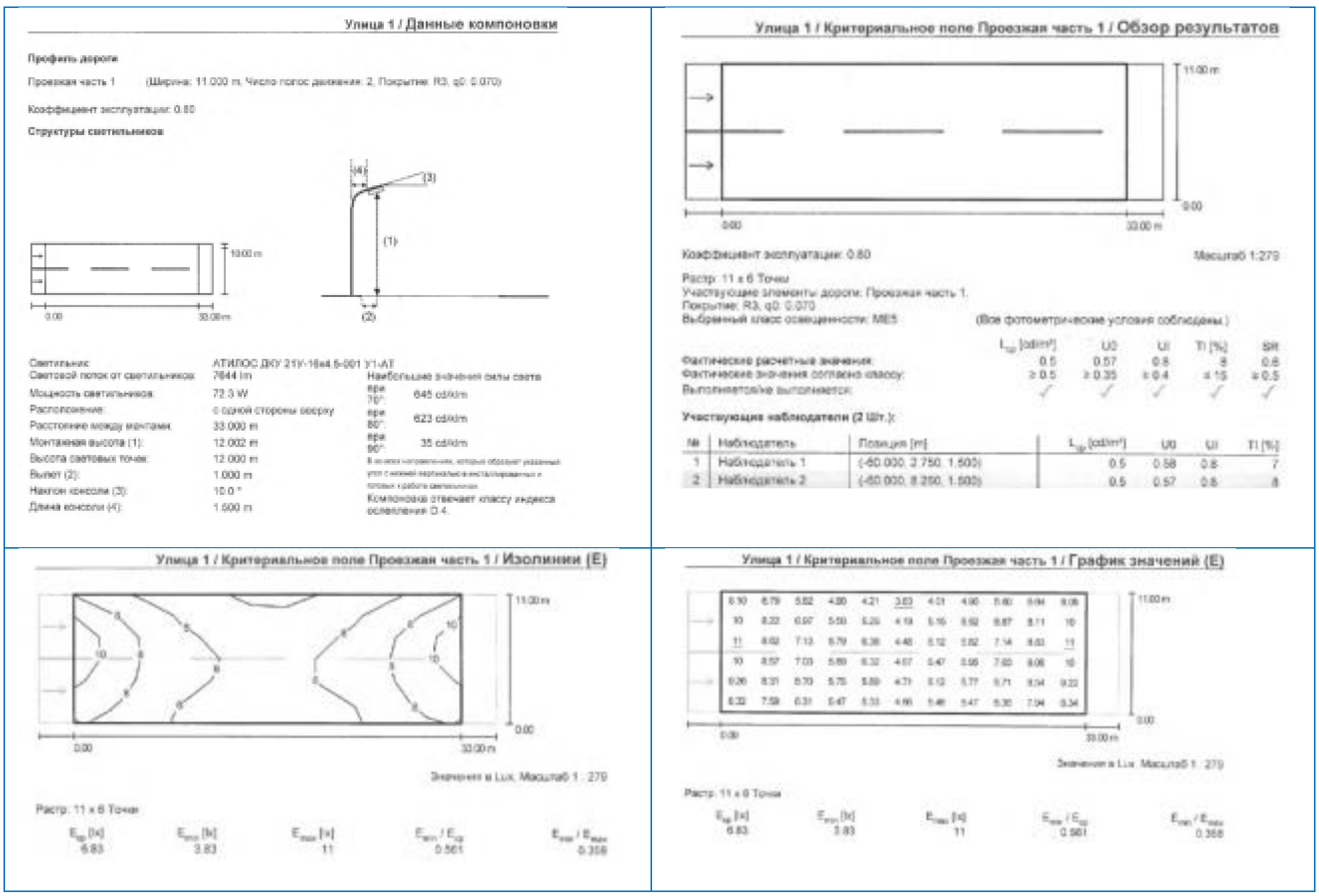
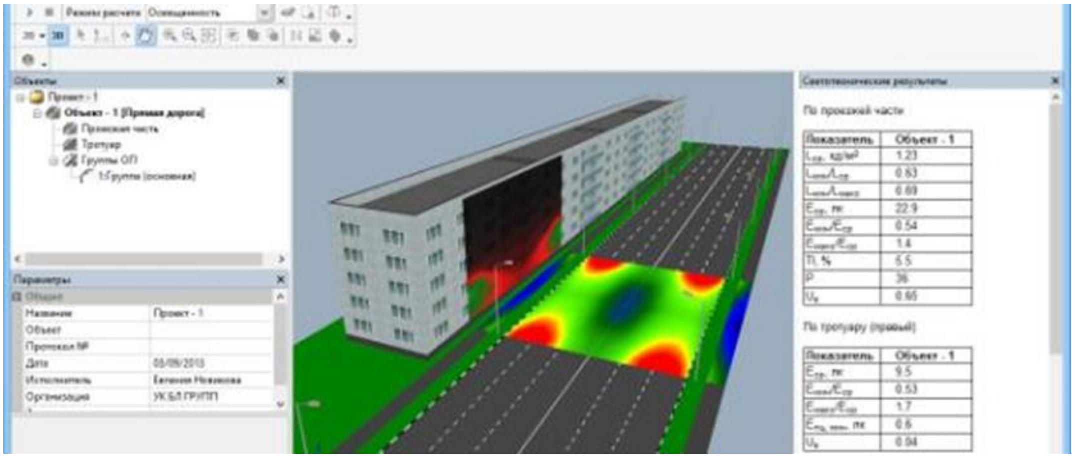


Table A1.15. Examples of lighting modelling and light calculation in Light-in-Night program:



- **Calculate technical and economic indicators and the total cost of the project**

This task is to make assessment and identification of cost effective measures for reducing energy cost and improving energy efficiency in street lighting. It provides results and summary tables presenting the cost and energy savings estimates for each recommended measure. It should also include a summary of the recommended measures and their costs, as well as the financial and energy indicators of the projects, and indicators to measure other impacts of the project (quality of service, impact on municipality's budget, to name a few).

Table A1.16. Normative time street lighting

Month		1	2	3	4	5	6	7	8	9	10	11	12
Normative time street lighting													
Night rate	start												
	end												
	Hours a day												
	The time of validity of the tariff												

Table A1.17. The base (rated) power consumption

Lighting fixtures	Total number [units]	Total capacity [kW]	Normative working time [hours]	Power consumption [kWh/year]

- **Proposed technical installations**

Based on the analysis of the baseline and assessment of the current infrastructure and operations conditions from the field visit and information and data collected, the auditor should consider and identify technically viable EE measures/options and, for each one, calculate the investment needed, energy consumption and energy/O&M cost savings, simple payback period, net present value, environmental and other benefits.

For the assessment of EE potential the auditor should consider all likely EE measures including: lamp replacement (with higher efficiency technology, such as LED); replacement of fixtures (including replacement of ballasts, reflectors, etc.); redesign of system (including number, height and spacing of poles); control systems (e.g., dimmers), and other options as appropriate. The assessment should include the long-list of options considered, their relevant costs and financial information, indicate which options were not considered for technical reasons, and include a separate summary table of options with positive NPVs. The financial analyses should also specify all assumptions, such as electricity tariffs, electricity costs, technology costs, equipment lifetime, hours of operation, grid emissions factor, and rate of inflation.

Table A1.18. Existing technical installations

	Quantity pcs	Capacity [kW]	Annual electricity consumption [kWh]		Electricity cost [EUR]	Woking hours annual
			night	day		
Existing equipment						
Fixtures/ lamps [W]						
Fixtures/ lamps [W]						
Proposed technical installations						
Fixtures/ lamps [W]						
Fixtures/ lamps [W]						

Table A1.19. Proposed technical installations

	Day hours	Night hours	Tariff [EUR/kWh]		Total electricity consumption [kWh]	Average cost [EUR]
			night	day		
Existing equipment						
Fixtures/ lamps [W]						
Fixtures/ lamps [W]						
Proposed technical installations						
Fixtures/ lamps [W]						
Fixtures/ lamps [W]						

Table A1.20. Savings

	Existing situation	After implementation	Net savings
Consumption savings kWh/year			
Electricity [kW/year]			
Maintenance costs			
Savings Total			
Electricity Savings %			

From	To	items	Investment costs [EUR]	Electricity savings [EUR]	M&O savings [EUR]	Pay-back period	NPV [EUR]	IRR [%]

- **Develop technical activities and offer program for energy efficient modernization of the street lighting system.**

Table A1.21. Proposed measures , estimates, calculations

	Quantity pcs	Capacity kW	Annual electricity consumption [kWh]		Electricity costs [EUR]
			night	day	
Possible options to change					
LED [W] without control system					
LED [W] with distance control system					
LED [W] with control system and dimming control					
fixtures without replacement, if any					

Table A1.22. Estimates, calculations

	Working hours annual	Day hours	Night hours	Tariff [EUR/kWh]		Total electricity consumption [kWh]
				night	day	
Current situation						
Possible options to change						
LED [W] without control system						
LED [W] with distance control system						
LED [W] with control system and dimmer control						
fixtures without replacement, if any						

Energy saving measures	Item	Cost [EUR]	Total [EUR]
Total			

Table A1.23. Indicators for pre and post installation technology

Parameters	Pre-installation	Post-installation
Street Name		
Street width, m		
The location of the fixtures (S-on one side of the street, B-on both sides, opposite to each other, C-in staggered order)		
Number of light points [pcs]		
Lighting Technology		
Wattage [W]		
Lumens [lm]		
Efficacy [lm/W]		
Annual operating hours		
Lifetime [years]		
Illuminance [lx]		
Colour rendering Index [CRI]		
Electricity consumption per year [kWh]		

Risks and their mitigation-assessment of potential technical and financial risk and a risk mitigation plan should be presented in energy audit report.

The audit report must include all attachments and calculation sheets (in Excel), corresponding analysis, surveys of the networks, simulation models used in performing analyses, existing and modified plans of the proposed equipment, specifications of the assessed and proposed equipment, supply systems diagram, etc.

In producing the report, the auditor should review relevant available documentation (e.g., plans of public lighting system, collection of equipment nameplate data, O&M manuals, specification data for major equipment, performance data, energy bills[20], etc.). In addition, information on current infrastructure and operational conditions, including data from the field visit, and relevant country norms, should by reviewed.

[20] Monthly electricity bills should be reviewed.

Annex 2 MEASUREMENT AND VERIFICATION OF STREET LIGHTING PROJECTS

Introduction

The objective of Measurement and Verification (M&V) is to quantify the energy savings resulting from implementation of energy conservation activities in a defined, rigorous, and transparent way. The basic principle of M&V is to compare the measured energy consumption and demand before and after the implementation of energy conservation measures (ECM) in order to determine the energy savings. M&V is not just a collection of tasks conducted to help a project meet selected M&V guideline requirements, but it also serves to enhance and improve facility operation and sustainability of savings. The M&V activities overlap with other project efforts, for example:

- data collection to identify ECMs and establish energy baselines
- commissioning and verifying actual installation of ECMs, and
- installing monitoring systems to track savings persistence.

Identifying these project synergies and establishing roles and responsibilities of parties involved during project planning phase will contribute to the successful implementation of the project. [91]

One of the main M&V priorities is a timely maintenance and repair of the street lightning. The common automated monitoring of the street lighting is based on measuring each lamp's current and comparing it to its nominal value. This way the error in the network can be identified. Monitoring street lighting is presently conducted by traditional inspection and check-out method. The traditional inspection of the street lighting is based on measuring the consumed current of each lamp and comparing it with the lamp nominal current. Check-out method for monitoring and remote sensing of the street lighting system is available where the system performance is simulated and verified with appropriate software. This method is completely isolated from electricity network and relies on taking picture of the street lighting network, processing the image to separate the light sources and report identified issues.

The recommended M&V steps for a street lighting system [92]

1. Create a M&V Plan that outlines and documents the measurement boundary, the variables to be measured and the time periods.
2. Establish a baseline before the system upgrade by:
   - 2.1. Measuring illuminance
   - 2.2. Measuring the lighting circuit power
   - 2.3. Determining the operating hours based on lighting timer settings, log records or staff knowledge.
3. Measure energy consumption after the system upgrade:
   - 3.1. Similarly to Step 2.1, measure the illuminance to confirm that it meets the specification.
   - 3.2. Similar to Step 2.2, measure the lighting circuit power.
4. Calculate the power reduction.
5. Calculate the reduction in energy consumption.

List of key elements of a typical M&V plan

1. Description of energy conservation measures, intended results, and the measurement boundary
2. Documentation of the facility's base year conditions and energy consumption data
3. Identification of any planned changes to the base year conditions
4. Methodology for making relevant baselines adjustments for unforeseen changes
5. Identification of the post retrofit measurement period
6. Specification of reference conditions to which all energy measurements will be adjusted
7. Specification of M&V options and data analysis
8. Procedures, algorithms, and assumptions for performing the statistical validation and anticipated level of accuracy of measurements and results
9. Software Requirements Specification, and budget
10. Documentation and data availability for another party to independently verify reported savings

These elements are specified within the International Performance Measurement and Verification Protocol (IPMVP). The IPMVP specifies four generic approaches from which practitioners can choose when planning and conducting M&V. These are known as Options A, B, C and D.

Options A and B isolate the energy use of a piece of equipment, process or functional area and are used in conjunction with an ECM-based measurement boundary.

Options C and D are used to measure the effects of one or more ECMs on total site energy usage, and are used in conjunction with a facility boundary.

Details of Measurement and Verification requirements [93]

To provide a useful comparison of measurements for different lighting technologies several parameters must be considered:

- **Operating hours**-identified during an initial survey of the facility and assumed to be the same before and after the retrofit.
- **Existing lighting controls**-if lighting controls other than the new controls or modified controls being implemented already exist and are not scheduled to be replaced in the areas to be measured, it is important to leave the existing control settings the same after the retrofit. This ensures that the energy effect of only the new control equipment will be measured. If it is not possible, or practical, to maintain existing control settings then it is recommended to deactivate these controls for a reasonable period, say two weeks, prior to installing the new controls in order to provide a comparable baseline of pre-existing conditions for comparison.
- **Light levels**-typical lighting levels of occupied areas (illuminance on task surfaces), are often necessarily or unavoidably changed from pre-retrofit to post-retrofit conditions. Implementing changes in light levels by installing a new lighting system (with or without controls), will affect the energy use and therefore potentially skew the results. Therefore, it is important to capture the lighting levels of occupied areas before and after the retrofit to be able to adjust savings for a fair comparison or, at least, to recognize that this change is an important element of the system's energy use.

- **Site selection**-the specific characteristics of an evaluation site or area (like road width, number of lanes, coverage, type of fixture, power of lamp, poles location, distance between poles, mounting height, height of light points, slope of the console, console length), can have a large effect on the measured potential savings. If more than one control system is being evaluated then the selected evaluation areas should be similar with above characteristics to one another.
- **Effects on heating and cooling systems**-assessment of potential effects on the energy use by heating and cooling systems by the changes in energy use by lighting is beyond the scope of this plan.
- **Stable Operational Baseline**-when assessing any lighting control system it is desirable that the basic lighting system be in a stable operating condition before and after the retrofit of controls. This ensures that the effect of only the new control equipment is captured in any measured energy savings. However, lighting retrofits commonly involve multiple changes, including change in lamp technology (i.e., from fluorescent to the LED fixtures), and light level adjustments (i.e., increase or reduction to meet recommendations or occupant's needs). These changes will affect energy use and, consequently, any fair comparison of control options or true energy savings from the installed control equipment.
- **Stable Conditions for Measurement**-the chosen test site should provide stable conditions before and after the retrofit installation. An effective comparison of lighting technologies requires an environment and conditions that eliminate unnecessary variables that could invalidate the results. The test site should be located where the surrounding conditions will be the same for both the baseline and the post-installation retrofit testing. Changes in surrounding structures, occupants, weather, or other conditions could affect the results and may make comparative measurements difficult.
- **Equipment Burn-in and Warm-up**-for newly installed retrofit or replacement lighting equipment the energy consumption and light output may change until the product has been operated for a reasonable amount of time (also known as seasoning). This has been a concern in some fluorescent light systems but is typically not of much concern for other technologies, including the LED.
- **Measurement Access**-an illuminated area should be available for light level measurements during all phases of the project implementation.
- **Instrumentation Recommendations**-while equipment accuracy is important it is not a critical parameter beyond a tight tolerance within a few percent. However, for M&V purposes, a reasonably achievable minimum accuracy of standard measuring instruments is recommended. Testing documentation should include the actual specifications and measurement accuracies of any equipment used.

Instrumental inspection of street lighting systems; choice of equipment and tools for M&V analyses

The purpose of taking measurements in lighting systems is to determine the main parameters of the system that affect energy consumption. These parameters are:

- average illumination of the working surface
- coefficient of natural illumination
- value of line voltage
- reflection coefficients, and

- time of use of artificial lighting.

The measurements of street lighting system are also taken to verify the compliance with the project specifications and provide an objective assessment of the compliance of the installation with the entire set of technical requirements, as this will subsequently allow more accurate calculation of the energy saving potential.

The measured parameters as part of the survey of street lighting:

- The type and quantity of lighting fixtures, their condition and compliance for a specific class of lighting.
- The correct placement of lamps, the height of the overhang and suspension over the illuminated surface.
- The control system of lamps and the presence of the voltage regulators.

It is necessary to use lux meter in conducting measurements of illumination levels during the day to record the lighting data.

The requirements for ambient light measurements

The main part of taking measurements is limited to measuring the illumination of a specified surface by artificial and natural light sources. It should be performed when all luminaires of the lighting system are switched on.

When performing measurement and verification work, an access to electricity meters (installed, for example, in outdoor lighting cabinets), should be provided for recording their readings and perform other necessary measurements.

Energy metering equipment is available from several manufacturers. The typical system includes one or more power meters that capture circuit or equipment energy use as well as transformers' current and voltage. Many of the meter options are similar in operation but can offer a variety of options for data acquisition and transfer. Old energy metering systems provide only readout or hard-wire download capability. Newer equipment offers wireless data access and download through various options, like hardwired USB or similar cabling, wireless cell signal transfer, Wi-Fi connection transfer, or Ethernet connection transfer.

The measurement of power quality in street lighting systems

The deviation in power quality from the normative values has a great influence on the operation of street lighting installations, which in the dark should provide brightness levels of the order of 1 cd/m^2. The problem of power quality is important from the point of its influence on both the quality of lighting and the brightness of the road surface, which, in turn, strongly depends on the reflecting properties of the surface.

The decrease in power quality leads to additional losses, deterioration of work of lighting systems, and reduction of service life of sources of light.

The main cause of the power quality's deviation from the standards is the voltage fluctuation, which causes the greatest damage to the operation of lighting installations; working with lower voltages causes the luminaires to increase power consumption, and voltage increases lead to a sharp reduction in their service life.

The following instruments can be used in analysing power quality:

- MI 2392, MI 2492, MI 2592 by "METREL d.d.", Slovenia
- AR.5, mod. AR.5M, AR.5L by "CIR-CUTOR S.A.", Spain
- CW240 by "Yokogawa Electronics Manufacturing Korea Co., Ltd.", Korea
- Fluke 435 Fluke Industrial B.V., The Netherlands
- MAVOWATT 30, MAVOWATT 40, MAVOWATT 50, MAVOWATT 70 by "GMC-I Gossen-Metrawatt GmbH", Germany.

The following is the list of power quality parameters

- Steady-state voltage deviation
- Range of voltage variation
- Rate of flicker
- Coefficient of sinusoidal distortion of the voltage curve
- Coefficient of the n-th harmonic component of the voltage
- Coefficient of unbalance of stresses in the reverse order
- Coefficient of unbalance of stresses in the zero sequence
- Frequency deviation
- Duration of voltage failure
- Impulse voltage
- Coefficient of temporary overvoltage

The charts below show the results of measurements of some of power quality parameters using the quantity and quality indicators analyser.

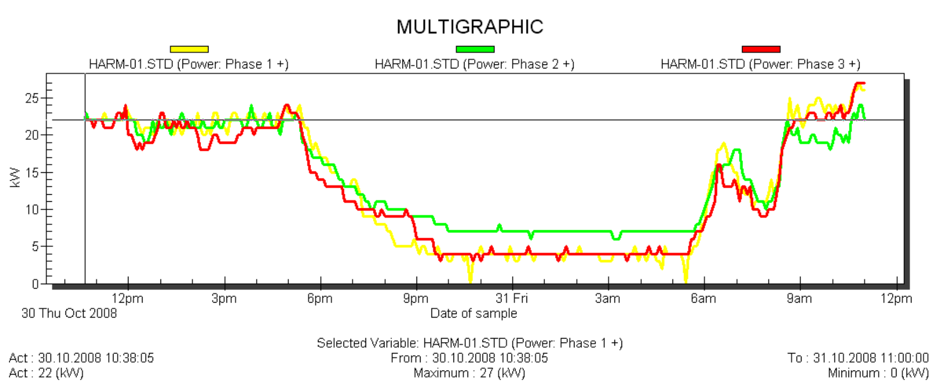


Fig. A2.1. Active power consumption

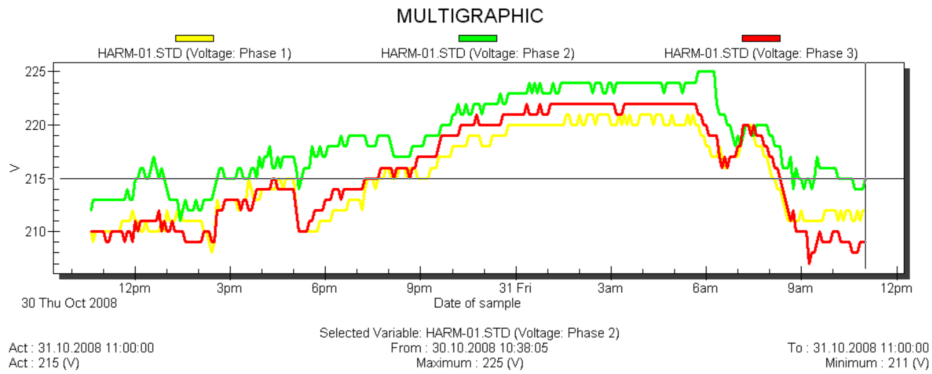


Fig. A2.2. **The level of the phase voltages**

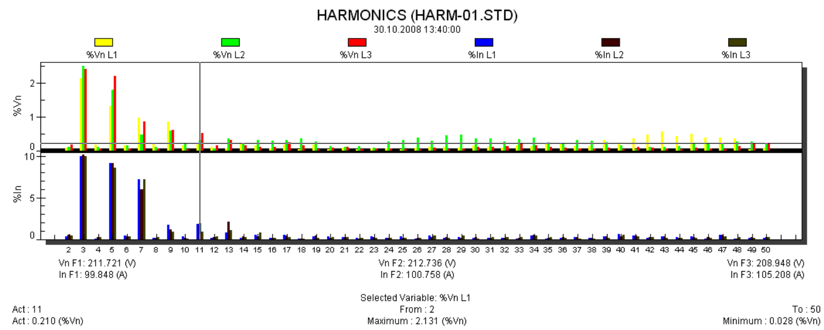


Fig. A2.3. **Harmonic components**

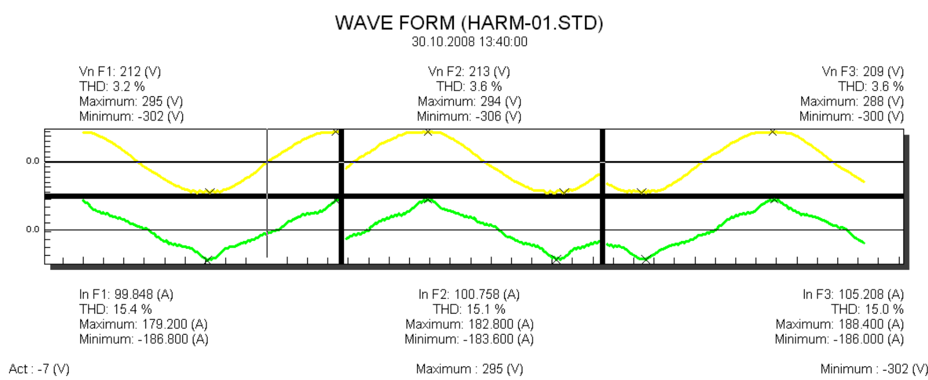


Fig. A2.4. **The shape of the phase currents and voltages**

Thermal monitoring of electrical equipment

The principle of operation of thermal imaging is based on the fact that some types of defects in the electrical equipment cause changes in temperature. Accordingly, the change in the intensity of infrared (i.e., thermal) radiation is detected by thermal imaging devices. When comparing the temperature of similar parts of the surface of electrical equipment operating under the same heating and cooling conditions, the existing defects can be identified. The main advantage of carrying out thermal imaging diagnostics of electrical equipment is the possibility of mass inspection of a significant amount of electrical equipment at minimal cost. During the thermal imaging diagnostics there is no direct contact with the electrical equipment, which considerably speeds up the work. With the help of thermal imagers, the electrical equipment in pre-emergency condition is identified. These types of defects cannot be detected by any other methods.

Thermography is a proven technology for detecting elevated temperatures within operating electrical distribution systems. Typically performed on an annual basis, infrared inspections can detect evidence of overheating caused by loose/deteriorated connections, overloaded circuits and imbalanced loads. While infrared inspections can be valuable in helping to prevent unexpected failures, they provide a single 'snapshot' leaving the subject components unmonitored for the balance of the year.

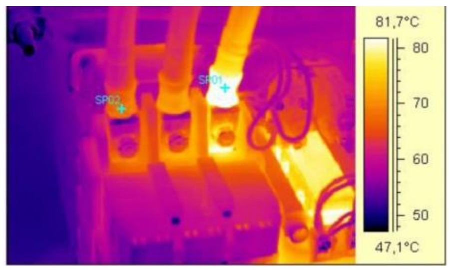


Fig. A2.5. Example of thermographic survey

There is also software available on the market which can efficiently control and verify the condition of street lighting systems regardless of their size, number of lamp controllers, and even geographically unconnected regions.

Highly interactive and user friendly software provides powerful management and reporting tools, like detailed lamp operational parameters, real time error notifications and advanced maintenance scheduling. In addition, grouping, filtering, and updating can be performed through the bulk operations interface, making it easier for the software user to manage large number of lamps, groups of lamps, system users, or scheduled actions.

Annex 3 BEST PRACTICE-EXAMPLES

Lights replacement in a small locality

A good example is the replacement of mercury-vapor lamps by LED luminaires in a small village. 46 250 W mercury-vapor lamps were successfully replaced by 52 W LED luminaires, reducing electrical power consumption by 79 %. New luminaires were equipped with a control system, which reduces power during deep night hours. This additionally results in power consumption being reduced by 16% in comparison with new non-dimmable lighting system based on LED luminaires. Part of the street with modernized lightning system is shown below.

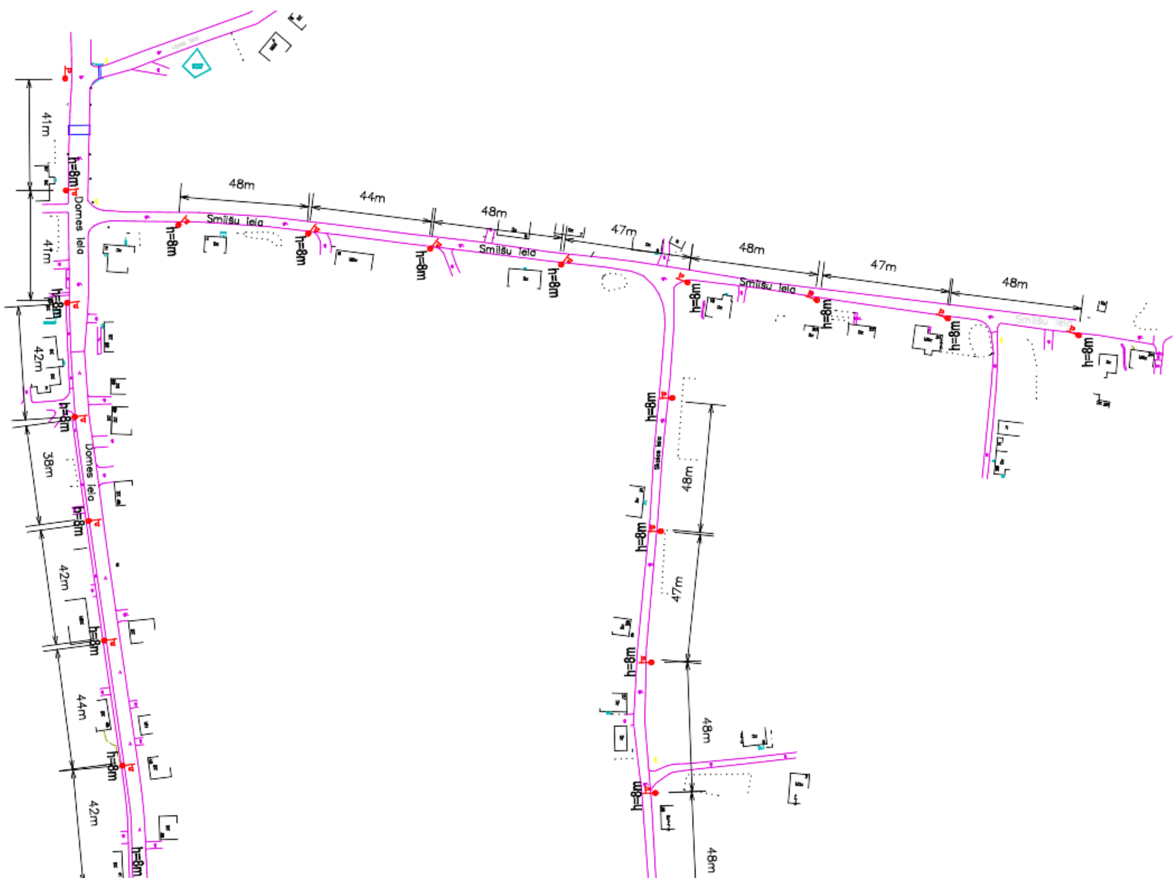


Fig. A3.1. Example of replacement of mercury lights with LED lights in a small locality

Lights replacement in a large municipality

The City of Los Angeles LED street lighting project has been the largest LED street lighting retrofit ever undertaken globally. Over a period of five years (2009-2014), 140,000 of the city's more than 209,000 street lights were replaced with LED technology which is expected to enhance the quality of municipal street lighting, reduce light pollution, improve street safety, and save energy and money.

The project focused on retrofitting high pressure sodium vapor (HPSV) cobra-head street light fixtures that are located on residential streets and offer poor optical efficiency (approximately 65 percent), relative to the high optical efficiency (over 80 percent) of many LED fixtures. While the project focused on HPSV cobra-head fixtures, metal halide, mercury vapor, and incandescent cobra-head fixtures will also be replaced in later phases. The new LED fixtures would be installed with remote monitoring units (RMUs), which would automatically monitor energy usage and report streetlight failures for immediate attention.

The project generates energy and maintenance cost savings that will create a cash flow to repay the loan and provide budgetary savings in later years. According to economic analysis, the project is expected to yield US$8.1 million per year in energy and maintenance savings, providing a payback period of seven years and an internal rate of return (IRR) of 10 percent. The total financial return for the project after factoring in the energy rebates is even more attractive. With total savings of US $10 million per year the payback period is reduced to only 5.7 years and the IRR is increased to 23 percent.

The required investment of US $56.9 million will provide an estimated US $10 million in annual energy and maintenance cost savings (68.6 GWh/year), while avoiding at least 40,500 tons of CO_2 emissions each year.

Intelligent Street Lighting System

The first patent requests for intelligent street lighting system is from the late 1990s.

The first large implementation took place in Oslo, Norway. Since 2004 Oslo has reduced energy consumption by 70% and CO_2 emissions by 1,440 tons per year by introducing an innovative and energy-efficient intelligent street lighting system. The intelligent streetlight system remotely monitors and controls the lights, dimming them based on traffic intensity, weather and available ambient light. Maintenance teams no longer need to patrol the streets; they receive detailed notifications with any malfunction, including possible defect analysis and necessary materials.

The system, comprised of 10,000 intelligent street lights, is operated by a central database that monitors and administers commands. The system utilizes general packet radio service (GPRS) telecommunications technology between the central database and the switch cabinet located at the street level. The switch cabinet receives messages from the central database and transmits them to individual lights via the existing 230V power cables.

The benefits of this type of technology are:

- Energy savings
- Reduction of light pollution

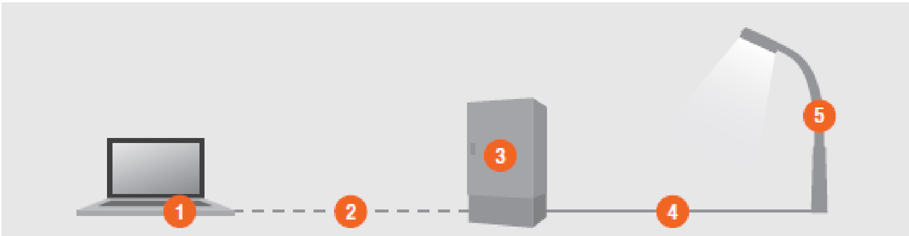


Fig. A3.2. Example of Street Lighting Control (SLC)

The following is the description of how the Street Light Control (SLC) works:

1. Street lighting control (SLC) software

The software is the central interface for the user of the system. It facilitates the administration, programming and analysis of the lighting installation. The SLC software can be installed locally or in the cloud. For each user only the allocated functional area is visible.

2. Internet protocol (IP)

The communication between the software and the gateway at the street level is via a secure IP connection, e.g. by GPRS, Ethernet, or fiber optics.

3. Street lighting control gateway

The gateway, usually mounted in the field in the switching cabinet, stores, processes, and translates the control commands and polls initiated by the SLC software. Depending on the requirements the gateway can be used to incorporate a series of auxiliary components, such as meters, relays or light sensors.

4. Power line

The data is transmitted between the gateway and the connected luminaires through the main power supply lines. An additional communication infrastructure, such as additional wiring or antennas, is not necessary.

5. Luminaire Controller / Pole Controller

The control elements give the operator of the street lighting system the ability to perform individual control and monitoring of each single luminaire. The components are available as pole mounting or luminaire mounting and facilitate individual switching and dimming of all luminaires. In order to ensure optimum communication each controller can also act as a signal amplifier.

Functional applications of intelligent street lighting control system:

- Remote monitoring and control of street lighting system
- Establishing the lighting for a fixtures on a cable lines connected to the street cabinets and also provide the possibilities to control lighting of individual lighting fixtures and architectural illumination systems
- Monitoring lighting, gathering and storing information about events, energy consumption, and technical condition
- Informing the operator or responsible person about critical events in the system
- Providing reports in accordance with the needs.

The cost of the system

The cost is determined by project documentation and depends on the size and parameters of the system. Modernization of the street lighting system allows a municipality to obtain the energy savings of 30%.

Technical solutions

The end user has the ability to work from any workstation with the access to Internet (or by contacting a central server using any means of communication). The main software is installed on a central server and can be accessed from remote workplaces. The system implements a flexible approach; it is possible to consider several options for its location in accordance with the needs and requirements of the client:

Local solutions

The city hosts the system in its own computer center. In this case, what is needed is a separate room and a server equipped with an uninterrupted power supply. The minimum requirements of the server are: processor iCore 5 or equivalent, 16GB RAM, and 2 TB HDD.

At the customer's request, a specification for intelligent street lighting control system development can be enabled with the Giscuit_EET (GIS server), Windows server, and MS SQL server or similar equipment. The acquisition of software will require purchasing a license. System maintenance requires specialists with adequate qualifications.

Obtaining management services

The municipality can secure the licenses and establish the required number of workplaces to manage the system. The system includes control equipment installed in the cabinets at the street level as well as controllers and GSM modems.

The system works only with compatible lighting system. Currently, there is a list of compatible hardware from many manufacturers to define the appropriate model. The standard management protocols used by the system allow other manufacturers to upgrade lighting fixtures for use in the system.

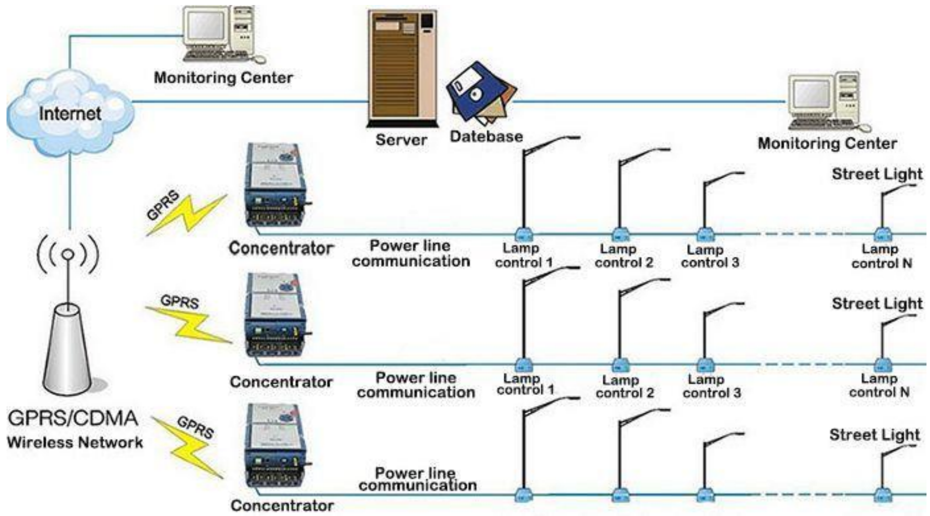


Fig. A3.3. Intelligent street lighting control system model.

Geographic Information Systems (GIS) provides enhanced analysis and improved visual renderings for a variety of project needs. The use of GIS in projects allows for clients to receive attributed data providing various levels of detailed information to clients that cannot be achieved in some forms of Computer Aided Design (CAD). GIS utilizes two-dimensional and three-dimensional layers to portray and analyze various features including population density, road locations and driving times, wetland locations and buffer zones, and property boundaries. GIS operates utilizing polygons, points, or lines, each of which can be portrayed in various ways to allow for easier interpretation by users.

GIS system capabilities:

- To provide and correct the current information on the status of the lamps (lamps relay wear, the degree of illumination), power network, and switching points
- To predict the possible failure of lamps due to expiration of their guaranteed life (according to the instructions)
- To give full and visual information in the automatic mode to the operating organization about the state of illumination of streets, alleys, and squares in real time
- To prepare the calculated information in automatic mode
- To design an efficient distribution of new light points and optimization of the network routing
- To simulate emergency situations and to predict the most vulnerable areas
- To plan the optimum replacement of fixtures and repair of the supports
- To generate data for certification of outdoor lighting networks
- To automate the generation of reports
- To work in the control, autonomous, and manual modes
- To communicate with the control cabinets
- To graphically represent the lighting control panels displayed on an interactive map
- To remotely power control lamps according to the annual calendar schedule and to adjust the schedule manager

- To remotely monitor the consumption of electricity
- To interface and integrate with existing information systems.

Annex 4 FURTHER RESOURCES

Link	Description
https://www.cen.eu/Pages/default.aspx http://www.cencenelec.eu/aboutus/Pages/default.aspx http://www.etsi.org	The webpages of three European Standardization Organizations – CEN[21], CENELEC[22] and ETSI[23]
http://www.iiec.org/	International Institute for Energy Conservation
https://www.theilp.org.uk/about/	The Institution of Lighting Professional
https://www.iald.org/	International Association of Lighting Designers
http://www.americanlightingassoc.com/	American Lighting Association
https://www.thelia.org.uk/	The Lighting Industry Association
https://www.dial.de/en/home/	The main webpage of the creators of DIALux freeware lighting design software.
https://www.dial.de/en/dialux/download/	DIALUX 4, DIALUX Evo 6 and LTD Editor download page
http://www.ledsmagazine.com/index.html	Professional lighting design software. Worldwide recognized lighting planning tool. Includes (or can be downloaded for free) electronic luminaire catalogues of the world's leading luminaire manufacturers.
https://www.fhwa.dot.gov/publications/research/safety/08053/	Pedestrian safety on crosswalks – lighting principles (open source)
http://darksky.org/	The International Dark-Sky Association. Site contains a good description of "light pollution" term, effect on the environment and people, how to avoid it
http://www.lrc.rpi.edu/programs/nlpip/lightinganswers/lightpollution/lightPollution.asp	Definition of light pollution by Lighting Research Center
http://www.cie.co.at/	The Commission Internationale de l'Eclairage
http://www.iesna.org/	Illuminating Engineering Society of North America (IESNA)
http://www.iec.ch/	International Electrotechnical Commission
http://www.theiet.org/	The Institution of Engineering and Technology
http://www.zhagastandard.org/	Global lighting-industry consortium that aims to standardize LED light engines and associated components, and to simplify LED luminaire design and manufacturing
http://www.lrc.rpi.edu/	The Lighting Research Center (LRC) at Rensselaer Polytechnic Institute is the world's leading center for

[21] European Committee for Standardization

[22] European Committee for Electrotechnical Standardization

[23] European Telecommunications Standards Institute

	lighting research and education.
http://www.lumileds.com/products/high-power-leds	LUMILEDS. One of the leading LED manufacturers. High power LEDs (suitable for street lighting). Latest products and tendencies.
http://www.osram-os.com/osram_os/en/products/product-catalog/leds-for-general-lighting/index.jsp	OSRAM. One of the leading LED manufacturers. Latest products and tendencies.
http://www.nichia.co.jp/en/product/led.html	NICHIA. One of the leading LED manufacturers. Latest products and tendencies.
http://www.cree.com/LED-Components-and-Modules	CREE. One of the leading LED manufacturers. Latest products and tendencies.
http://www.seoulsemicon.com/en/html/main/	Seoul Semiconductor. One of the leading LED manufacturers. Latest products and tendencies.
http://www.eib.org/epec/ee/	The European PPP (Public Private Partnership) Expertise Centre (EPEC). A joint initiative of the EIB, the European Commission and European Union Member States and Candidate Countries.
http://intelilight.eu/financial-and-business-case/street-lighting-savings-calculator/	Street Lighting Energy Saving Calculator
https://www.osram.com/osram_com/news-and-knowledge/oem-news/2016/properties-of-high-quality-led-drivers/index.jsp	OSRAM. Properties of high-quality LED drivers.
http://luxreview.com/article/2015/06/five-ways-we-can-control-street-lighting-better	Five ways to control street lighting better
http://www.electronics-tutorials.ws/diode/diode_8.html	The Light Emitting Diode. Electronics Tutorials
https://ec.europa.eu/digital-single-market/en/smart-cities	Definition of term “Smart Cities” by European Commission. Digital Single Market. Digital Economy and Society
https://ec.europa.eu/digital-single-market/en/content/nobel-smart-energy-management-smart-cities	Nobel | Smart energy management for smart cities
http://www.smart-cities.eu/	An interesting interpretation of term “Smart City”. Comparison of different cities.
http://www.photometrictesting.co.uk/File/blog_photobiological_safety.php	Photobiological Safety Testing
http://fgg-web.fgg.uni-lj.si/~/pmoze/esdep/master/wg01b/l0300.htm	Basics of wind load on metal constructions. Wind load map of Europe is available on this resource
https://www.iea.org/russian/	
http://www.dot.state.mn.us/trafficeng/lighting/2010_Roadway%20Lighting_Design_Manual2.Pdf	
http://cdm.unfccc.int/methodologies/	
http://documents.worldbank.org/curated/en/home	

Professional organizations in Ukraine

Компанія «Шредер-Україна» - дочірнє підприємство відомої бельгійської компанії-виробника обладнання для вуличного освітлення.

Сайт: http://www.schreder.com/uas-uk/

ТОВ «БП» «Атілос»- Виробник світлодіодного освітлювального обладнання та світлофорів, м.Чернігів

Сайт: http://www.atilos.com.ua/

ООО «Світлодіодні технології Україна»- Виробник світлодіодного освітлювального обладнання, м.Харків

Сайт: http://ltu.ua/

ITW Systems -Виробник світлодіодного освітлювального обладнання, м. Київ.

Сайт: http://itw-systems.com/

ТОВ «СУ-24»- Виробник світлодіодного освітлювального обладнання, м . Харків

Сайт: http://ledlighting.com.ua/

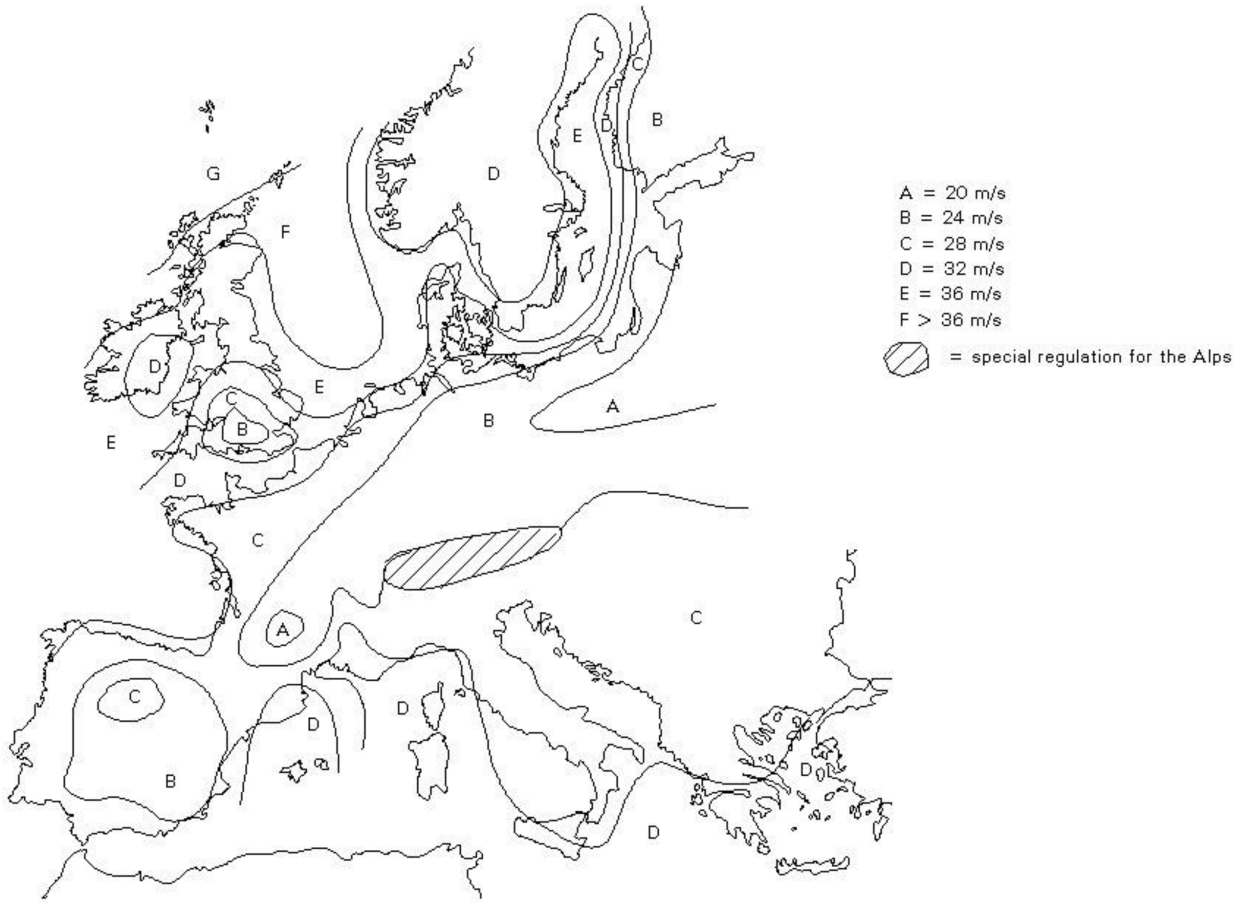
Design software

Software	Location
AGI32	www.agi32.com
Calculux Road	*www.lighting.philips.com/gb_en/*
DIALux	www.dial.de
Streetlight.Vision	http://www.streetlight-vision.com/
3DViz	www.3dviz.com.au
Relux	http://relux.com/en/
Light-in-Night	www.l-i-n.ru/
WinElso	www.winelso.ru
Lightscape	*https://www.digitalbroadcasting.com/doc/lightscape-software-0001*

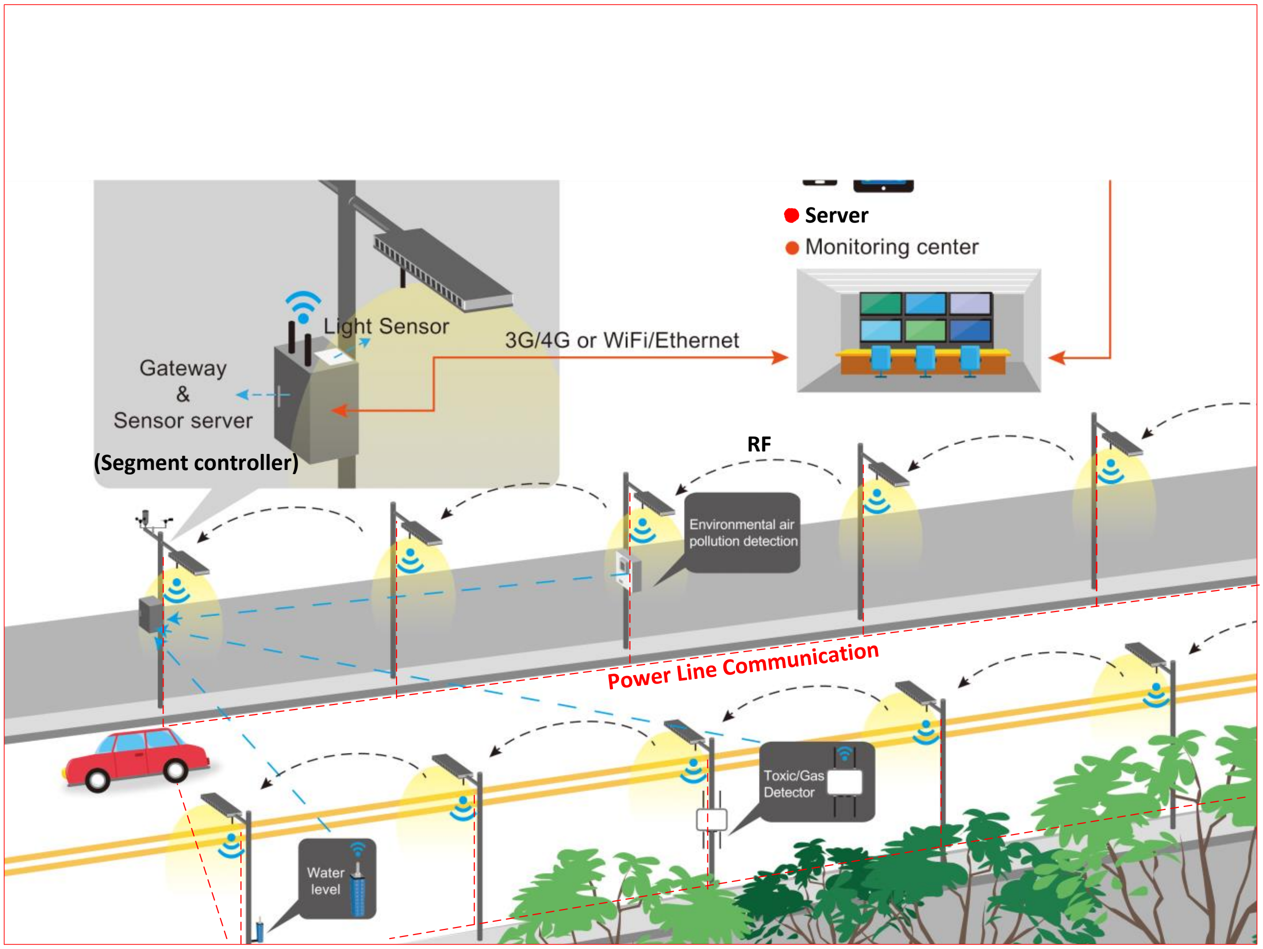
Ukrainian standards

- ДСТУ-Н Б В.2.5-83:2016 «Настанова з проектування засобів і обладнання зовнішнього освітлення міст, селищ та сільських населених пунктів»
- ДБН В. 2.5-28-2006 Естественное и искусственное освещение
- ДСТУ IEC 081-2001 Лампи люмінесцентні двоцокольні. Експлуатаційні вимоги
- ДСТУ IEC 60081:2007 Лампи люмінесцентні двоцокольні. Вимоги до робочих характеристик
- ДСТУ IEC 60188:2003 Лампи дугові ртутні високого тиску. Технічні умови
- ДСТУ IEC 61167:2005 Лампи металогалогенні
- ДСТУ IEC 62035:2005 Лампи розрядні (крім люмінесцентних). Вимоги безпеки
- ГОСТ 12.2.007.13-2000 Лампы электрические. Требования безопасности
- ДСТУ 2339-94. Енергозбереження. Основні положення.
- ДСТУ 2155-93. Енергозбереження. Методи визначення економічної ефективності заходів по енергозбереженню.
- ДСТУ 4065-2001. Енергозбереження. Енергетичний аудит. Загальні технічні вимоги (ANSI/IEEE 739-1995, NEQ)
- ДСТУ 4472-2005. Енергозбереження. Системи енергетичного менеджменту. Загальні вимоги.
- ДБН В.2.5-28-2006. Природне і штучне освітлення.
- Правила улаштування електроустановок. Розділ 6. Електричне освітлення. - К: 2006.

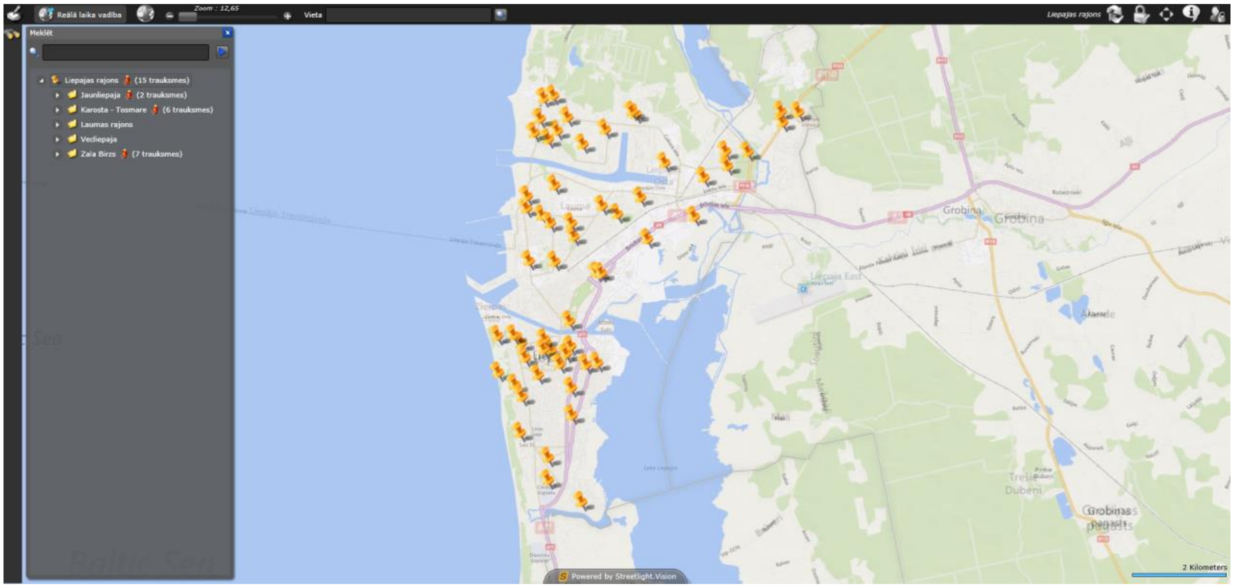
Annex 5 WIND MAP OF EUROPE [89]

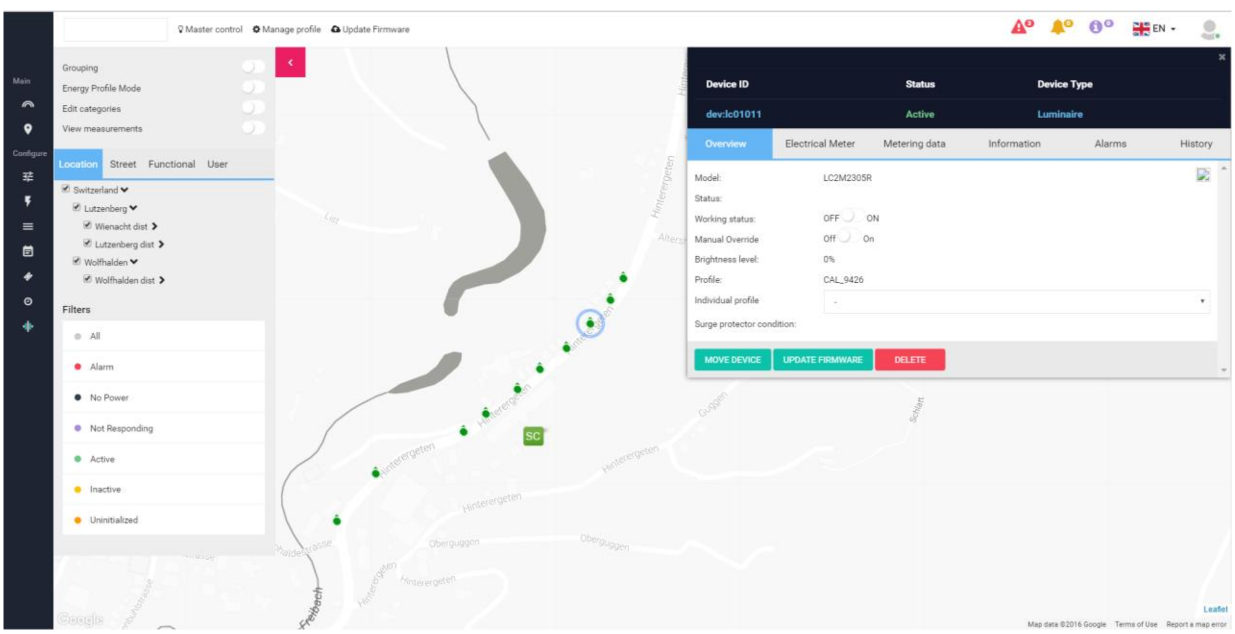


Annex 6 CONCEPT OF SMART STREET LIGHTING SYSTEM [90]



Annex 7 SAMPLES OF USER INTERFACES OF CONTENT MANAGEMENT SYSTEM (CMS) FOR STREET LIGHTNING





REFERENCES

[1] ANDOR an Oxford Instruments Company, "Radiometry & Photometry," An overview of the science of measuring light. [Online]. Available: http://www.andor.com/learning-academy/radiometry-and-photometry-an-overview-of-the-science-of-measuring-light. [Accessed: 16-Jul-2016].

[2] Editors of Encyclopædia Britannica, "Electromagnetic spectrum." [Online]. Available: https://www.britannica.com/science/electromagnetic-spectrum. [Accessed: 16-Jul-2015].

[3] R. Nave, "The Electromagnetic Spectrum," HyperPhysics, Electricity and Magnetism. [Online]. Available: http://hyperphysics.phy-astr.gsu.edu/hbase/ems1.html#c1. [Accessed: 16-Jul-2016].

[4] E. F. Schubert, Light-Emitting Diodes, Second Edi. New York: Cambridge University Press, 2006.

[5] C. DeCusatis Eit, Handbook of Applied Photometry. New York: American Institute of Physics, 1997.

[6] International Commission on Illumination (CIE), "Selected Colorimetric Tables," Downloads. [Online]. Available: http://files.cie.co.at/204.xls. [Accessed: 15-Sep-2014].

[7] R. Nave, "The Lumen," HyperPhysics, Electricity and Magnetism. [Online]. Available: http://hyperphysics.phy-astr.gsu.edu/hbase/vision/lumpow.html. [Accessed: 16-Jul-2016].

[8] A. Ryer, "Light Measurement Handbook." [Online]. Available: http://www.dfisica.ubi.pt/~hgil/fotometria/HandBook/Light-Measurement.1.pdf. [Accessed: 16-Jul-2016].

[9] A. E. F. Taylor, "Illumination Fundamentals III," Lighting Research Center. [Online]. Available: http://www.lrc.rpi.edu/resources/publications/pdf/illuminationfund.pdf. [Accessed: 15-Jul-2016].

[10] D. Erdmann, "Color Rendering Index (CRI)." [Online]. Available: http://www.ianiro.com/media/formato2/ianiro_517.pdf. [Accessed: 29-Nov-2014].

[11] M. D. Fairchild, Color Appearance Models. Willey, 2005.

[12] International Commission on Illumination (CIE), "Chromaticity Difference Specification for Light Sources," Technical note CIE TN 001:2014., 2014. [Online]. Available: http://files.cie.co.at/738_CIE_TN_001-2014.pdf. [Accessed: 18-Sep-2014].

[13] U.S. Department of Energy Energy Efficiency and Renewable Energy, "Color Stability of LEDs Understanding the Basics," Presentation. [Online]. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/royer_stability_lightfair2014.pdf. [Accessed: 18-Jul-2016].

[14] I. AspenCore, "Cooling high-power LEDs," Selecting a solution based on junction temperature ensures that the most critical parameter is identified and thermally managed, 2008. [Online]. Available: http://www.electronicproducts.com/Optoelectronics/LEDs/Cooling_high-power_LEDs.aspx. [Accessed: 18-Jul-2016].

[15] Lighspot, "What is COB?" [Online]. Available: http://www.cob-led.com/What-is-cob-LED-chips-on-board.html. [Accessed: 18-Jul-2016].

[16] J. CAREY, "New LED architectures and phosphor technologies lower costs and boost quality," LEDs Mag., vol. September, 2014.

[17] Seoul Semiconductor, "What is WICOP?" [Online]. Available: http://www.seoulsemicon.com/WICOP/WICOP_en.asp. [Accessed: 18-Jul-2016].

[18] The ZHAGA Organization, “Frequently-Asked Questions (FAQs).” [Online]. Available: http://www.zhagastandard.org/knowledge/faqs/. [Accessed: 18-Jul-2016].

[19] LED Light for you, “High Brightness LED Module - LS-CU301 - 300W.” [Online]. Available: https://www.ledlightforyou.com/Partners/Highlights/en-High-Brightness-LED-Module-300W.php. [Accessed: 18-Jul-2016].

[20] G. LIGHTING, “GE Debuts Landmark LED Modules at Light+Building,” 2014. [Online]. Available: http://www.ledinside.com/news/2012/4/ge_debuts_led_modules_light_building_20120413. [Accessed: 18-Jul-2016].

[21] Luminature, “Engine DOBBY 30W.” [Online]. Available: http://luminature.co.kr/led-dob-light-engine-30w/. [Accessed: 18-Jul-2016].

[22] Edmund Optics Inc., “Diffuser Selection Guide.” [Online]. Available: http://www.edmundoptics.com/resources/application-notes/optics/diffuser-selection-guide/. [Accessed: 14-Jul-2016].

[23] M. Electronics, “Newest products: Ledil.” [Online]. Available: http://www.mouser.ee/new/ledil/lediloslonssl/. [Accessed: 18-Jul-2016].

[24] Ledil, “Ideal Industries and LEDil collaborate on LED interconnect components for solid-state lighting applications Ideal Industries and LEDil collaborate on LED interconnect components for solid-state lighting applications,” LEDs Magazine, 2014. [Online]. Available: http://www.ledsmagazine.com/ugc/2014/07/28/ideal-collaborates-with-ledil-to-develop-costsaving-simpletointegrate-led-components.html. [Accessed: 18-Jul-2016].

[25] Cypress Semiconductor, “What is Power Line Communication?,” Designlines, Industrial Control. [Online]. Available: http://www.eetimes.com/document.asp?doc_id=1279014. [Accessed: 18-Jul-2016].

[26] TechTarget, “ZigBee,” IoT Agenda. [Online]. Available: http://internetofthingsagenda.techtarget.com/definition/ZigBee. [Accessed: 18-Jul-2016].

[27] “CEN/TR 13201-1:2014,” Standard. .

[28] Riegens A/S, “Maintenance factor for lighting installations.” [Online]. Available: http://riegens.com/maintenance-factor-lighting-installations. [Accessed: 16-Jul-2015].

[29] Cree Inc., “Cree® XLamp® LED Long-Term Lumen Maintenance,” CLD-AP28 Rev 2D. [Online]. Available: http://www.cree.com/~/media/Files/Cree/LED Components and Modules/XLamp/XLamp Application Notes/XLamp_lumen_maintenance.pdf. [Accessed: 18-Jul-2016].

[30] Michael and P. Royer, “Design for the future: Understanding Lumen Deprecation and Light Loss factor,” Presentation, 2015. [Online]. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/royer_lumenmaintenance_lightfair2014.pdf. [Accessed: 16-Jul-2015].

[31] Philips LUMEC, “LLF (Light Loss Factor) used by Philips Lumec for LED products.” [Online]. Available: http://www.lumec.com/pdf/LLF_used_by_Philips_Lumec_for_LED.pdf. [Accessed: 06-Mar-2017].

[32] J. R. Benya, “Lighting Calculations in the LED Era.” [Online]. Available: http://www.mouser.ee/applications/lighting_calculations/. [Accessed: 06-Mar-2017].

[33] R. Briden, “Light poles. A guide to the selection, installation and maintenance including the cause and effects of pole vibration.,” 2016. [Online]. Available: http://www.cooperindustries.com/content/dam/public/lighting/resources/library/literature

/Invue1/wp513001en-light-poles-white-paper-bro.pdf. [Accessed: 06-Mar-2017].

[34] Arch Media Group LLC, “Light Distribution Curves.” [Online]. Available: https://www.archtoolbox.com/materials-systems/electrical/readlightdistributiondiagram.html. [Accessed: 18-Jul-2016].

[35] P. R. Boyce, Human Factors in Lighting, Second Edition. CRC Press, 2003.

[36] Lighting Research Center, “Light pollution,” Light. Answers, vol. 7, no. 2, 2003.

[37] A. Žakauskas, M. S. Shur, and R. Gaska, Introduction to Solid-State Lighting. New York: John Willey, 2002.

[38] Cree Inc., “Cree First to Break 300 Lumens-Per-Watt Barrier,” Cree press releases, 2014. [Online]. Available: http://www.cree.com/News-and-Events/Cree-News/Press-Releases/2014/March/300LPW-LED-barrier. [Accessed: 27-Sep-2014].

[39] European Commission, “Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products,” Off. J. Eur. Union, pp. 10–35, 2009.

[40] U.S. Government Printing Office, “Energy Independence and Security Act of 2007,” Security, vol. Public Law, pp. 1–311, 2007.

[41] Lamptech, “Museum of Electric Lamp Technology.” [Online]. Available: http://www.lamptech.co.uk/. [Accessed: 18-Jul-2016].

[42] ZEISS, “Tungsten-halogen incandescent lamps.” [Online]. Available: http://zeiss-campus.magnet.fsu.edu/articles/lightsources/tungstenhalogen.html. [Accessed: 18-Jul-2016].

[43] “Low Pressure Sodium lamp,” Product Description, 2016. [Online]. Available: http://download.p4c.philips.com/lfb/c/comf-1613/comf-1613_pss_en_aa_001.pdf. [Accessed: 13-Jul-2016].

[44] M.Whelan and R. DeLair, “Edison Tech Center,” Sodium Lamp. [Online]. Available: http://www.edisontechcenter.org/SodiumLamps.html. [Accessed: 13-Jul-2016].

[45] LEDWATCHER, “HID Lights for Beginners – High Intensity Discharge Lamps Explained.” [Online]. Available: http://www.ledwatcher.com/high-intensity-discharge-lamps-explained/. [Accessed: 14-Jul-2016].

[46] Engineering Society of North America, “Measurement of Light and Other Radiant Energy,” in IESNA Lighting Handbook: Reference & Application, 9th ed., M. S. Rea, Ed. New York, 2000, p. 1000.

[47] Deco: The Complete Engineering Solutions, “The Working Principle of Induction Lamp.” [Online]. Available: http://www.decoae.com/li-induction.php. [Accessed: 18-Jul-2016].

[48] Technopali North Europe, “Lighting poles,” Catalogue. [Online]. Available: http://www.tecnopali.lv/en/catalogue. [Accessed: 28-Jul-2016].

[49] Abacus, “Ligting Columns,” The Complete Range of Base Hinged & Standard Columns, 2015. [Online]. Available: http://www.abacuslighting.com/pdf/brochure-lighting-columns.pdf. [Accessed: 04-Aug-2016].

[50] Industrial Lighting Systems UK Ltd, “Aluminium Lighting Columns from ILS.” [Online]. Available: http://ilsuk-ltd.com/our-products/aluminium-columns/. [Accessed: 04-Aug-2016].

[51] Passive Safety UK and in association with Traffic Engineering & Control, “Passive Safety UK Guidelines for Specification and Use of Passively Safe Street Furniture on the UK Road

Network," 2010. [Online]. Available: http://www.ukroads.org/webfiles/guidelines Print ready.pdf. [Accessed: 28-Jul-2016].

[52] "ForesightPower Solar Street Lighting." [Online]. Available: http://www.slideshare.net/ForesightPower/foresightpower-solar-street-lighting. [Accessed: 04-Aug-2016].

[53] Mean Well, "Difference between DC 1-10V or 0-10V dimming methods in MW dimmable LED driver," 2015. [Online]. Available: http://www.meanwell.eu/ExclusivePDF/DIMMING-NOTE.pdf. [Accessed: 04-Aug-2016].

[54] Schréder, "Constant Light Output (CLO)." [Online]. Available: http://www.schreder.com/be-en/LearningCentre/LightingBasics/Pages/Constant-Light-Output.aspx. [Accessed: 04-Aug-2016].

[55] International Organization for Standardization, "The consumer and standards: Guidance and principles for consumer participation in standards development," 2013. [Online]. Available: http://www.iso.org/iso/standardsandconsumer.pdf. [Accessed: 08-Sep-2016].

[56] Philips, "How do I know that a light fitting is safe?" [Online]. Available: http://www.lighting.philips.com/main/support/support/faqs/industry-standards. [Accessed: 06-Sep-2016].

[57] QMS, "CE Marking - Council of the European Union." [Online]. Available: http://www.qmsitalia.com/en/standards/CE-Marking. [Accessed: 05-Oct-2016].

[58] "AGREEMENT ON THE EUROPEAN ECONOMIC AREA," 2016. [Online]. Available: http://www.efta.int/sites/default/files/documents/legal-texts/eea/the-eea-agreement/Main Text of the Agreement/EEAagreement.pdf. [Accessed: 05-Oct-2016].

[59] European Commission, "CE marking," 2016. [Online]. Available: https://ec.europa.eu/growth/single-market/ce-marking_en. [Accessed: 05-Oct-2016].

[60] G. Jones, "CE Marking of LED Lighting Products," LinkedIn Pulse, 2015. [Online]. Available: https://www.linkedin.com/pulse/ce-marking-led-lighting-products-gareth-jones. [Accessed: 06-Oct-2016].

[61] IECEE, "The IECEE, Taking conformity assessment further," Brochure, 2015. [Online]. Available: http://www.iec.ch/about/brochures/pdf/conformity_assessment/IECEE_brochure_LR.pdf. [Accessed: 07-Oct-2016].

[62] QSC Consultants Pvt Ltd, "CB SCHEME." [Online]. Available: http://qscpl.com/cb-scheme.html. [Accessed: 08-Oct-2016].

[63] ILAC, "ILAC MRA and Signatories - Benefits." [Online]. Available: http://ilac.org/ilac-mra-and-signatories/benefits/. [Accessed: 07-Oct-2016].

[64] ETICS European Testing Inspection Certification System, "ENEC webpage." [Online]. Available: http://www.enec.com. [Accessed: 01-Jan-2011].

[65] TUV Rheinland, "Product Safety and Quality Certification Marks." [Online]. Available: http://www.tuv.com/en/usainformationcenter/informationcenter/testmarkcatalog/sub_testmarks.html. [Accessed: 08-Oct-2016].

[66] DEKRA, "KEMA-KEUR: Reducing risks and controlling costs for manufacturer, wholesaler, retailer, and consumers." [Online]. Available: http://www.dekra-certification.com/en/kema-keur. [Accessed: 08-Oct-2016].

[67] VDE Institute, "Certification Marks and Attestations." [Online]. Available:

https://www.vde.com/tic-en/marks-and-zertificates/pruefzeichen-und-bescheinigungen. [Accessed: 08-Oct-2016].

[68] Philips, “What is CELMA?” [Online]. Available: http://www.lighting.philips.com/main/support/support/faqs/industry-standards. [Accessed: 05-Sep-2016].

[69] International Commission on Illumination (CIE), “Advancing knowledge and providing standardization to improve the lighted environment.” [Online]. Available: http://www.cie.co.at/index.php/LEFTMENUE/About+us. [Accessed: 09-Oct-2016].

[70] Philips, “What is Zhaga?” [Online]. Available: http://www.lighting.philips.com/main/support/support/faqs/industry-standards/. [Accessed: 05-Sep-2016].

[71] Philips, “What is PAS?” [Online]. Available: http://www.lighting.philips.co.uk/support/support/faqs/industry-standards/what-is-pas.html. [Accessed: 09-Oct-2016].

[72] Philips, “What are the LED lighting standards referenced in the Energy Star specification.” [Online]. Available: http://www.lighting.philips.com/main/support/support/faqs/industry-standards. [Accessed: 05-Sep-2016].

[73] TUV NORD, “ISO 9001 - Quality Management Systems.” [Online]. Available: https://www.tuv-nord.com/us/en/quality-systems/iso-certification/iso-9001-certificate/. [Accessed: 09-Oct-2016].

[74] ISO, “Abstract of ISO 14000 standard,” Environmental management systems -- Requirements with guidance for use. [Online]. Available: http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=60857cuments/iso-14000_en. [Accessed: 09-Oct-2016].

[75] iQ-Laboratory, “ISO 17025.” [Online]. Available: http://www.iq-labonline.com/iso-17025/. [Accessed: 09-Oct-2016].

[76] European Committee for Standardization (CEN), “CEN/TR 13201-2: Road lighting - Part 2: Performance requirements,” 2004. .

[77] W. van Bommel, Road Lighting: Fundamentals, Technology and Application. Springer, 2015.

[78] M. Green, “Seeing Pedestrians At Night,” Human factors. [Online]. Available: http://www.visualexpert.com/Resources/pedestrian.html. [Accessed: 06-Mar-2017].

[79] KH Energia-Konsult, “Pedestrian Crossing.” [Online]. Available: http://www.energia-konsult.ee/en/outdoor-lighting/pedestrian-crossing-solution/. [Accessed: 01-Nov-2016].

[80] “Außenbeleuchtung.” [Online]. Available: https://wiki.watt24.com/index.php?title=Außenbeleuchtung. [Accessed: 01-Nov-2016].

[81] European Committee for Standardization (CEN), “CEN/TR 13201-1: Road lighting - Part 1: Road lighting - Part 1: Guidelines on selection of lighting classes,” 2004. .

[82] C. van Santen, Light Zone City: Light Planning in the Urban Context. Basel: Birkhauser, 2006.

[83] L. Loe, K. P. Mansfield, and E. Rowlands, “Appearance of lit environment and its relevance in lighting design: Experimental study,” Light. Res. Technol., vol. 26, no. 3, pp. 119–133, Jan. 1994.

[84] The Institution of Lighting Engineers, The Outdoor Lighting Guide. New York: Routledge, 2015.

[85] D. Lorenz, “Light Pollution Atlas 2006.” [Online]. Available:

https://djlorenz.github.io/astronomy/lp2006/. [Accessed: 22-Nov-2016].

[86] International Dark-Sky Association, "Light Pollution." [Online]. Available: http://darksky.org/light-pollution/. [Accessed: 22-Nov-2016].

[87] Commission Internationale de L'Eclairage, "CIE 154:2003 The maintenance of outdoor lighting systems," 2003. .

[88] A. S. A Sanders, "Review of luminaire maintenance factors," CSS Street Lighting Project SL3/2007, 2008. [Online]. Available: https://www.theilp.org.uk/documents/css-sl3-maintenance-factors/css-sl3-maintenance-factors.pdf. [Accessed: 24-Oct-2016].

[89] "ESDEP WG 1B STEEL CONSTRUCTION: Introduction to design," Lecture 1B.3: Background to Loadings. [Online]. Available: http://fgg-web.fgg.uni-lj.si/~/pmoze/esdep/master/wg01b/l0300.htm. [Accessed: 23-Nov-2016].

[90] K. Liu, "Green Ideas Technology Introduces Blind-spot-free Smart Lighting Control System," Taiwanese company aims to make street lighting and surveillance cheaper and more efficient. [Online]. Available: http://www.cens.com/cens/html/en/news/news_inner_48111.html. [Accessed: 04-Aug-2016].

[91] Conservation First Framework, Version 2.0 – Retrofit Program, Project Measurement & Verification Procedures, April 11, 2016.

[92] M&V Guidelines: Measurement and Verification for Performance Based Contracts Version 4.0 November 2015.

[93] Measurement & Verification Process for Calculating and Reporting on Energy and Demand Performance -General Guidance.

[94] Standard Measurement and Verification Plan for Lighting Retrofit Projects for Buildings and Building Sites, October 2012.

BIBLIOGRAPHY

Гужов С, Полищук А, Туркин А. Концепция применения светильников со светодиодами совместно с традиционными источниками света. СТА: современные технологии автоматизации №1'2008. М.: СТА-ПРЕСС. стр. 14-18.

Сергеев Б.С, Рошман Э.М, Савельев Е.О. Управление светодиодными матрицами с помощью реактивных элементов. Электричество №9, 2004. М.: Знак. стр. 13-16.

Справочная книга по светотехнике. Под. Ред. Айзенберга Ю.Б. Изд. 3-е перераб. и доп. М.: Знак, 2006. 972 с, ил.

Демирчян К.С, Нейман Л.Р, Коровкин Н.В, Чечурин В.Л. Теоретические основы электротехники: В 3-х т. Учебник для вызов. Том 2. 4-е изд. СПб.: Питер, 2003. - 576 с.

Справочная книга по светотехнике/Под ред. Ю.Б. Айзенберга. М.: Энергоатомиздат, 1995. 528с.

Современные энергосберегающие электротехнологии: Учеб. пособие для вузов/Ю.И. Блинов, А.С. Васильев, А.Н. Никаноров и др. СПб.: Изд-во СПбГЭ-ТУ ЛЭТИ, 2000. 548с.

Гужов С.В. О применении светильников со светодиодами в уличных осветительных установках. Промышленная энергетика, М., 2008. — 99 с.

LED Application Series: Outdoor Area Lighting. U.S. Department of Energy. (2008) http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/outdoor_area_lighting.pdf

DOE Municipal Solid-State Street Lighting Consortium. U.S. Department of Energy. (2013) http://www1.eere.energy.gov/buildings/ssl/consortium.html

Qualified Products List. Design Lights Consortium. (2013) http://www.designlights.org/QPL

Considerations in Led Street Lighting in Massachusetts. Department of Energy Resources. (2011) http://mapc.org/sites/default/files/SL-MAPC-pres-Powelka.pdf

How to Use the Maintenance, Repair & Operations (MRO) Products, Supplies and Equipment Statewide Contract (FAC76). Massachusetts Operational Services Division. (2012) http://www.mass.gov/anf/docs/osd/uguide/fac76-05-03-2013.pdf

Improving Efficiency in Municipal Street and Public Lighting. Efficiency Vermont. http://www.efficiencyvermont.com/for_my_business/solutions_for_me/municipal_and_state_government/general_info/municipal_street_lighting.aspx

Solid-State Lighting GATEWAY Demonstration Results. U.S. Department of Energy. (2013) http://www1.eere.energy.gov/buildings/ssl/gatewaydemos_results.html

Ann Arbor's LED Streetlight Program. City of Ann Arbor, Michigan. http://www.a2gov.org/government/publicservices/systems_planning/energy/Documents/LED_Summary.pdf

Los Angeles' LED Street Lighting Energy Efficiency Program is Shining Bright. Alcon Lighting. (2011) http://www.alconlighting.com/energy_efficient_blog/2011/08/19/los-angeles-led-street-lighting-energy-efficiency-program-is-shining-bright/

City of Anchorage, Alaska CREE. (2008) http://www.betaled.com/us-en/LEDApplications/street-lighting/City-of-Anchorage-Alaska.aspx

LED Streetlights. Seattle City Light. (2012) http://www.seattle.gov/light/streetlight/led

Efficiency Valuation Organization. 2007. International Performance Measurement & Verification Protocol - Concepts and Options for Determining Energ y and Water Savings Volume 1. California, USA

World Bank, Energy Sector Management Assistance Program (ESMAP). 2009. Energy Efficient Cities

Initiative. Good Practices in City Energy Efficiency: Akola Municipal Corporation, India - Performance Contracting for Street Lighting Energy Efficiency. Washington DC, USA.