Aalto University
School of Electrical Engineering
Lighting Unit
Finland

Road lighting in transition

Sub study 1 - LEDs and other light source technologies

Report prepared by:
Puolakka M., Ylinen A-M., Halonen L.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS AND SYMBOLS

AC	Alternating Current
ALI	Averaged LED Intensity
ANSI	American National Standards Institute
CALiPER	Commercially Available LED Product Evaluation and Reporting
CCT	Correlated Colour Temperature
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CIE	International Commission on Illumination (Commission Internationale de l´Eclairage)
CFL	Compact Fluorescent Lamp
CRI	Colour Rendering Index
DC	Direct Current
DOE	U.S. Department of Energy
EC	European Commission
EMC	Electromagnetic Compatibility
ENTSOE	European Network of Transmission System Operators for Electricity
EPA	Environmental Protection Agency
ETSI	European Telecommunications Standards Institute
EU	European Union
EuP	Energy using Products
HID	High Intensity Discharge
HPS	High Pressure Sodium
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IES	Illuminating Engineering Society
ISO	International Organization for Standardization
LED	Light Emitting Diode
LPS	Low Pressure Sodium
LSF	Lamp Survival Factor
MH	Metal Halide
MV	Mercury Vapour
NEMA	National Electrical Manufacturers Association
NIST	National Institute of Standards and Technology
PAS	Publicly Available Specifications
SDO	Standard Development Organization
SSL	Solid State Lighting

EXECUTIVE SUMMARY

Outdoor lighting is built to increase the safety and security of drivers, pedestrians and other night-time road users. Outdoor lighting sector covers the lighting of roads, streets, pedestrian and bicycle ways, parks and other outdoor areas. Outdoor lighting is facing major changes in the ongoing and coming years. In Europe, the mercury vapour (MV) lamps and retrofit high pressure sodium (HPS) lamps, which are commonly used in road lighting, will be phased out from the European markets by April 2015.

An option for the conventional lamps in outdoor lighting is the LED (light emitting diode) technology. In the recent years there has been huge development of LEDs, and it is foreseen that they will become the most energy-efficient light source in the future. The advantages of LEDs are high luminous efficacy (ratio of the light output to the input electrical power), long lifetime and instant start characteristics. Also, LEDs are easy to control and they contain no mercury. The extra benefits of using LEDs is the white light with good colour rendering properties, as compared for example to the yellowish light of the high-pressure sodium lamps.

There are still barriers to be overcome before wider adaption of LED outdoor lighting will take place; these include high investments costs and the large differences in the quality of LED luminaires currently on the market. The costs of LED light sources have decreased substantially over the past years. However, the prices of LED luminaires are still higher than those of the conventional ones used in outdoor lighting.

The energy efficiency and lifetime of the light sources are of particular interest in outdoor lighting, where the operating times of the installations and annual operating hours are long. The high maintenance and lamp replacement costs place also strong demands for long product lifetime. In weighting the alternative light source and luminaire options for outdoor lighting, the cost efficiency evaluations should be based on lifecycle cost analysis. Life cycle cost analysis takes into account the costs of the lighting installation over its entire life span (typically 30 years in road lighting). These include the investment costs (construction, installation and acquisition) and operating costs (energy and maintenance).

The durability and maintenance needs of LED luminaires over the installation lifetime are still unknown, as this would require several years of operation and the products are still young. Incorrect luminaire design, thermal management and power supply design may reduce the lifetime of the installed LED luminaires, thus care has to be taken in the choice of the luminaires.

The high pace of LED development means that regulations and standards follow years after products are on the market. The technical information given in the luminaire datasheets vary from manufacturer to another as there are no established practices for specifying LED luminaire performance. Also, the reported characteristics of LED products on the market do not always match laboratory measurement results. There are needs for reliable, unbiased product performance information and standardization of LED products to ensure proper performance of the installed systems.

The current market penetration of LED lighting in Europe is still low: the LED market share (in value) reached 6.2% in 2010. However, several studies predict that LEDs will account for more than 70% of Europe's general lighting market by 2020. The U.S. DOE predicts that by 2030, the LED outdoor luminaire market is expected to represent 87% of the total market, which correlates to 46% reduction from the baseline energy consumption.

1 INTRODUCTION

The total electricity consumption accounted for approximately 2 830 TWh in 2010 in the European Union (EU). The consumption has increased by 30% between 1990 and 2010 [1]. Lighting accounts for 19% of the global total electricity consumption, of which the share of outdoor lighting is 8% [2]. Outdoor lighting covers lighting for roads and streets, pedestrian/bicycle ways, parks and other outdoor areas.

The European Commission (EC) has set a goal to reduce energy consumption by 20% by 2020. This is done by giving minimum performance requirements for various energy using products, including lighting equipment, through a number of programs and directives. The EU has adopted the Energy-Related Products (ErP) Directive 2009/125/EC. The Implementing Agreement of this directive (EC Regulation No. 245/2009) applies to fluorescent and high intensity discharge (HID) lamps and their ballasts and luminaires, which are typically used in the tertiary sector including outdoor lighting [3]. As a result of this regulation, the mercury vapour (MV) lamps and retrofit high pressure sodium (HPS) lamps, which are commonly used in road lighting will be phased out from the European markets by April 2015. Additionally, further efficacy and performance requirements are given for high pressure sodium and metal halide (MH) lamps.

HID lamps are the conventional lamps used in outdoor lighting. These include mercury vapour (MV), high pressure sodium (HPS) and metal halide (MH) lamps. To some extent, also low pressure sodium (LPS) lamps are used, but their use is decreasing due to poor colour characteristics of the yellow light they provide. HID lamps have been in use for many years and their performance characteristics are well known. The development potential of HID lamps is, however, slowing down.

The recent development of light emitting diode (LED) lighting products has rapidly become competitive with HID light sources giving a new option for outdoor lighting. LEDs hold great promises as future light sources in outdoor lighting. The first commercially available high power LED (~ 1 W) was available in 1999 [4] with the luminous efficacy of approximately 20 lm/W. Today, the luminous efficacy of a white LED is around 165 lm/W and is ever increasing.

LEDs are expected to be the most energy efficient light sources in the near future. Other advantages of LEDs are long lifetime (around 50 000 h), instant start characteristics, control of light intensity and colour, no mercury contain. The luminous efficacy of LEDs is not yet near its fundamental limit and huge resources are put in the development of the technology.

There are still barriers to be overcome before wider adaption of LED outdoor lighting will take place; these include high investments costs and the large differences in the quality of LED luminaires currently on the market. The municipalities are also concerned with the maintenance of LED lighting, as the durability and maintenance needs of LED luminaires over the installation lifetime are still unknown. Incorrect luminaire design, thermal management and power supply design can reduce the lifetime of LED luminaires.

The reported efficiencies and other metrics of LED products on the market do not always match laboratory measurement results. Standardization of LED products is needed to ensure proper performance of the installed systems. Reliable testing methods capable of providing accurate projections of LED life-time do not currently exist. These accelerated testing methods would reduce costs and time-to-market of LED products.

The outdoor lighting practices are also due to change with respect to photometry. Currently, all lighting dimensioning is based on photopic (i.e. daytime vision) functions. The newly published [5] mesopic photometry (low light levels i.e. outdoor lighting), on the other hand, favours light sources that have higher content in the shorter wavelength region, such as MH lamps and white LEDs.

2 DEVELOPMENT OF CONVENTIONAL AND LED TECHNOLOGIES

Today, white-light LEDs compete with conventional light sources in outdoor lighting. The ability to improve the performance of HID lamps is limited as these technologies are quite mature. On the other hand, there are huge possibilities in the development of LED light sources and great efforts are put in it. Luminous efficacy (lm/W) is a measure for describing the light output versus input power of a light source.

Figure 1 shows the historical development of luminous efficacy of conventional lamps and the future expectations of the luminous efficacy of LEDs [6, 7].

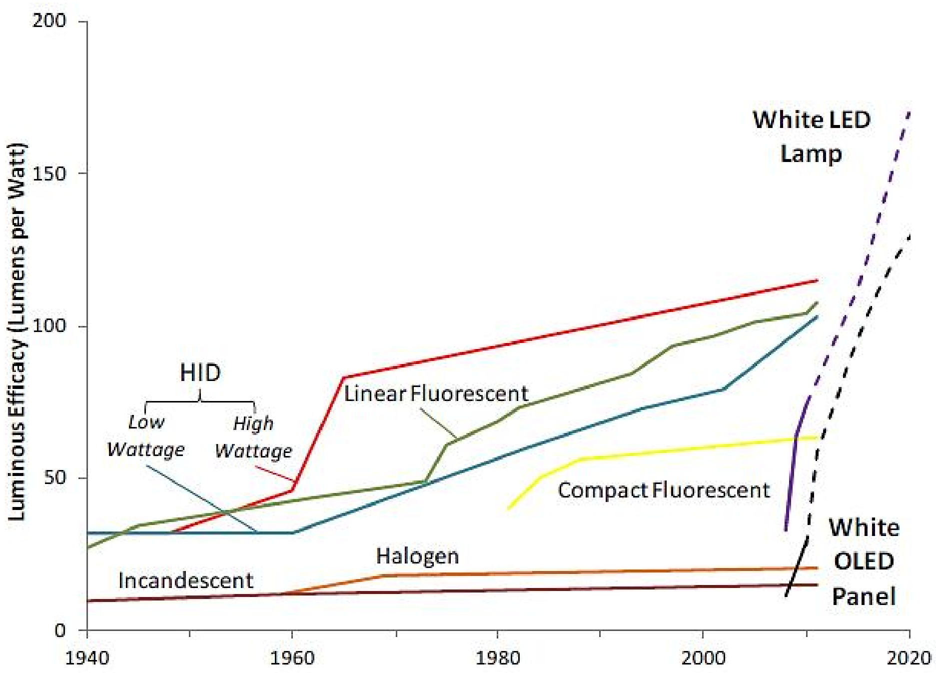


Figure 1. Historical and predicted luminous efficacy of light sources. [6]

2.1 HID lamps

Discharge lamps like mercury vapour (MV), high pressure sodium (HPS), low pressure sodium (LPS) and metal halide (MH) are widely used in outdoor lighting. In HID lamps a constant arc between two electrodes housed inside an arc tube produces the light. The discharge tube is filled with different gasses and metal compounds (MH). Each discharge lamp produces light related to the type of gas, gas pressure and metal compound that is contained in the arc. Discharge lamps require a ballast to regulate the current flow and provide appropriate voltage to the arc. [8]

Commercial **high pressure sodium** (**HPS) lamps** were developed in the 1960's. HPS lamp ballasts have traditionally been magnetic ballasts, however, in the recent years electronic ballasts have been employed. Compared to magnetic ballasts, electronic ballasts increase lamp life, lamp lumen maintenance and system efficacy. Typical of HPS lamps:

- Luminous efficacy 80 – 150 lm/W
- Lamp life 20 000 h – 24 000 h
- Wattage range 35 W - 1000 W
- CRI (colour rendering index) 20 – 25
- CCT (correlated colour temperature) 1900 K - 2200 K

Commercial **metal halide (MH) lamps** were also developed in the 1960's. The arc tube contains various metal halides, mercury and argon. The lamp spectrum depends on the metal halides used in the arc tube. Typical characteristics of MH lamps:

- Luminous efficacy 60 – 110 lm/W
- Lamp life 6 000 h – 20 000 h
- Wattage range 20 W - 1000 W
- CRI 2700 K – 5000 K
- CCT 65 - 95

Metal halide lamps have been developed from the early probe-start magnetic ballast lamps to pulse-start electrical ballasts ceramic MH lamps. This has increased the luminous efficacy and lamp life and improved the colour quality of the light.

The development options to improve MH lamp luminous efficacy are limited. There are still possibilities to improve the pulse start technology, the arc tube design including the arc tube material and the arc tube shape, arc tube filling gas, lamp electrodes, and ballasts. The maximum practical efficacy of white light metal halide lamp is 230 lm/W [8]. Currently, the maximum luminous efficacy is around 120 lm/W and laboratory results have reported luminous efficacies exceeding 150 lm/W [9]. Further improvements in ceramic metal halide lamps are expected through improved driver efficiencies and breakthroughs in microwave technology [8, 9, 10].

Table 1 gives estimates of the improvement of conventional lighting technologies by 2030 with baseline technology in 2010. Compared to the improvement potential of LEDs it is clearly seen that the development potential of HID lamps are modest.

Table 1. Outdoor lamp technology performance, 2010 and 2030. [6]

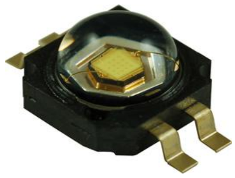
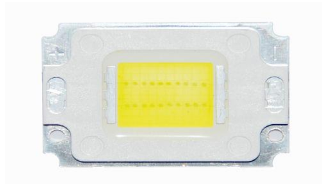
	Baseline technology in 2010				Percent improvement by 2030	
Lamp types	**Mean system power (W)**	**Lamp life (1000 h)**	**Mean system efficacy (lm/W)**	**Luminaire efficiency (%)**	**Mean system efficacy**	**Lamp life**
Mercury vapour	219	20	30	65%	0%	0%
Metal halide	247	18	60	65%	15%	15%
High pressure sodium	241	28	84	65%	5%	5%
Low pressure sodium	107	25	89	65%	5%	5%

2.2 LEDs

White LED light is produced by either phosphor conversion, discrete colour mixing or hybrid approach which mixes the phosphor conversion and discrete colour mixing. Most LEDs produce light by phosphor conversion. The efficacies of phosphor converted LEDs are today up to 144 lm/W for cool white (CW) emitters and 111 lm/W for warm white (WW) emitters. In April 2012 Cree announced that it has reached 254 lm/W with white power LED in laboratory conditions [11].

The luminous efficacy of LED luminaire is always lower than that of the LED dye (chip). LED lighting products are commonly categorized to LED die (chip), LED package, LED module, LED lamp and LED luminaire [12].

LED die (or chip) is a small block of light-emitting semiconducting material on which a functional LED circuit is fabricated. Examples of LED dyes:

LED package is an assembly of one or more LED dies that contain wire bond connections possibly with an optical element and thermal, mechanical and electrical interfaces.

The performance of the LED package depends on the desired colour characteristics: correlated colour temperature (CCT) and CIE (Commission Internationale de l´Eclairage) colour rendering index (CRI). Table 2 gives projections of LED package efficiency. Cool white LED assume CCT = 4746 – 7040 K and CRI = 70 - 80, and warm white LED assume CCT = 2580 – 3710 K and CRI = 80 - 90.

Table 2. Progress projections for LED package luminous efficacy (lm/W). [6]

Metric	2011	2013	2015	2020	Goal
Cool white (colour-mixed)	135	164	190	235	266
Cool white (phosphor)	135	157	173	192	199
Warm white (colour-mixed)	97	129	162	224	266
Warm white (phosphor)	98	126	150	185	199

LED module is the LED dye (chip) together with mechanical and optical components making a replaceable item for use in luminaire. Examples of LED modules:




LED luminaire is a complete lighting unit consisting of LED-based light emitting elements and a matched driver together with parts to distribute light, to position and protect the light emitting elements, and to connect the unit to a branch circuit. Examples of LED outdoor luminaires:

LED luminaires are complete lighting units intended to connect directly to electrical circuit, that consist of LED based light emitting elements, drivers, optics, housing and electrical connections. Luminaire performance ultimately determines the actual energy savings. The efficiency the LED package, the efficiency of the driver, the optical efficiency of the fixture and thermal impact of the assembly must be considered for the overall luminaire efficacy. Forecasts for the technology improvements are shown in Table 3.

Table 3. Forecasts of WW (CCT = 2580 - 3710 K, CRI = 80 - 90) LED luminaire performance targets [6].

Metric	**2011**	**2013**	**2015**	**2020**	**Goal**
Package luminous efficacy (lm/W)	97	129	162	224	266
Thermal efficiency	86%	87%	88%	90%	90%
Efficiency of driver	85%	87%	89%	92%	92%
Efficiency of fixture	86%	87%	89%	82%	92%
Resultant luminaire efficiency	63%	66%	69%	76%	76%
Luminaire luminous efficacy (lm/W)	**61**	**85**	**112**	**170**	**202**

3 MARKET OVERVIEW

3.1 Share of light sources

According to International Energy Agency (IEA, 2006), the global distribution of light sources in outdoor lighting was estimated as following: 62% high and low pressure sodium lamp luminaires, 30% mercury vapour lamp luminaires, 6% metal halide lamp luminaires, and the remaining 2% miscallenous [13].

In Europe, the distribution in 2007 was estimated to be: 47% high pressure sodium lamp luminaires, 32% mercury vapour lamp luminaires, 9% low pressure sodium lamp luminaires, 8% compact fluorescent lamp luminaires 3%, and metal halide lamp luminaires [14].

In the U.S., the distribution of outdoor light sources in 2002 [15] and 2010 [16] are shown in Figure 2. The mercury vapour lamp luminaires have been almost completely replaced by other light sources between 2002 and 2010. Also, the LED luminaires represent 11% of the installed outdoor luminaires in 2010.

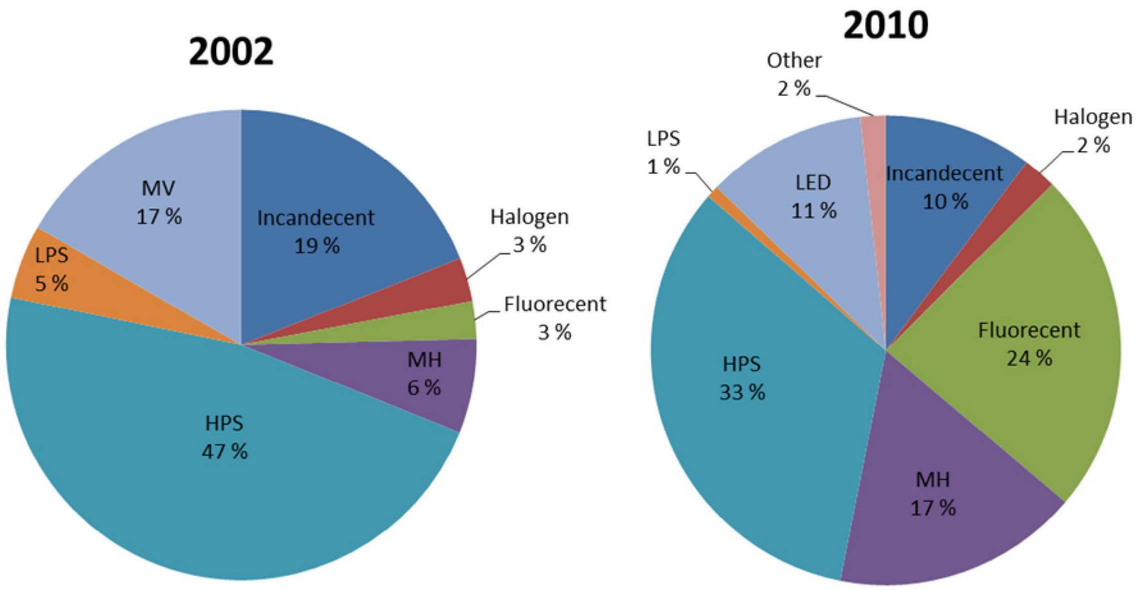


Figure 2. Distribution of light sources in U.S [15, 16].

In Finland, the distribution of outdoor luminaires was studied by Aalto University Lighting Unit in 2009 and in 2011. The estimated number of outdoor lighting luminaires in Finland in 2009 was 1.3 million pieces, of which 51% were MV lamp luminaires and 45% HPS lamp luminaires. The rest were low LPS, MH, induction lamp luminaires and LED luminaires. The survey in 2011 indicated that thousands of MV lamps had been replaced mostly by HPS lamp luminaires. Also, the amount of LED installations were increasing each year between 2009 and 2011.

The energy consumption of outdoor lighting can be reduced by dimming the light sources (decreasing light levels with decreasing power), employing proper design, operation and maintenance of the lighting installations, as well as employing energy efficient technologies. According to CELMA, solid state lighting (SSL) products have an 80% overall energy savings potential in outdoor lighting in the future [17], Figure 3.

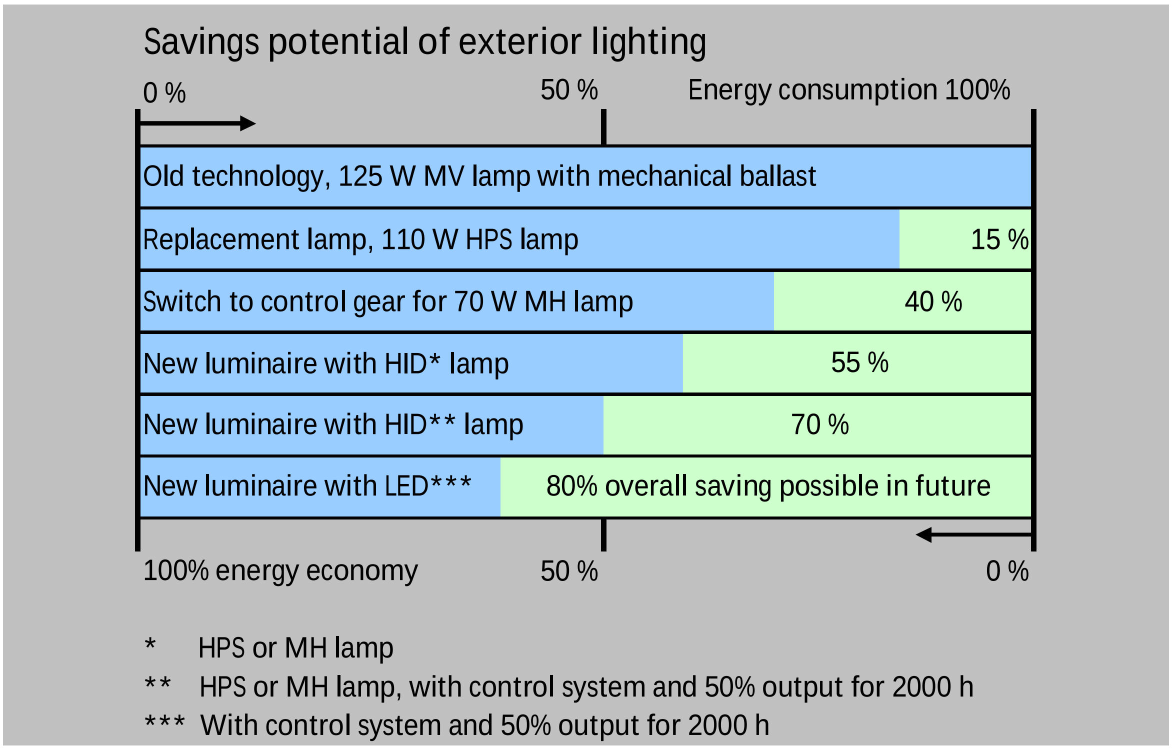


Figure 3. Energy saving potential in outdoor lighting according to CELMA [17].

3.2 LED markets

In the outdoor lighting sector, the efficiency of lighting and the light source lifetime are of particular interest. Long lifetime is a high priority due to the long annual operating hours and potentially high maintenance costs associated with outdoor lighting. HPS lamps have traditionally dominated the outdoor lighting. Recently, MH lamps have become a major contender due to their better colour characteristics.

The prices of light sources are typically compared on a price per kilolumen basis. While the first cost of a light source or luminaire is an important parameter, it is the lifecycle cost of the installation that ultimately determines the overall economic benefit especially in outdoor lighting. In street lighting the lifecycle costs are typically calculated over 25-30 years performance period.

The prices of LED light sources have reduced during the past few years as the manufacturing costs have reduced and competition has intensified. The price of LED based luminaires providing 8 000 – 10 000 lumen output has decreased from around 150 $/klm to around 80 $/klm and the efficacy has increased from around 50 lm/W to around 80 lm/W [6].

LED lighting has a tremendous potential especially for the outdoor lighting sector and it is estimated to penetrate this sector the quickest due to the high initial costs of the HID lamp and ballasts systems. LED luminaires are projected to represent 87% of the outdoor lighting sales by 2030. Figure 4 presents the forecast for outdoor lighting service between 2010 and 2030. [7]

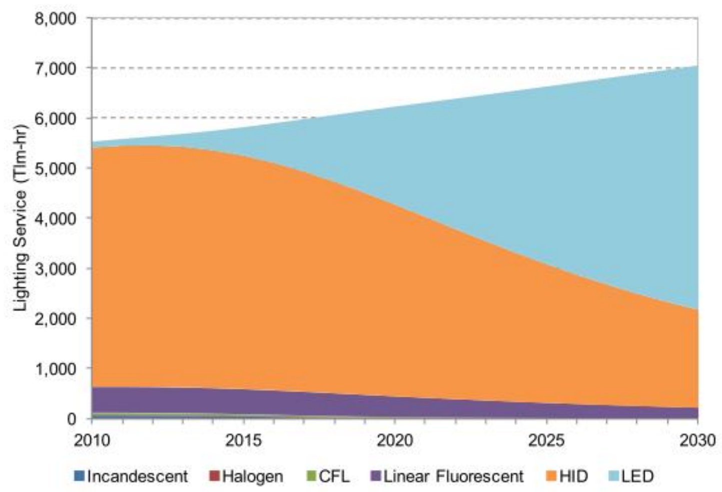


Figure 4. Outdoor stationary lighting service forecast in U.S. [7].

Figure 5 shows the predicted outdoor HID lighting market shares as baseline without LED lighting and with the predicted LED scenario in the U.S. MH lamps are somewhat less efficacious than HPS lamps, but offer white light with good colour rendering properties in contrast to the yellowish light of the HPS lamps. The LED luminaires are expected to have significant impact on the outdoor HID lamp submarket. LED luminaires are expected to monopolize the outdoor HID lamp market by 2030 at 87% market share. [7]

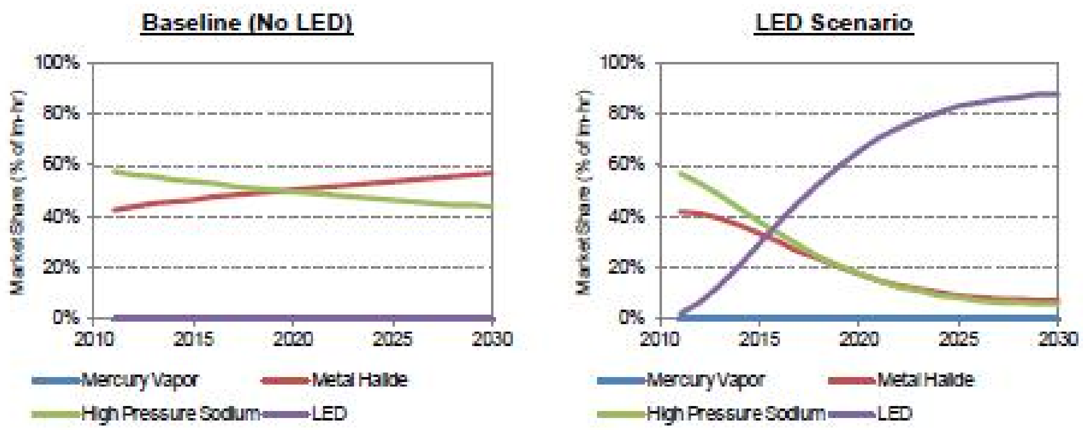


Figure 5. Outdoor stationary HID market share forecast in the U.S. 2010-2030. [7]

4 STANDARDS AND STANDARD DEVELOPMENT NEEDS

4.1 Need for standardisation

Customers need to understand what a specific product does and trust that the product works as promised. Standards ensure the quality, environmental friendliness, safety, reliability, efficiency and interchangeability of products. Standards eliminate inconsistencies in lighting product attributes such as colour, intensity and service life. Standards also help to compare product performance based on common and meaningful metrics accepted by the industry. [18]

ISO/IES [19] defines standard as

"document, established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context"

Standardized products are accepted, trusted and valued as they are perceived as safe, secure, high quality and flexible. Standards provide technological, economic and societal benefits. This means that products and services that meet the specifications can be developed and are internationally accepted.

The conventional testing standards do not always work well with the solid state lighting (SSL) products due to unique characteristics of LEDs. An example is the operating temperature ranges that have little effect on incandescent lamp life time but can have a major impact on the life time of a LED product.

The basic metrics like light output, input power, colour quality and expected life time for LED remains the same as for any other light source. However, until 2008, there were no industry-accepted standards for testing and representing these basic attributes for LED lighting products.

SSL standards are being developed in addition to existing lighting standards and guidelines. The standardization work is performed in various organizations throughout the world. In Europe the SSL lighting standards are mandate to the European Committee for Standardization (CEN), the European Committee for Electrotechnical Standardization (CENELEC) and the European Telecommunications Standards Institute (ETSI). In the U.S the standardization is performed at the American National Standards Institute (ANSI) together with federal and local government regulatory positions. In the U.S. the Department of Energy (DOE) together with industry partners sponsor a program to promote SSL research, development, and commercialization and work closely with a network of standards-setting organizations and offer technical assistance and support.

In its Guiding paper ***Apples & Pears, a CELMA guiding paper: Why standardisation of performance criteria for LED luminaires is important*** the CELMA (Federation of National Manufacturers Association for Luminaires and Electrotechnical Components for Luminaires in the European Union) is concerned about the vast number of new and unproven entrants in the lighting markets in recent years [12]. According to CELMA, '*Some are making dubious claims about their products' performance that are too good to be true, and not supported on a technical basis.*' The IEC recently published two Public Available Specification (PAS) performance requirement documents (IEC/PAS 62717 Performance requirements – LED modules for general lighting, IEC/PAS 62722 Performance requirements – LED luminaires for general lighting). The CELMA Guiding paper is intended to help bring clarity by introducing a universal set of quality criteria that are described in the two IEC/PAS documents.

4.2 Organizations related to SSL standardization

The international and national organizations related to SSL lighting standardisation:

The International Organization for Standardization (ISO) is the world's largest developer of voluntary international standards covering almost all aspects of technology and business [18]. ISO is a network of the national standards institutes. ISO also works in co-operation with other standards development organizations and publishes joint standards (see CIE).

The International Commission on Illumination (CIE) [20] is devoted to worldwide cooperation and the exchange of information on all matters relating to the science and art of light and lighting, colour and vision, photobiology and image technology. The CIE has become a professional organization and has been accepted as representing the best authority on the subject and as such is recognized by ISO as an international standardization body.

The International Electrotechnical Commission (IEC) [21] is an organization for the preparation and publication of International Standards for all electrical, electronic and related technologies. In IEC the standards concerning LED products are standardized in the subcommittees of the technical committee TC 34 Lamps and related equipment.

The American National Standards Institute (ANSI) [22] is responsible for establishing standards and conformity assessment system within the United States.

The National Electrical Manufacturers Association (NEMA) [23] is the trade association for the electrical manufacturing industry in the United States. NEMA provides a forum for the development of technical standards that are in the best interests of the industry and final consumers.

The National Institute of Standards and Technology (NIST) [24] is a physical science laboratory in the United States. NIST's mission is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve peoples' quality of life.

The Institute of Electrical and Electronics Engineers (IEEE) [25] is a professional association dedicated to advancing technological innovation and excellence. The IEEE Standards Association (IEEE-SA) develops and advances global technologies through IEEE.

The European Committee For Electrotechnical Standardization (CENELEC) [26] is a non-profit international organization. CENELEC acts as a platform for experts to develop European Standards (ENs) in co-operation with the European Committee for Standardization (CEN) and the European Telecommunications Standards Institute (ETSI). The European EN standards are mostly based on IEC standards and are enforced as national standards.

The Zhaga [27] an industry-wide cooperation aimed at enabling the interchangeability of LED light sources made by different manufacturers. Zhaga specifications cover the physical dimensions, as well as the photometric, electrical and thermal behavior of LED light engines.

4.3 LED related standards

The following lists standards, guidelines and recommendations concerning LED outdoor lighting products.

Modules

- **IEC 62031** (2008-01) Ed. 1.0, LED modules for general lighting - Safety specifications [28]
- **IEC/PAS 62717** (2011-04) Ed1.0, LED modules for general lighting - Performance requirements [29]

Drivers

- **IEC 61347-1** (2007-01) Ed. 2.0, Lamp control gear - Part 1: General and safety requirement [30]
- **IEC 61347-2-13** (2006-05) Ed. 1.0, Lamp control gear - Part 2-13: Particular requirements for DC or AC supplied electronic control gear for LED modules [31]
- **IEC 62384** (2006-08) Ed. 1.0, DC or AC supplied electronic control gear for LED modules - Performance requirements [32]
- **IEC 62386-207** (2009-08) Ed. 1.0, Digital addressable lighting interface - Part 207: Particular requirements for control gear - LED modules (device type 6) [33]
- **NEMA SSL-1, 2010,** Electronic Drivers for LED Devices, Arrays, or Systems [34]

Luminaires

- **IEC 60598-1** (2008-04) Ed. 7.0, Luminaires - Part 1: General requirements and tests [35]. The requirements and related tests of this standard cover: classification, marking, mechanical construction and electrical construction. In addition, special requirement standard for the luminaire purpose (portable luminaires, street luminaires, hand lamps etc.) is needed.

Electromagnetic compatibility

- **IEC 61000-3-2** (2009-04) Ed. 3.2, Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current ≤16 A per phase) [36]
- **IEC 61000-3-3** (2008-06) Ed. 2.0, Electromagnetic compatibility (EMC) - Part 3-3: 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 [37]
- **CISPR 15/ EN 55015** (2009-01) Ed. 7.2, Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment [38]

Colour characteristics

- **ANSI C78.377-2008, Specifications for the Chromaticity of Solid-State Lighting Products** [39]. The purpose of this standard is to specify the range of chromaticities recommended for general lighting with solid state lighting (SSL) products, as well as to ensure that the white light chromaticities of the products can be communicated to consumers.

Other LED related standards

- **IEC/TS 62504 (2011-03) Ed. 1.0, General lighting – LEDs and LED modules – Terms and definitions** [40]
- **NEMA SSL 3-2011, High-Power White LED Binning for General Illumination** [41]. This standard applies to LEDs emitting incoherent, visible radiation in solid state lighting applications. It specifies bins and bin codes for LEDs for colour, lumens and forward voltage.

SSL guidelines and recommendations

- **CIE 127:2007 Measurements of LEDs** [42] The report describes in detail the measurement conditions for Averaged LED Intensity (ALI), Total and Partial LED Flux and Spectral Power Distribution.
- **IES G-2, Guideline for the Application of General Illumination ("White") Light-Emitting Diode (LED) Technologies** [43]. The Guideline provides lighting and design professionals a general understanding of LED technology as it pertains to interior and exterior illumination, as well as useful design and application guidance for effective use of LEDs.
- **IES LM-79-2008, Approved Method for the Electrical and Photometric Testing of Solid-State Lighting Devices** [44]. This approved method describes the procedures and precautions for performing reproducible measurements of total luminous flux, electrical power, luminous intensity distribution and chromaticity of solid-state lighting (SSL) products for illumination purposes under standard conditions.
- **IES LM-80-2008, Approved Method for Measuring Lumen Depreciation of LED Light Sources** [45]. The purpose of LM-80-08 is to allow a reliable comparison of test results among laboratories by establishing uniform test methods. It addresses the measurement of lumen maintenance testing for LED light sources including LED packages, arrays and modules only. It does not provide guidance or recommendations regarding prediction estimations or extrapolations for lumen maintenance beyond the limits of the lumen maintenances determined from actual measurements.
- **IES LM-82-2012, Approved Method for the Characterization of LED Light Engines and LED Lamps for Electrical and Photometric Properties as a Function of Temperature** [46]. The intent of this document is to establish consistent methods of testing and data presentation for ease of interpretation and comparison, which will assist luminaire manufacturers in selecting suitable LED light engines and integrated LED lamps for each luminaire product. This approved laboratory method defines the procedures to quantify the performance of LED light engines and integrated LED lamps as a function of temperature.
- **IES TM-21-2011, Projecting Long Term Lumen Maintenance of LED Light Sources** [47]. This document recommends a method for projecting the lumen maintenance of LED light sources from the data obtained by the procedures found in IES document LM-80-08 Approved Method for Measuring Lumen Maintenance of LED Light Sources.

Standards under development

Several SSL standards are currently under development including e.g.:

- **IEC/PAS 62707-1 ed1.0, LED - Binning - Part 1: General requirements and white grid** [48]. This PAS (Publicly Available Document) specifies general requirements, a grid and a corresponding code for the colour binning of white LEDs emitting incoherent, visible radiation.
- **IEC/PAS 62722-1 Ed 1. Luminaire performance – Part 1: General requirements** [49]**.**
- **IEC/PAS 62722-2-1**. **Ed 1, Luminaire performance - Part 2-1: Particular requirements for LED luminaires** [50]**.**
- **IES LM-XX3, Approved Method for Measuring Lumen Maintenance of LED Lamps, Light Engines, and Luminaires** [51].
- **IES TM-XX1, Method for Projecting Lumen Maintenance of LED Lamps, Light Engines, and Luminaires** [52].
- **IES TM-XX5, Method for Estimating the Rated Life of an LED Product** (incorporates lumen degradation and other failure modes) [53].

THE IEC/PAS stands for ‘Publicly Available Specification’. The objective of PAS is to speed up standardization in areas of rapidly evolving technology.

4.4 Zhaga specifications

The Zhaga consortium [27] was founded on February, 2010. Zhaga is a global industry wide co-operation aimed at the development of standard specifications for interfaces of LED light engines. Currently, there are 270 company members in Zhaga. Zhaga promotes interchangeability by defining interfaces for a variety of application-specific light engines. Zhaga standards cover the physical dimensions as well as photometric, electrical and thermal behaviour of LED light engines.

The Zhaga standards are published as Books. The development process is divided into five phases. In the first phase the members make proposals for a light engine types with the same mechanical fit. In the second phase the members study the proposals and try to merge them into single proposal. The third phase is the Book development phase where members draft and review the specification and build prototypes and verify interchangeability. The fourth phase is the maintenance phase by Zhaga work group (7 different work groups). The work group collects problem reports and creates revisions of the specifications. The fifth phase is the maintenance performed by Standard Development Organization (SDO) (IEA, ANSI, CEN/CENELEC, etc.). The goal of Zhaga is to transfer Zhaga specifications to a formal SDO after the Zhaga specification is stable and broadly used.

So far the Zhaga has published eight Books. The Book 4 describes the specifications for a flat emitting street light engine with separate control gear.

5 VERIFICATION SYSTEMS FOR SSL PRODUCTS

Solid-state lighting (SSL) products with varied characteristics are constantly entering the lighting markets, and products exhibit a wide range of performance. There is a need for reliable, unbiased product performance information to make sure the products fulfill and maintain the requirements set for them.

The current voluntary verification systems are mainly intended for LED products intended for residential use. The intention of these voluntary labels is to promote the acceptance of LED products and, thus, increase their sales. The products that have the voluntary label are measured in accredited laboratory and the performance values are what they claim to be.

5.1 CALiPER

The U.S. Department of Energy (DOE) Commercially Available LED Product Evaluation and Reporting (CALiPER) program [54] tests and provides information on the commercially available SSL lighting products for general illumination. CALiPER has been purchasing and testing SSL products using approved method LM-79-08 and accredited independent test laboratories since 2006. These products include LED luminaires for outdoor and indoor purposes and various LED lamp types. The test results are available for public for non-commercial and educational purposes.

The CALiPER tested outdoor LED luminaires in 2010. The test included five arm-mounted roadway luminaires, two post-top outdoor luminaires and one LED based replacement lamp for outdoor use. All of the arm-mounted outdoor luminaires meet or come close to meeting manufacturer ratings for expected light output and efficacy (within approximately 10% of manufacturer published efficacy). Half of the arm mounted LED luminaires did not meet the ANSI colour tolerances for CCT.

For the other post-top luminaire the manufacturer did not provide any performance data and for the other the claims for light output and efficacy which were approximately 25% overstated. The light output and the efficacy of the replacement LED lamp given by the manufacturer were overstated by 2½ times.

The CALiPER program has shown that there is a wide range of the actual measured photometric values and the claimed values of the SSL lighting products especially for outdoor luminaires.

5.2 LED Lighting Facts®

The Lighting Facts® [55] label is a voluntary program sponsored by DOE. The purpose of the label is to assure that LED lighting products are represented accurately on the market. The label is indented for LED lighting products, including self-contained replacement lamps and full luminaire products.

Luminaire manufactures commit to test products according to IES LM-79-2008 in an approved testing laboratory. The LED Lighting Facts® label provides metrics for luminous flux, luminous efficacy, power consumption, correlated colour temperature, and colour rendering index. Optional metrics are the warranty and the lumen maintenance which estimates the percentage amount of light the LED light source is projected to emit at 25 000 hours at a given ambient test temperature, compared to its initial light output. This percentage is based on LM-80, in-situ performance, and TM-21 projections. Additional metrics may be considered in the future editions of the label.

The LED Lighting Facts also keeps a complete list of the LED products that have received the LED Lighting Facts label. Currently there are over 5300 products listed, of which 642 are outdoor area/roadway luminaires.

Table 4. Parameters presented at the label of LED Lighting Facts® [55].

Parameter	Requirement
Coverage	LED lighting products including lamps and luminaires.
Lamp Wattage	Energy required lighting the product.
Initial luminous flux	The total integrated luminous flux of the product.
Correlated colour temperature (CCT)	The colour of the light. Cool 3600 K – 5000 K Warm 2700 K – 3500 K
Colour rendering index	The colour accuracy of the product.
Lumen maintenance	Listed as a percentage, this metric estimates the amount of light the LED light source is projected to emit at 25000 hours at a given ambient test temperature, compared to its initial light output.
Power factor	Not required
Efficacy	The total integrated luminous flux of the product per the total energy consumption.
Lamp life	Not required

5.3 ENERGY STAR

ENERGY STAR is an international voluntary labelling for energy-efficiency. It is a joint program of the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Energy (DOE) [56]. The purpose of ENERGY STAR label is to reduce inefficient use of energy and provide consumers information about energy-efficient products. The product categories include computers, servers, appliances, heating and cooling systems, home electronics, imaging equipment, lighting, and new homes. European Community participates in the ENERGY STAR scheme as far as it is related to office equipment.

The lighting category includes decorative light strings, light bulbs for consumers and luminaires for consumers and for commercial use. The product can earn the ENERGY STAR label by meeting the energy efficiency requirements set for the product specification. The principal specifications states that

- the product must contribute significant energy savings nationwide and
- must deliver the features and performance demanded by consumers, in addition to increased energy efficiency,
- the payback time through utility bill saving of the product must be reasonable if the product costs more than a conventional less energy-efficient equivalent product
- non-proprietary technology is used to achieve the energy efficiency
- product energy consumption can be verified and measured with testing
- product labelling is visible and differentiates the product efficiently from other products

The specifications [57], [58], [59], [60] set requirements for the lighting products that must be fulfilled in order to earn the ENERGY STAR label. All the lighting products that have ENERGY STAR have been tested for

- total Luminous Flux
- luminaire Efficacy
- Correlated Color Temperature
- Color Rendering Index
- Steady State Package/Module/Array Temperature
- Maximum Power Supply Case/TMPPS Temperature

in an accredited laboratory according to accepted testing methods in the US. Thus, products that have the ENERGY STAR label meet the claimed photometric quantities.

Table 5. Requirements for ENERGY STAR for LED luminaires for residential outdoor use. [60]

Parameter	Requirement
Coverage	Directional residential outdoor post-mounted luminaires Non-directional residential outdoor ceiling and close-to-ceiling mount, porch (wall-mounted), pendant, and security luminaires.
Lamp Wattage	≤ 250W
Initial luminous flux	Non-directional: minimum 800 lm Directional: Not defined
Correlated colour temperature (CCT)	2700 K, 3000 K, 3500 K, 4000 K The luminaire, LED light engine or GU24 based integrated LED lamp shall also fall within the corresponding 7-step chromaticity quadrangles.
Colour rendering index	CIE CRI ≥ 80
Lumen maintenance	≥ 70% lumen maintenance (L70) at 35000 hours of operation.
Power factor	≤ 5 W, power factor ≥ 0.5 > 5 W, power factor ≥ 0.7
Luminous efficacy	Non-directional: Until September 1, 2013: ≥ 65 lm/W per source After September 1, 2013: ≥ 70 lm/W per source Directional: ≥ 70 lm/W
Lamp life	≥ 35000 hours

5.4 Apples & Pears, a CELMA guiding paper

The CELMA (Federation of National Manufacturers Association for Luminaires and Electrotechnical Components for Luminaires in the European Union) has published the ***Apples & Pears, a CELMA guiding paper*** in September 2011 [12]. The guiding paper aims for enabling like-for-like comparison of LED luminaire performance based on initial specifications that are in compliance with IEC/PAS performance requirements. The IEC/PAS are Publicly Available Specifications by IEC, which are pre-standards. The guiding paper refers to IEC/PAS publications:

IEC/PAS 62717:2011(E) LED modules for general lighting – Performance requirements. This specifies the performance requirements for LED modules, together with the test methods and conditions, required to show compliance with this PAS and was publish in April 2011.

IEC/PAS 62722: 2011(E) Luminaire performance – Part 1: general requirements. This covers specific performance and environmental requirements for luminaires.

The above IEC/PAS documents suggest that the following quality criteria for LED luminaires should be considered when evaluating manufacturer's claims:

- Rated input power (W)
- Rated luminous flux (lm)
- LED luminaire luminous efficacy (lm/W)
- Luminous intensity distribution
- Correlated Colour Temperature (CCT)
- Rated Colour Rendering Index (CRI)
- Rated chromaticity co-ordinate values both initial and maintained
- Lumen maintenance code
- Rated life (in h) of the LED module and the associated rated lumen maintenance (Lx)
- Failure fraction (Fy), corresponding to the rated life of the LED module in the luminaire
- Ambient temperature (t_q) for a luminaire

The Lumen maintenance code is described as [12]:

The measured initial luminous flux (initial value) is normalised to 100% and used as the first data point for determining the LED module life. The maintained luminous flux (maintained value) is measured at 25 % of rated life time up to a maximum of 6.000 hours and expressed as percentage of the initial value. The maintained value determines the lumen maintenance code.

The Rated life is described as [12]:

The length of time (in hours) during which a population of LED modules provides more than the claimed percentage(x) of the initial luminous flux always published in combination with the failure fraction.

The CELMA Guiding paper states, that LED luminaire manufacturers should publish product specifications that are in compliance with the IEC/PAS performance requirements.

5.5 IEA Implementing Agreement 4E

The IEA Co-operating Programme on Efficient Electrical End-Use Equipment (4E) is a forum consisting of thirteen countries from the Asia-Pacific, Europe, North America and Africa to share information and transfer experience in order to support good policy development in the field of energy efficient appliances and equipment [62]. The 4E was launched in 2008 and is due to end in February 2014.

The goal of the 4E Solid State Lighting Annex is to develop simple tools to help government and consumers worldwide quickly and confidently identify which SSL lighting products have the necessary efficiencies and quality levels to effectively reduce the amount of energy that is currently consumed by artificial lighting. The main tasks of the Annex are: Develop SSL Quality Assurance, Harmonize SSL Performance Testing and Standards and Accreditation.

The 4E is currently preparing ***Performance Tiers for LED Street Light Luminaires***. In August 2012, a draft performance tiers for street lighting luminaires was published. Relevant stakeholders are asked to review the draft document and submit their comments to it by October 15, 2012. The draft documents includes specifications for e.g. luminaire luminous efficacy (lm/W), CCT and its tolerance (K, Du'v'), CRI, minimum rated lamp life, operating temperature and upward light output.

In October 2012, the 4E launched the 2013 ***Interlaboratory Comparison (IC) of SSL product testing***. The 4E encourages laboratories to participate in this IC, which is organised to investigate the test method and to verify the proficiency of laboratories worldwide for measuring SSL products. The 4E hopes that this work could help to promote establishing SSL testing accreditation worldwide and ultimately lead to a robust and reliable international network of laboratories proficient in SSL testing so that end-users can rely on information given in test reports.

6 LIGHT SOURCE SPECIFICATION DATA

6.1 Information available by manufactures

The provided technical information of lighting products varies between manufacturers. While basic information is typically given by all manufacturers, the amount of additional information varies and for some information the representation practices are different. The manufacturers mostly use the same datasheet templates for all their products and thus product comparison between the same manufacturers is possible.

The datasheets that the manufacturers provide for their products are also marketing sheets, thus some datasheets may create a vision of the product without giving any facts, while some datasheets provide pure facts.

The LED technology is under constant rapid development, and new product types are coming all the time on the market. It is challenging for the end-users and designers to keep up with the latest information of the products. In the LED business there are plenty of new comers to the lighting industry and some are promoting their products without having the expertise needed.

6.2 HPS and MH lamps

The technical information provided in manufacturers datasheets are for most part the same for the conventional light sources like HPS and MH lamps. The general information provided by the manufactures include:

- lamp dimensions
- bulb material, bulb finish and bulb type
- cap base
- burning position
- nominal wattage [W]
- luminous efficacy [lm/W] (excluding the ballasts)
- luminous flux [lm]
- colour temperature [K]
- CIE Colour Rendering Index
- lamp life [h]

The lamp life may be given as lamp survival factor (LSF) or as lamp lumen maintenance factor (LLMF). The datasheets may also provide information about the mercury content, chromaticity coordinates, re-ignition time, lamp voltage and current, spectral output, luminous intensity diagram, and other performance related diagrams.

In the outdoor lighting field it is customary to talk about the luminous efficacy of the lamps, for example HPS lamp has higher luminous efficacy than MH lamp. The discharge lamps do, however, need a ballast (magnetic/electronic) to function, and the ballast power consumption must be included in the luminaire luminous efficacy. In turning to LED lighting we must also talk about the LED luminaire luminous efficacy, not that of the individual LED chips or LED modules.

6.3 SSL products

LED dyes (chips)

The LED chip manufacturers mostly provide similar type of information of their products. The information is given as typical values which reflect statistical figures. These data do not necessarily correspond to the actual parameters of each single product. This is due to the unique manufacturing process of the LED chips. The manufacturing process of LEDs is unique and there may be huge variation in the colour properties and light output between individual LED chips. Each manufacturer has its own layout and not all information is given in all the datasheets in the same format.

Typical information given in LED chip datasheets include:

- mechanical dimensions
- LED technology and structure
- typical luminous flux [lm]
- typical colour temperature [K]
- CIE Colour Rendering Index
- forward voltage [V]
- forward current [mA]
- viewing angle [°]
- thermal resistance [°C/W]
- temperature coefficient [mV/°C]
- maximum junction temperature [°]

The datasheets also contain various graphs like spectral power distribution and typical radiation pattern. Also, data on forward current, forward voltage, luminous flux, junction temperature, case temperature, and chromaticity coordinate shift may be given in various graphical formats.

In manufacturing LEDs they are broadly grouped into colour categories such like red, red-orange, cool white, warm white, etc. These groupings may encompass quite a wide colour range which may be too wide for many applications. The binning of LEDs means that the manufacturer tests each LED individually for defining e.g. their exact colour, luminous output and forward voltage in order to assign them a specific 'bin' number. The luminaire manufacturers can then select the bin (or set of bins) that best meets the performance requirements of their luminaire.

The manufacturers have their own set of bins and provide information of these sets. Guidelines for binning have been given by the IEC [48] and ANSI [39].

LED luminaires

The technical information given in outdoor LED luminaire datasheets vary as there are no established practices for specifying LED luminaire performance.

The comparison of LED luminaires by different manufacturers is difficult and sometimes not even possible, as data provided by the manufacturers is not in a comparable format. The naming practices of outdoor luminaires are diverse: for example the title of the luminaire may end up with 60x1W, 60 W or just 60. The number can give approximate indication of the LED chip power, luminaire power or the number of the chips or it can be an unrelated manufacturer's own serial naming practice.

Typically, the LED luminaire datasheets provide information about:

- luminaire dimensions and other manufacturing information
- input power [W]
- luminous flux [lm]
- colour temperature [K]
- CIE Colour Rendering Index
- luminaire luminous efficacy [lm/W]
- lifetime [h]

The interpretation of the given technical information is not always straightforward. The given values may not concern the luminaire as whole; the given power value may be that of the LED module, not the power of the luminaire including its power supply. There are also differences in the provided luminaire power data and the measured luminaire power [54].

The CELMA Guiding paper [12] says, that when evaluating LED luminaire performance claims from different manufacturers, a standardised set of quality criteria should be compared and that these quality criteria should be measured in compliance with the appropriate standard. CELMA calls for LED luminaire manufacturers to publish product specifications that are in compliance with the IES/PAS (pre-standard) performance requirements. The CELMA Guiding papers lists the quality criteria that should be used in evaluating manufacturers' claims (Chapter 5.4).

Luminaire life claims

In promoting LED lighting one of the major claims is the long lifetime. Lifetimes as high as 100 000 hours may be given in the datasheets. When talking about LED luminaire lifetimes it should be kept in mind, that the LED luminaire lifetime is distinct from the lifetime of an individual LED chip.

For a LED package, a 'useful lifetime' has usually been understood as a point at which the lumen output has been decreased to 30% of its initial value, i.e. the lumen maintenance is 70% (L_{70}). There are claims that the L_{70} is 50 000 h or even up to 100 000 h. The LED luminaire must be considered as a system including the LEDs, electronics, heat sinks, materials, housing, wiring etc. The luminaire will last as long as its critical component with the shortest life. The luminaire life can be much shorter than the LED package L_{70} lifetime. Poor luminaire design may shorten the lifetime dramatically. The DOE publication *LED LUMINAIRE LIFETIME: Recommendations for Testing and Reporting* [63] provides a working definition for defining useful lifetime and taking all failure mechanisms into account. However, it is also acknowledged that measuring full luminaires is most expensive and the DOE SSL programme is currently looking for software approaches to simulate failure rates [6, 12].

Currently, many LED luminaire manufacturers use test results typically provided by the LM-80; these are the L_{90}, L_{70}, L_{50} lumen maintenance thresholds of LED luminaires. The LM-80 requires testing of LEDs for 6 000 hours and recommends testing for 10 000 hours. Leading LED manufacturers test their products at 6 000 and 10 000 hours according to LM-80, and apply extrapolation methodologies given in TM-21 to get the L_{90}, L_{70} and L_{50} values. [12]

According to the pre-standard IEC/PAS 62722 [50], the LED luminaire life should be published as a combination of life at a specific lumen maintenance (L_x) and failure fraction (F_y). The failure fraction describes the combined effect of gradual and abrupt failure of all luminaire components.

Colour Rendering Index and LEDs

Colour rendering is one important characteristic of the light source. It is an effect of the light source on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under reference illuminance. The current method for describing the ability of the light source to render object colour is the CIE Colour Rendering Index (CRI). However, the CRI has limitations and several problems with white LEDs. The CIE Technical Committee TC 1-69 'Colour Rendition by White Light Sources' is currently working on the issue.

The technical committee has not yet reached an unanimous agreement about the metric for colour rendering, although it was expected to be announced in 2010. Meanwhile the CRI remains the only internationally recognized metric for colour rendering for all light sources including solid state lighting.

7 DEVELOPMENT PROSPECTS OF OUTDOOR LIGHTING

7.1 Scenarios for LED lighting

The worldwide electricity consumption in 2009 was 18 456 TWh [64]. The total electricity consumption in the EU was 2 713 TWh in 2009 [1]. The European Network of Transmission System Operators for Electricity (ENTSOE) expects the electricity consumption in EU to grow annually by 1.5% throughout 2010-2020 [65]. Lighting is a large and rapidly growing source of energy demand, in 2005 the electricity consumption for lighting was 19% of the total global electricity consumption [2].

DOE gives a scenario for outdoor lighting energy consumption projections for the U.S., according to which the electricity consumption in outdoor lighting is expected to decrease with expected savings of 24% by 2020, and of 52% by 2030, Figure 6. By 2030, the LED outdoor luminaire market is expected to represent 87% of the total market, which correlates to 46% reduction from the baseline energy consumption. [7].

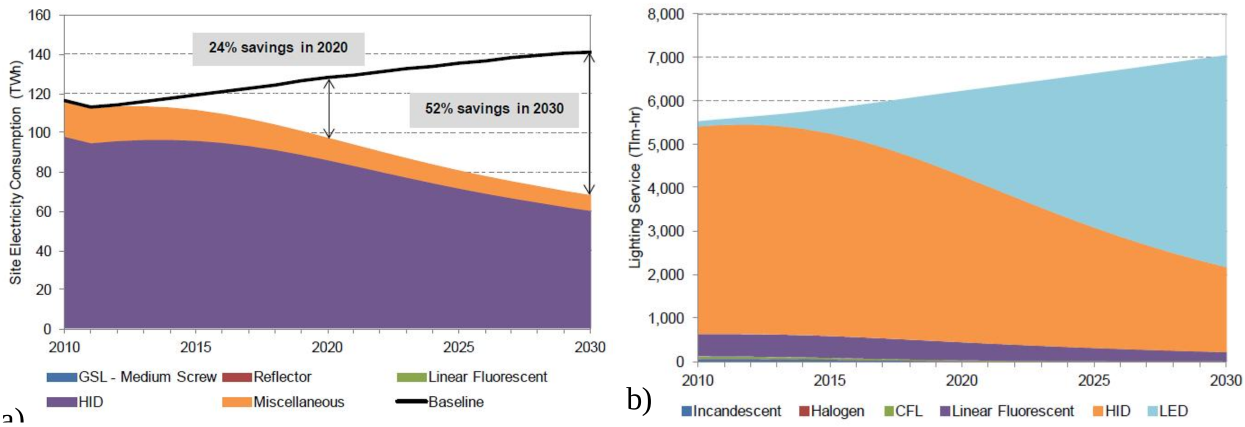


Figure 6. Outdoor lighting a) energy consumption forecast b) lighting service forecast in the U.S. 2010-2030.[7]

The European Commission published its Green Paper on SSL lighting in December 2011. According to it, the total market revenues of general lighting worldwide in 2010 were around 52 billion euro, of which close to 30% was spent in Europe. It is estimated, that by 2020, the world market will reach 88 billion euro with Europe's share decreasing to less than 25%. The current market penetration of SSL in Europe is low: the LED market share (in value) reached 6.2% in 2010. However, several studies predict that SSL will account for more than 70% of Europe's general lighting market by 2020 [66].

7.2 LED Roadmaps

The DOE ***SSL Research and Development: Manufacturing Roadmap*** was published in August 2012 [67]. The projections of LED package luminous efficacy (lm/W) for warm white (WW) and cool white (CW) LEDs and the corresponding prices for kilolumens between 2010 – 2020 are presented in Table 6.

Table 6. Scenarios for WW and CW LED luminous efficacy and price between 2010-2020 [67].

Metric	Unit	2010	2012	2015	2020
LED efficacy (warm white)	lm/W	96	141	202	253
LED price (warm white)	$/klm	18	7.5	2.2	1
LED efficacy (cool white)	lm/W	134	176	224	258
LED price (cool white)	$/klm	13	6	2	1

The luminous efficacy of a warm white LED is projected to increase from 141 lm/W in 2012, to 253 lm/W in 2030 and in the meantime the price per kilo lumen is expected to decrease by 87%. For the cool white LED the luminous efficacy is expected to increase from 176 lm/W to 258 lm/W, while the price will decrease by 83%. According to DOE scenarios, the performance and price differences between CW and WW LED packages are expected to disappear by 2020 [67].

The LED package is one component of an LED luminaire. In considering the luminaire luminous efficacy, the efficiency of the driver, the optical efficiency and thermal impact of the assembly must be considered. Table 7 presents the DOE projections for WW LED luminaire performance targets between 2011-2020 [6]. It is estimated, that a WW LED luminaire luminous efficacy in 2020 would be 170 lm/W, while the end goal is 202 lm/W.

Table 7. Scenarios for WW LED luminaire performance metrics between 2011-2020. (*color-mixed case)

Metric	2011	2013	2015	2020	Goal
Package luminous efficacy (lm/W)*	97	129	162	224	266
Thermal efficiency	86%	87%	88%	90%	90%
Efficiency of driver	85%	87%	89%	92%	92%
Efficiency of luminaire	86%	87%	89%	92%	92%
Resultant luminaire efficiency	63%	66%	69%	76%	76%
Luminaire luminous efficacy (lm/)	61	85	112	170	202

7.3 Mesopic photometry

The basis of all lighting technology and practice lies in photometry, the measurement of visible light. Photometry provides a method with which to assess light in terms of human visual spectral sensitivity. So far, the basis of all photometry has been the CIE photopic *V*(λ) established in 1924. A major breakthrough for the CIE and the lighting community was made in 2010, when the CIE recommended system for visual performance based mesopic photometry was published [5]. The CIE Recommended System for Visual Performance Based Mesopic Photometry is valid between 0.005 cd/m^2 and 5 cd/m^2 and it thus covers the luminance encountered in outdoor lighting.

LEDs offer new solutions also to various mesopic applications, not least because of the possibilities of producing light sources with different spectral properties. Depending on the LED spectra, their luminous efficacy may change substantially when mesopic luminous efficiency functions are used instead of the photopic. A CIE system for mesopic photometry gives manufacturers foundations on which to develop LEDs that are optimised for low light level applications. It is foreseen, that the new CIE system for mesopic photometry has major impact on the evolution and adoption of LEDs in outdoor lighting.

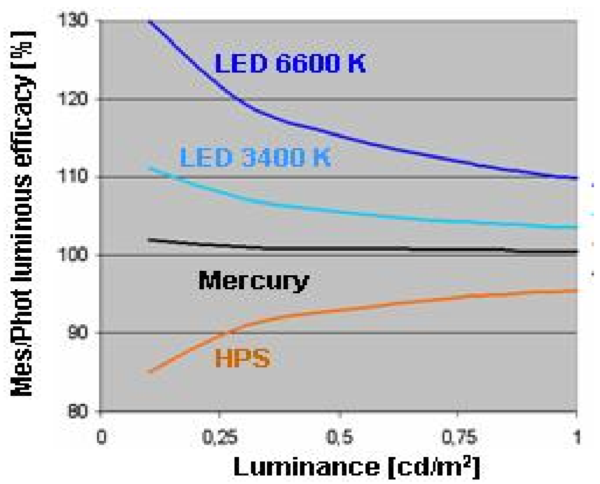


Figure 7. Ratio of mesopic and photopic luminous efficacy of a cool white LED, warm white LED, MV lamp and HPS lamp.

An ongoing CIE joint technical committee JTC -1 'Implementation of CIE 191 Mesopic Photometry in Outdoor Lighting' is working to provide guidelines for implementing mesopic photometry. The JTC-1 started its work in January 2012 and it is chaired by Prof Liisa Halonen (Aalto University, Finland).

8 WEIGHING OPTIONS FOR OUTDOOR LIGHTING

8.1 Conventional technology vs. LEDs

The HID technology is the conventional technology in outdoor lighting. Currently, high pressure sodium (HPS) and mercury vapour (MV) lamps dominate the outdoor lighting sector, while the share of metal halide (MH) lamps is lower. MH lamps have, however, been increasingly installed in outdoor applications, where good colour quality and white light is preferred. Mercury lamps will be phased out from the EU markets by 2015, which results in huge changes in the outdoor lighting sector in the ongoing and coming years.

The development potential of HID lamp luminous efficacy is low (MH lamps 15%, HPS lamps 5%) compared to LEDs. The rapid development of SSL technology is foreseen to pave way for LED technology in outdoor lighting. The high pace of LED development means that regulations and standards follow years after products are on the market. Both high and low quality LED products exist on the worldwide markets.

8.2 Barriers and challenges for LEDs

The EC conducted a public consultation on the Green Paper "Lighting the Future: accelerating the deployment of innovative lighting technologies" from 15 December 2011 to 29 February 2012. The objective was to explore the barriers for the wide deployment of SSL technology. There were 125 interested parties who submitted their views on the existing challenges for LED-based lighting solutions and how to overcome them. The three main concerns raised by respondents include [68]:

- risk of buying products of unproven or insufficient quality
- lack of information for consumers and professional end users
- high initial purchase costs

The European Lighting Industry (CELMA) acknowledges the listed concerns raised by the respondents and is willing to work together with the EC and the value chain to improve them. [69].

According to the EC Green Paper, the reasons that the cities are reluctant to replace old outdoor lighting technologies and use SSL widely in outdoor lighting are caused by [66]:

- relatively high investment costs together with tight annual city budgets (even if this is generally offset by significantly lower lifetime costs)
- lack of trust quality certification schemes
- lack of standards to develop proper specifications.

8.3 Comparison of products

CELMA points out that when comparing LED luminaire performance claims from the manufacturers, this should be done against standardised set of quality criteria. CELMA calls for luminaire manufacturers to publish product specifications that are measured in compliance with the IEC/PAS (pre-standard) performance requirements.

In comparing the luminous efficacy of HID and LED lighting, the comparison should be based on the total luminous efficacy of the luminaires, and not merely on light sources. For HID lamp, ballast is required and its power losses must be included in the luminaire power consumption. In LED luminaires the efficiency of the driver, the optical efficiency and thermal impact of the assembly must be considered in defining the overall luminaire luminous efficacy. The luminous efficacy of commercial LEDs is not yet near its fundamental limit, thus the luminous efficacy of LED luminaires is expected to increase in the coming years.

In Finland, the Finnish Transport Agency (FTA) publishes data on outdoor luminaires, which fulfil the FTA testing requirements. The performance and characteristics of the luminaires are tested and their ability to fulfil specific lighting class requirements is analysed. The testing includes also mechanical testing. The FTA list of approved luminaires includes several LED alternatives and the number of LED luminaires is increasing yearly.

8.4 Installation lifetime considerations

The costs of LED light sources have decreased substantially over the past years. The prices of LED luminaires for outdoor lighting are, however, still higher than those of the conventional HID luminaires. In outdoor lighting the efficiency of lighting and the light source lifetime are of particular interest, as the operating time of the installations is around 25-30 years. Long lifetime of the luminaires is also a high priority due to the long annual operating hours and potentially high maintenance costs associated with outdoor lighting. The cost efficiency evaluations should be made on the basis of lifecycle calculations.

The marketing claims of LED light sources give figures up to 100 000 hours for the LED lifetime. As with other light sources, the light output of LEDs decreases with time. For a LED package, a ‘useful lifetime’ has usually been understood as a point at which the lumen output has been decreased to 30% of its initial value, i.e. the lumen maintenance is 70% (L_{70}). Currently, luminaire lifetimes of around 50 000 hours are claimed by the manufacturers. It must be remembered, that the LED luminaire must be considered as a system including the LEDs, electronics, heat sinks, materials, housing, wiring etc. The luminaire will last as long as its critical component with the shortest life.

The future of LED lighting in the outdoor sector is promising. Due to the high maintenance and replacement costs in outdoor lighting, there are strong demands for long product lifetime. While LEDs are already strongly penetrating the outdoor lighting markets, they have even higher market potential as the LED luminaire lifetime continues to increase. It is expected that the annual costs of LED lighting will be half of those of HPS lighting in 2030 [7].

8.5 Energy saving opportunities

It is estimated, that LED lighting has tremendous potential for the outdoor lighting applications. Compared to other lighting sectors, LEDs are expected to penetrate the outdoor lighting sector the quickest. It is estimated, that by 2030 LED luminaires would represent 87% of outdoor lighting sales, which correlates to 46% reduction from the baseline energy consumption. [7].

In intelligent street lighting the luminance level of the street surface is controlled to match the actual lighting needs, for example during low traffic density the light levels can be reduced based on monitored amount of cars on the road. In a case study in Finland, it was calculated that the energy savings of an intelligent street lighting system based on HPS lamps are around 40%, when compared to a HPS street lighting system with no control [71]. In applying LEDs to intelligent lighting control, the expected energy savings are even higher than in using HID lamps and several studies are ongoing on intelligent LED street lighting control.

REFERENCES

[1] European Commission, ”Eurostat,” 2012. [Online]. Available: http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home. [Haettu 29 06 2012].

[2] IEA Annex 45, ”Guidebook on Energy Efficient Electric Lighting for Buildings, Summary Report”, Aalto University, Lighting Unit, 2010.

[3] European Comission, ”Comission regulation (EC) No 245/2009,” *Official Journal of the European Union,* . L 76, pp. 17-44, 2009.

[4] G. E. Hofler, C. Carter-Coman, M. R. Krames, N. F. Gardner, F. A. Kish, T. S. Tan, B. Loh, J. Poss, D. Collins ja G. Sasser, ”High-flux high-eff iciency transparent-substrate AlGaInP/GaP light-emitting diodes,” *Electronics Letters,* 34, nro 18, pp. 1781-1782, 1998.

[5] International Comission on Illumination, "Recommended System for Mesopic Photometry Based on Visual Performance," 191-2010.

[6] Bardsley Consulting, Navigant Consulting, Inc., Radcliffe Advisors, Inc., SB Consulting, Solid State Lighting Services, Inc., ”Solid-state Lighting Research and Development: Multi-Year Program Plan 2012,” U.S. Department of Energy, 2012.

[7] Navigant Consulting, Inc., ”Energy Savings Potential of Solid-State Lighting in General Illumination Applications,” Solid-State Lighting Program, Building Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, 2012.

[8] ICF Consulting, ”High Intensity Discharge Lighting Technology Workshop Report 2005,” Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Building Technologies, Conventional Lighting R&D, 2006.

[9] U.S. Department of Energy Office of Energy, Efficiency and Renewable Energy, Building Technologies Program, ”Framework Document for High-Intensity Discharge Lamps,” 2012.

[10] National Electrical Manufacturers Association, Lamo Section, ”The Strengths and Potentials of Metal Halide Lighting Systems,” 2010.

[11] ”CREE,” [Online]. Available: http://www.cree.com/news-and-events/cree-news/press-releases/2012/april/120412-254-lumen-per-watt. [Accessed 07 05 2012].

[12] CELMA (Federation of National Manufacturers Association for Luminaires and Electrotechnical Components for Luminaires in the European Union), ”CELMA guiding paper: Why standardisation of performance criteria for LED luminaires is important”, September 2011.

[13] International Energy Agency (IEA), Light’s Labour’s Lost - Policies for Energy-efficient Lighting, IEA Publications, 2006, p. 558.

[14] P. Van Tichelen, T. Geerken, B. Jansen, M. Vanden Bosch, V. Hoof, V, L. Vanhooydonck ja A. Vercalstern, ”Final Report Lot 9: Public street lighting,” 2007.

[15] Navigant Consulting, Inc., ”U.S. Lighting Market Characterization Volume I: National Lighting Inventory and energy Consumption Estimate,” U.S. Department of Energy, 2002.

[16] Navigant Consulting, Inc., ”2010 U.S. Lighting Market Characterization,” U.S. DOE, 2012.

[17] CELMA, ”The importance of lighting.The quality of light. Enhancing life.,” 2011.

[18] ”International Organization for Standardization,” [Online]. Available: http://www.iso.org/iso/home.htm. [Accessed 09 07 2012].

[19] ISO/IEC, ”ISO/IEC Directives, Part 2: Rules for the structure and drafting of International Standards,” 2011.

[20] ”InternationalCommission on Illumination,” [Online]. Available: http://www.cie.co.at /home.htm. [Accessed 12 10 2012].

[21] “International Electrotechnical Commission,” [Online]. Available: http://www.iec.ch/. [Accessed 03 04 2012].

[22] “American National Standards Institute,” [Online]. Available: http://www.ansi.org/. [Accessed 03 04 2012].

[23] ”National Electrical Manufacturers Association,” [Online]. Available: http://www.nema.org. [Accessed 03 04 2012].

[24] ”National Institute of Standards and Technology,” [Online]. Available: http://www.nist.gov. [Accessed 03 04 2012].

[25] ”Illuminating Engineering Society,” [Online]. Available: http://www.ies.org. [Accessed 02 04 2012].

[26] ”European Committee For Electrotechnical Standardization,” [Online]. Available: http://www.cenelec.eu. [Accessed 03 04 2012].

[27] ”Zhaga Consortium,” [Online]. Available: http://www.zhagastandard.org/. [Accessed 09 07 2012].

[28] International Electrotechnical Commission, ”LED modules for general lighting - Safety specifications,” 2008.

[29] International Electrotechnical Commission, ”LED modules for general lighting – Performance requirements,” 2011.

[30] International Electrotechnical Commission, ”Lamp controlgear – Part 1: General and safety requirements,” 2007.

[31] International Electrotechnical Commission, ”Lamp controlgear – Part 2-13: Particular requirements for d.c. or a.c. supplied electronic controlgear for LED modules,” 2006.

[32] International Electrotechnical Commission, ”DC or AC supplied electronic control gear for LED modules – Performance requirements,” 2008.

[33] International Electrotechnical Commission, ”Digital addressable lighting interface – Part 207: Particular requirements for control gear – LED modules (device type 6),” 2009.

[34] National Electrical Manufacturers Association (NEMA), ”Electronic Drivers for LED Devices, Arrays, or Systems,” 2010.

[35] International Electrotechnical Commission, ”Luminaires – Part 1: General requirements and tests,” 2008.

[36] International Electrotechnical Commission, ”Electromagnetic compatibility (EMC) – Part 3-2: Limits – Limits for harmonic current emissions (equipment input current ≤16 A per phase),” 2009.

[37] International Electrotechnical Commission, ”Electromagnetic compatibility (EMC) - Part 3-3: 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,” 2008.

[38] International Electrotechnical Commission, ”Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment,” 2009.

[39] American National Standards Institute (ANSI), ”Specifications for the Chromaticity of Solid State Lighting Products,” 2008.

[40] International Electrotechnical Commission, ”General lighting – LEDs and LED modules – Terms and definitions,” 2011.

[41] National Electrical Manufacturers Association (NEMA), ”High-Power White LED Binning for General Illumination,” 2011.

[42] International Commission on Illumination (CIE), ”Measurement of LEDs,” 2007.

[43] Illuminating Engineering Society (IES), ”Guideline for the Application of General Illumination (“White”) Light-Emitting Diode (LED) Technologies,” 2010.

[44] Illuminating Engineering Society (IES), ”Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products,” 2008.

[45] Illuminating Engineering Society (IES), ”Approved Method: Measuring Lumen Maintenance of LED Light Sources,” 2008.

[46] Illuminating Engineering Society (IES), ”Approved Method for the Characterization of LED Light Engines and LED Lamps for Electrical and Photometric Properties as a Function of Temperature,” 2012.

[47] Illuminating Engineering Society (IES), ”Projecting Long Term Lumen Maintenance of LED Light Sources,” 2011.

[48] IEC/PAS 62707-1 ed1.0, LED - Binning - Part 1: General requirements and white grid

[49] IEC/PAS 62722-1 Ed 1. Luminaire performance – Part 1: General requirements.

[50] IEC/PAS 62722-2-1. Ed 1, Luminaire performance - Part 2-1: Particular requirements for LED luminaires.

[51] IES LM-XX3, Approved Method for Measuring Lumen Maintenance of LED Lamps, Light Engines, and Luminaires

[52] IES TM-XX1, Method for Projecting Lumen Maintenance of LED Lamps, Light Engines, and Luminaires

[53] IES TM-XX5, Method for Estimating the Rated Life of an LED Product

[54] U.S. Department of Energy, ”Solid state lighting CALiPER Program,” [Online]. Available: http://www1.eere.energy.gov/buildings/ssl/caliper.html. [Accessed 21 05 2012].

[55] ”LED Lighting Facts,” [Online]. Available: http://www.lightingfacts.com. [Accessed 26 06 2012].

[56] ”Energy Saving Trust,” 2012. [Online]. Available: http://www.energysavingtrust.org.uk/. [Accessed 29 06 2012].

[57] ”ENERGY STAR® Program Requirements for Compact Fluorescent Lamps (CFLs)”.

[58] ”ENERGY STAR® Program Requirements for Decorative Light Strings”.

[59] ”ENERGY STAR® Program Requirements for Integral LED Lamps”.

[60] ”ENERGY STAR® Program Requirements for Luminaires”.

[62] ”4E – Efficient Electrical End-Use Equipment, ” 2012. [Online]. Available: http://www.iea-4e.org/. [Accessed 13 10 2012].

[63] ”LED Luminaire Lifetime: Recommendations for Testing and Reporting”. Available: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide_june2011.pdf [Accessed 17 10 2012].

[64] International Energy Agency (IEA), ”Key World Energy STATISTICS,” 2011

[65] European Network of Transmission System Operators for Electricity, ”Ten-year network development plan 2010 - 2020,” 2010.

[66] European Commission ”Green Paper. Lighting the future. Accelerating the deployment of innovative lighting technologies.”, December 2011.

[67] ”Solid-state lighting research and development: Manufacturing roadmap July 2011,” U.S. Department of Energy, 2011.

[68] ”LED-Lighting: Concerns about quality and price”, Available: https://ec.europa.eu/digital-agenda/en/news/led-lighting-concerns-about-quality-and-price. [Accessed 17 10 2012].

[69] CELMA, ”The European Lighting Industry welcomes the European Commission Report on the results of the public consultation on the EU Green Paper Lighting the Future on Solid-State Lighting (SSL) ”, July 2012.

[70] Guo, L. “Intelligent road lighting control systems – Experiences, measurements and lighting control strategies”, Doctoral Thesis, Helsinki University of Technology, 2008.