24.05.2019

TECHNOLOGY – STATE OF THE ART

• Tallinn • Porvoo • Jūrmala • St. Petersburg • Hamburg •

Tallinn University of Technology

www.ttu.ee

Contact persons:
Argo Rosin / Roya Ahmadiahangar
Tel. +372 (0) 620 3708 / 620 3703
argo.rosin@taltech.ee / roya.ahmadi@taltech.ee

Interreg Baltic Sea Region
EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

CONTENTS

Abstract

This report presents the current state-of-the-art concerning modern, multi-functional LED lighting systems with a special focus on energy saving. The report starts with an introductory chapter; it is then divided into six main chapters:

- LEDification and savings potential in terms of energy and CO_2-emission reduction
- Lighting controls
- Lighting management systems
- Supporting technologies
- Reliability issues of urban lighting systems and their components
- Practical Examples

1 Introduction

From its earliest stages on earth, life has been based on light. For over 100 years, electric light has made it possible to learn, work and live at almost any place and time on earth. Over the recent decades, a lot of effort has gone into reducing the energy consumed to make this possible.

In the coming decade, the development of new lighting systems will enable mimicking the properties of natural lighting to increase the quality of life in many daily situations. This will be the case in education, leisure time, healthcare, elderly homes and business.

New systems' capabilities will adapt lighting conditions to suit the user, thus creating high value to society (as illustrated in Figure 1). Efficiency will go up, illness rates down, recovery will be faster, learning will be easier, but, more importantly, wellbeing and perceived quality of life will improve [1]. Case in point, with approximately 90 million streetlights installed worldwide, street lighting has become a ubiquitous utility that can be found in most urban areas. Effective street lighting can reduce both crime and traffic collisions, and encourage socio-economic activities at night and with no doubt, the installation of street lighting improves the perception of personal safety and security [2].

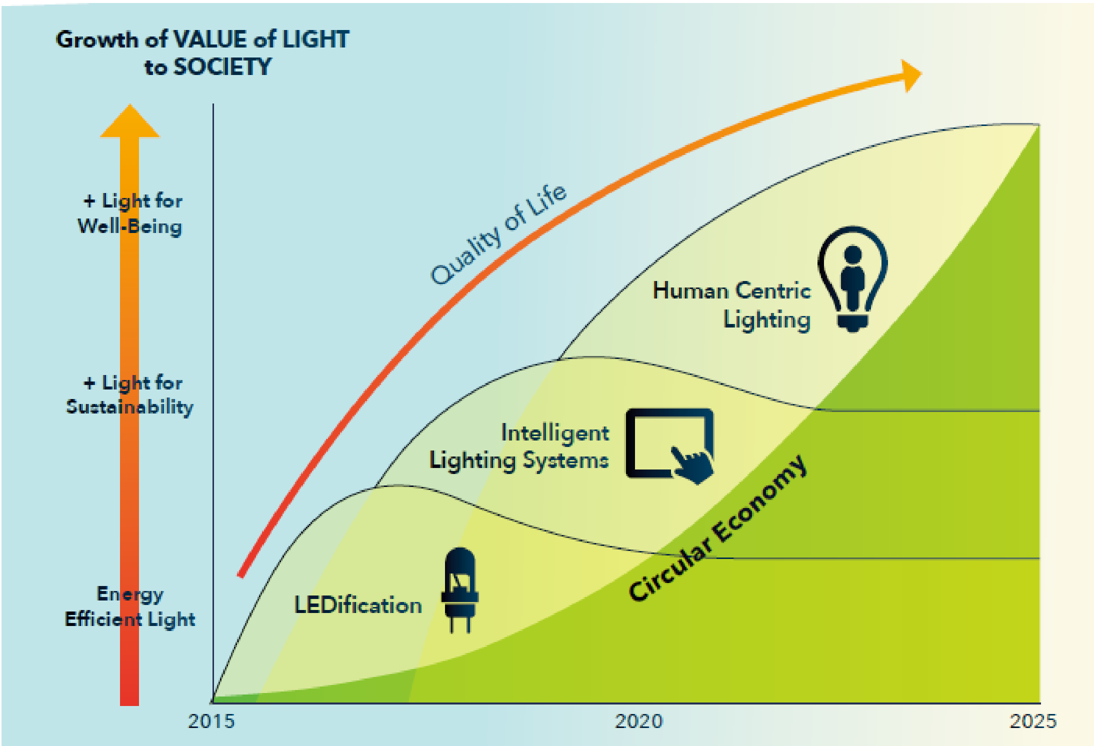


Figure 1: Growth of VALUE of LIGHT to SOCIETY [1]

2 LEDification and savings potential in terms of energy and CO_2-emission reduction

A great part of the energy consumption in Europe originates from urban areas that produce notable emissions of greenhouse gasses (GHG). Worldwide, over 90 million lighting poles count for more than 50% of the public energy consumption and about 60% of relative costs. Street lighting plays an essential role both for security and for life quality in urban areas. Innovations in lighting such as Solid-State LED (SSL) promise an energy saving of about one half and a notable reduction of maintenance costs [3].

LED lighting represents the next generation in the evolution of energy-efficient lighting solutions. LED lighting is also referred to as the fourth generation of lighting and has already been applied in illumination systems [4].

LEDs offer unique characteristics that make them a compelling source of light. They are compact, have long life, resist breakage and vibration, offer their best performance in cold operating environments, are instant-on, and some models are dimmable. Depending on the drive circuit and LED array in a particular light source, LEDs can also be adjusted to provide different coloured light or colour temperatures of white.

2.1 LED lightning

Unlike incandescent and fluorescent lamps, LEDs are not inherently white light sources. Instead, LEDs emit nearly monochromatic light, making them highly efficient for coloured light applications such as traffic signal and exit signs. To be used as a general light source, white light is needed, which can be achieved by combining different LEDs or using phosphors. Figure 2 shows the different ways white light can be achieved with LEDs [5].

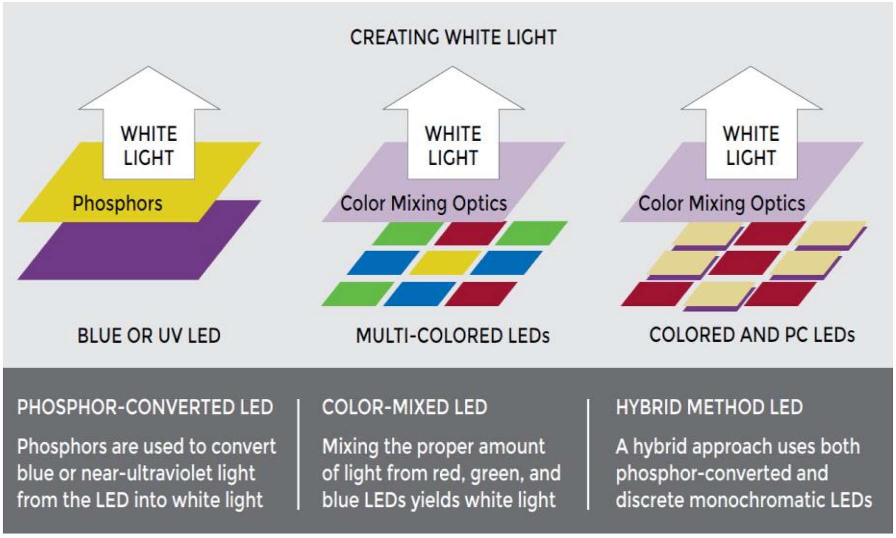


Figure 2: Producing white light with LEDs [5]

LEDs are highly energy efficient when measuring light output per watts of electricity input. In today's market, the most efficacious LED lamps operate at around 130 lumens per watt. Table 1 provides more details about typical key parameters of LED lamp and LED luminaire. This is more than double the energy performance of a compact fluorescent lamp (CFL) and over 10 times more efficient than an incandescent lamp.

CHARACTERISTIC	LED LAMP TYPICAL QUANTITY	LED LUMINAIRE TYPICAL QUANTITY
Luminous Efficacy Range(initial)	60-130 lm/W	80-150 lm/W
Lamp Lifetime	15000-30000 hr	20000-60000 hr
Colour Rendering Index (RI)	70-95	80-95
Correlated colour temperature	2700-6500K	2700-6500K
Dimmable?	If dimmable driver	If dimmable driver

Table 1: Light emitting diode (LED) lighting typical performance specification [5]

Figure 3 shows the projected market average efficacies of various types of commercial LED lamps and luminaires, as used by the US Department of Energy in their recent report calculating the energy savings potential of solid-state lighting. The trend for increasing efficacy also means users tend to get more and better-quality light at a lower running cost. That is, the higher energy efficiency of the LED sources translates into lower energy bills and greater reductions in CO_2 emissions.

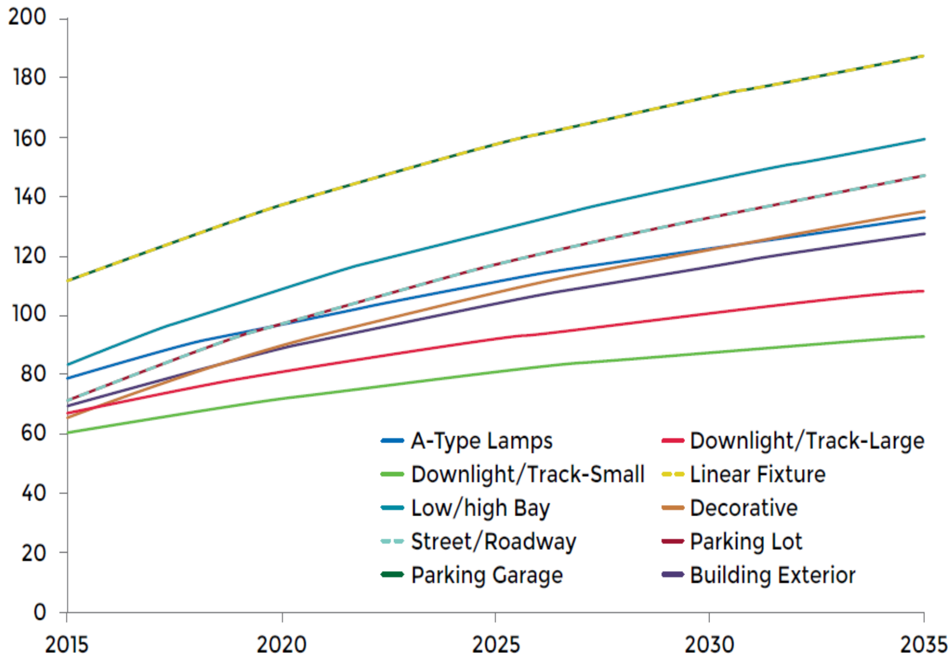


Figure 3: Market average LED lamp and luminaire efficacy projections [5]

2.2 Reducing CO_2 Emissions

There are several reasons why LED lights are better for the environment. One of the biggest ways is that they help reduce CO_2 emissions. These gasses are harmful to the planet and can lead to a depleted ozone layer, climate control issues, and other negative impacts on the planet. Compared to halogen and fluorescent lighting solutions, LED lights use less power per watt output. The fact that these lights offer not just the same, but actually better lumen outputs with every use, means that less energy is consumed which reduces the emissions of CO_2 gasses. When considering that they use less power continuously throughout the year, their operation is truly eco-friendly. In adition to the fact that LED lighting solutions use up to 90% less energy than other options, they also last longer than incandescent or fluorescent solutions. Since they last up to 20 times longer than other lighting options, they need to be replaced less often. However, even a green technology option, such as LED lighting solutions, uses power in factories to be produced. While many safe and green practices are put into place by certain companies to regulate this aspect, having to create new bulbs regularly in the form of less eco-friendly options such as fluorescents can create CO_2 emissions through the process of production. Thus, even though there is some CO_2 emissions creation in process of manufacturing LED lighting solutions, it is less than the other technologies [6]. Municipalities around the world are switching to LED lights as a way to save both money and energy. LED lights have approximately 50 per cent lower energy consumption compared to their HPS (sodium-vapor) luminaire predecessors. HPS lights, most installed in the mid-1980s, are at the end of their useful lives and need replacement. LEDs provide better service reliability and lower maintenance costs. The new LEDs have a longer lifespan - about four times that of the bulbs currently in use. This translates into ongoing savings in maintenance costs as result of the extended maintenance cycle for bulb replacement. Less maintenance also means fewer service vehicle trips for repairs and as a result, reduced carbon emissions [7]. The benefits of the transition to energy-efficient lighting mentioned in [5] are presented in Figure 4.

2.3 Advantages and Disadvantages

There are compelling reasons to replace conventional lighting with LED technology. LEDs can, for example, produce high quality light with unprecedented energy efficiency. They can reduce the energy consumption of a typical conventional lighting installation by 50%, or even up to 70-90% when coupled with smart controls. LEDs also offer lifetimes of 15+ years, so replacements are required far less frequently and maintenance is reduced. In addition, LED lighting systems are becoming easier to configure. Together with the fact that electricity for lighting is also a contributor to greenhouse gas emissions, it is no wonder that LED technology is forecast to account for 80% of the lighting market by 2020. However, LEDification raises challenges too. Rapid innovation is expanding product offerings and shortening product lifecycles. This not only increases consumption of the world's natural resources but also affects the availability of spare parts for example, since manufacturers tend to phase out earlier product ranges. For the users, this creates an issue: LED lighting comes with the promise of long life and lower costs, and service and spare parts are presumed to be available throughout the lifetime of the product. If they are not, the total cost of ownership starts to go up – the opposite of what LED technology promises.

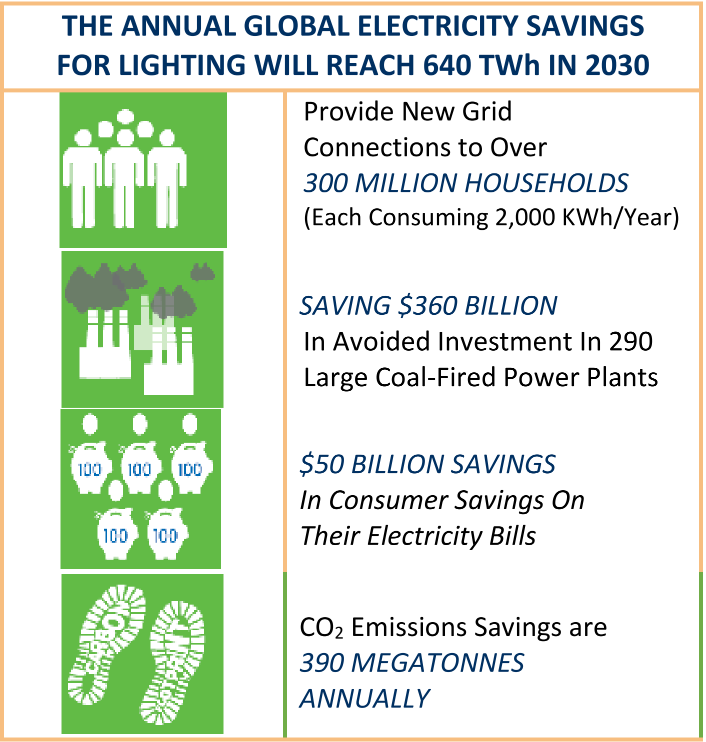


Figure 4: benefits of transition to energy-efficient lighting mentioned in [5]

Figure 5 shows average global retail price of an LED and a CFL replacement lamp for a 60 W lamp. Over time, LED costs fell rapidly, then slowed in 2017, reaching near parity with CFLs in 2020. Actual LED pricing in a given country may vary from these levels. They depend on, for example, volume of imports and consumer demand.

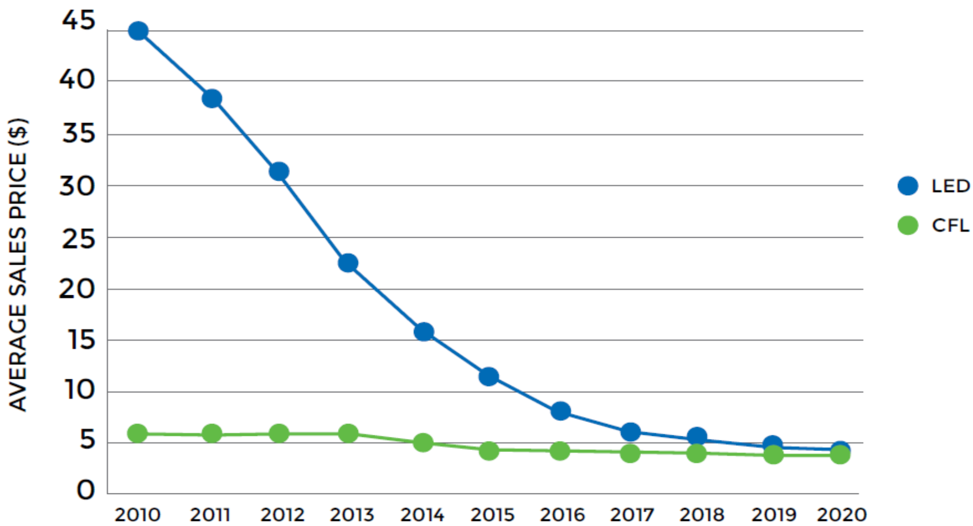


Figure 5: LED vs CFL Retail Price for a 60 W replacement lamp [5]

LEDification offers significant advantages. However, as with many technologies, constant innovation is bringing new products to the market all the time and shortening lifecycles. This downgrades the benefits of a long lifespan that the technology is supposed to offer. To realize the full benefits of LEDification and create a sustainable ecosystem, lighting manufacturers need a clear strategy, particularly for the serviceability, modularity and recyclability of LED lighting. Finally, Table 2 and Figure 6: LED lighting benefits mentioned in summarizes the advantages and disadvantages of LED lighting.

ADVANTAGES OF LED LIGHTING	DISADVANTAGES OF LED LIGHTING
• Highest efficacy light • Lowest running costs • long operating life–typically more than 20,000 hours • High flux in a small package, good for optical control • offering excellent colour rendering • Instant on, instant re-strike, dimmable • Contains no mercury	• Control gear (driver) required for operation • Higher relative first costs (but • competition is driving prices down) • Needs good thermal design because • waste heat is conducted, not projected

Table 2 : advantages and disadvantages of LED lighting

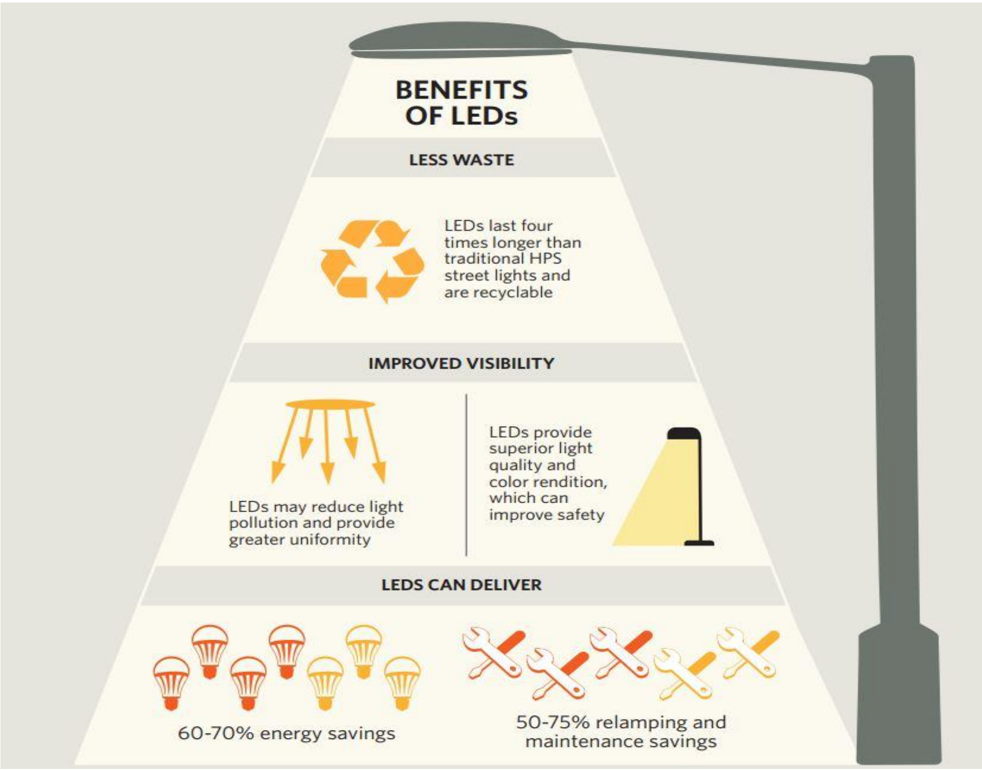


Figure 6: LED lighting benefits mentioned in [8]

3 Lighting controls: analysis and comparison of conventional controls, time-based dimming, zone based and adaptive control according to traffic density

3.1 Street lighting control systems

Active control of street lighting systems allows for significant energy savings, but potential savings must be weighed against added complexity and cost. Based on the type of management, there are three types of lighting control systems: autonomous control, centralized control, and dynamic control [9].

3.1.1 Autonomous control

With autonomous street lighting control, the luminaires are pre-programmed (usually by the manufacturer) with fixed time periods for operation. This is by far the simplest and cheapest solution, since it does not require further control and network systems. However, since the programming is usually limited there is often no way to adjust control for weekends and holidays. Furthermore, internal timers may not be accurate, and any upgrade of the system requires changes in every lamp post. Alternatively, sensors might detect the ambient light at every light post and decide on whether to activate the lamps. However, this causes additional expenses [9].

3.1.2 Centralized control

In centralized street lighting control, a central system sends the control signal to all luminaires within a group (usually by a signal sent via the power line). This setup is comparably simple and cheap to implement but does allow for some flexibility in adjusting the lighting to changing needs.

Furthermore, the information flow is in one direction only. While the central node can determine the status of the groups of lamps, it does not receive information about their individual status or any other local conditions.

Both centralized and dynamic control systems require the implementation of ICT (Information and Communications Technology) systems of varying degrees of complexity. While they provide additional options for saving energy, they also require additional resources and expertise for implementation and maintenance. Added complexity increases the risks of system failures. Thus, procurers and planners should consider whether expertise and support are available after implementation, even on a relatively short notice [9].

3.1.3 Dynamic control

With dynamic street lighting management, the greatest extent of control is possible. Not only can the lamps be controlled either in groups or on an individual basis, but the central control server can also collect information on their status depending on the options installed (e.g. failures, energy consumption, operating or ambient temperature, ambient light, traffic, and the presence of pedestrians). Changes to the programming can also be done on the central control server instead of requiring changes to the physical hardware.

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

State of the art intelligent management systems are generally controlled by a central command center, which is often a server maintained in the offices of the local authorities. This server monitors a high number of lamps and sends commands which determine the status of the individual lamps. The commands are not received by the lamp control systems directly but first pass through concentrators, which then pass on the messages to local area networks consisting of a limited number of lamps and the controlling actuators, as shown in Figure 7 [9].

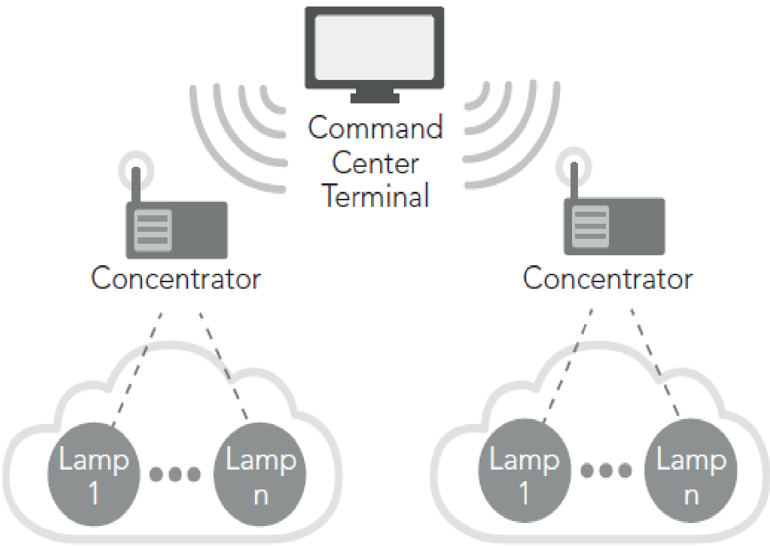
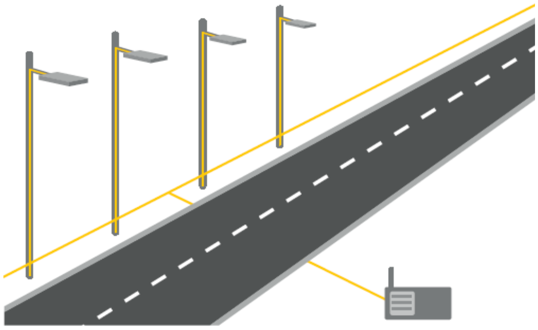


Figure 7: Street lighting control system architecture [9]

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

There are two layers of communication in a street lighting system that need to be bridged with communication technology: command center to concentrators, and concentrators to individual lamps. They can either transmit information via cable or as wireless signals, as shown in Figure 8, and both options have implications for the communication protocols that are available.

Wireless communication between the command center and the concentrators require that the comparably large distances can be bridged via wireless signals. Suitable protocols include Wi-Fi, GPRS (General Packet Radio Services), 6LowPAN and WiMax.



a

b

Figure 8: a: Power-line communication, b: Wireless communication [9]

Wireless signals between the concentrators and the individual lamps can be implemented as a mesh, which has the advantage that a lack of line-of-sight does not break the connection between individual nodes. If necessary, the signal strength can be boosted via repeaters. Suitable protocols for this layer include:

- DALI (Digital Addressable Lighting Interface): An IEC-adopted standard that has been developed for controlling ballast circuits used for lighting equipment monitoring. However, it can only control up to 64 nodes.
- ZigBee, a low-cost, low-power, and low-data rate alternative for wireless networks. However, it has shortcomings in terms of package delays and may cause slowdowns in network performance.
- 6LoWPAN (IPv6 over Low power Wireless Personal Area Networks). This standard does not define a specific routing protocol for a particular system. This allows for more flexibility but requires additional effort defining the protocols used for a particular installation [9].

3.2 Street lighting control strategies

Various strategies at different levels of complexity for street lighting control have been developed over the years, each with its own advantages and disadvantages. Some may even be combined for more complex strategies [9].

3.2.1 Astronomical timer

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

Astronomical timers might establish a simple on-/off scheme for illumination that specifies the time of activation of the lighting in the evening and the deactivation in the morning. Alternatively, they might specify periods later at night when less traffic is expected during which the lighting remains active but at reduced operating intensity.

One of the main advantages of astronomical timers is that they do not require any complex ICT systems to operate [9].

3.2.2 Daylight harvesting

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

The second option allows for more flexibility, but also requires the purchase of a large number of additional sensors and requires more maintenance for keeping the sensors clean.

The photo sensors can be embedded into a larger ICT infrastructure, which (depending on setup) can enable real time monitoring of the road illuminance. Thereby any problems with insufficient lighting can be quickly identified and addressed [9].

3.2.3 Traffic detection

On many roads, traffic may be consistently low, especially late at night. Thus, reducing their level of illumination in compliance with the requirements stipulated in EN 13201 offers potentially large energy savings. In order to ensure that traffic participants can still navigate these roads safely, traffic detection systems can be installed, which increases the level of illumination again when needed. The most common technology for detecting traffic – whether motorized vehicles, cyclists, or pedestrians – are motion sensors. Common types of motion detectors include the following [9]:

- Ultrasonic motion detectors – detect the shift in sound waves bouncing back from a moving object. This type of sensor does not require line of sight. It is cheap, can detect objects irrespective of their materials, and is little affected by air flows of up to 10 m/s (36 km/h). However, they have a low detection range and can be affected by humidity and high temperatures [9].
- Microwave motion detectors – detect shifts in microwaves bouncing back from a moving object, similar to radar speed guns. They are able to detect even small motions and are not affected by the ambient temperature of the target objects. However, they are costly and may cause false detection due to movements outside the specified zone [9].
- Infrared sensors – detect the heat of an object or a person relative to their surroundings. They are purely passive sensors – thus, they do not emit sound or radiation in order to collect information. However, they might trigger false detection from warm air, rainfall, or hot objects [9].

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

Motion detection systems can also be combined so that the disadvantages of one type are compensated by the capabilities of another. Any motion detector-based systems that are intended to cover more than pedestrian-only areas almost invariably require integration into a larger ICT setup. However, this has the added advantage of allowing traffic information data which can be useful to traffic controllers, urban planners, emergency services and other agencies [9].

3.2.4 Dimming

Depending on traffic, weather, and ambient lighting conditions, it may not be necessary to operate lamps at full power throughout the night. By combining proper astronomical timers, daylight harvesting, and traffic detection schemes with dimming, huge energy savings can be attained – in some projects, up to 85 % savings were achieved. Furthermore, gradually increasing and decreasing the illumination reduces discomfort glare for nearby residents. LEDs are especially suitable for dimming-based strategies as they can be dimmed smoothly with almost no technical complications, whereas other lamp types used in street lighting cannot be dimmed, produce drastic colour shifts when dimmed (high-pressure mercury and metal halide lamps) or are limited in how far they can be dimmed [9]. The study in [10] proposes an adaptive lighting scheme based on traffic sensing, which adaptively adjusts streetlight brightness based on current traffic conditions. The comparison of different dimming scenarios in Figure 9 is based on following lighting schemes:

- In conventional lighting system, the power is 100% during entire night;
- In part-night time control, the lighting system is switched off from 00.00 to 05.30 o'clock;
- In time-based dimming, the luminous flux of light sources is reduced e.g. by Philips Chronosense and Dynadimmer;
- In a multi-sensor solution, the luminous flux is always on a 40% level as compared to a conventional solution. If the distance between objects is less than 20 meters, then the luminous flux level increases to 70%. If the distance between objects is less than 10 meters, then the luminous flux level increase to 100%.
- In zone-based systems, the radius of a zone is considered to be 100 meters.

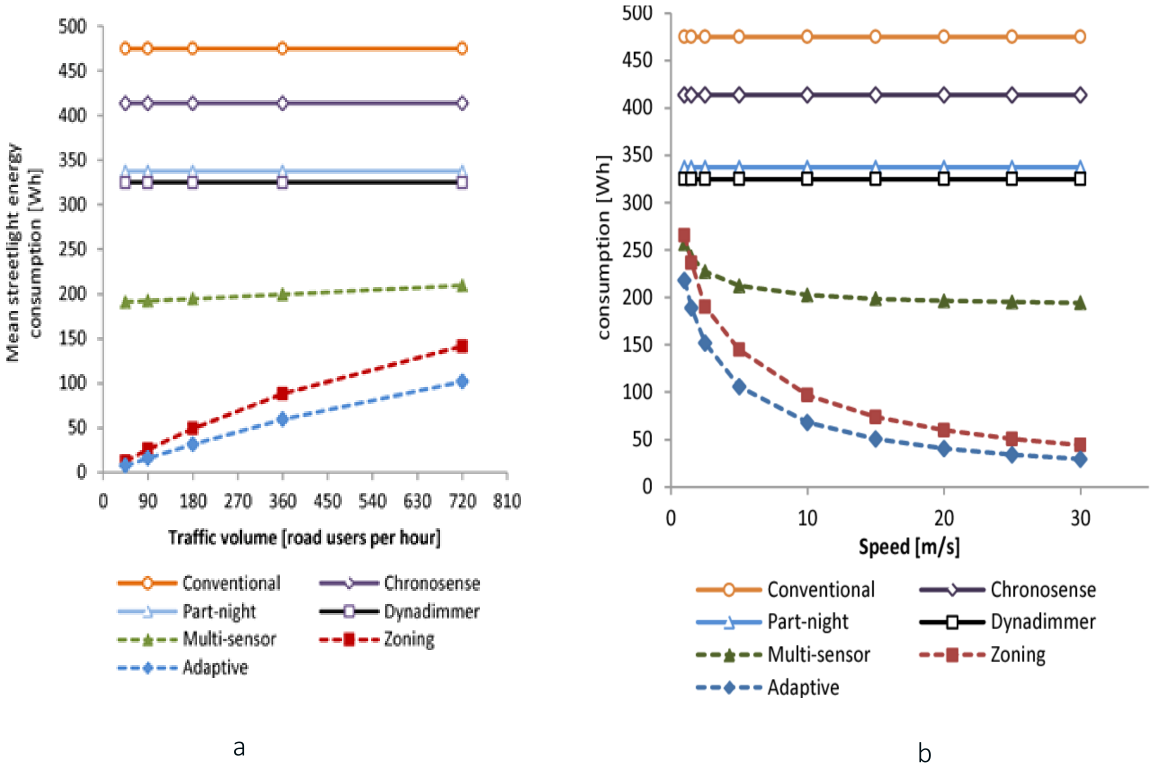


Figure 9: a: Effect of traffic volume on the energy consumption of various lighting schemes
b: Effect of travelling speed on the energy consumption of various lighting schemes [10]

Figure 9.a show the effect of traffic volume on the energy consumption of various lighting schemes. Based on simulation results, the adaptive lighting scheme saves nearly 38% energy compared to zoning lighting scheme proposed by Müllner and Riener [16] under relatively low traffic volume (45 road users per hour). Under relatively high traffic volume, the performance of adaptive lighting scheme slightly decreases to 28%. Despite the slight performance drop under high traffic volume, the adaptive lighting scheme still outperforms by demonstrating 32% less energy consumption, on average, compared to the zoning lighting scheme. Compared to others, 51% minimum energy saving can be achieved during high traffic volume and 96% during low traffic volume. In all simulation scenarios, only the adaptive and zoning lighting scheme exhibits observable changes in energy consumption with increasing traffic volume.

Both of these lighting schemes show an increase in energy consumption as more streetlights are turned on when the traffic volume is increased. This is because increased traffic volume results in a near-continuous stream of traffic within the detection zone of each streetlight; hence, the time each streetlight spends active is also prolonged. Furthermore, the streetlights are mostly at full-brightness, thus further increasing the energy consumption of these lighting schemes. This trend starts to saturate when traffic volume is increased to 720 road users per hour. Further saturation is expected with the increment of traffic volume from 720 road users per hour. The energy consumption of the adaptive lighting scheme remains lower, particularly during night and early morning when the traffic volume is low. Owing to the limited operation distance, the multi-sensor lighting scheme shows rather consistent energy consumption across different traffic volumes.

Figure 9.b shows the effect of travelling speed on the energy consumption of various lighting schemes. Based on the simulation results, slower travelling speeds exhibit higher energy consumption for adaptive, zoning and multi-sensor lighting scheme. A rapid reduction in energy consumption is observed when travelling speed is increased from 1 m/s to 5 m/s, but slowly saturated with higher travelling speed (from 10 m/s to 30 m/s). This trend is caused by a shorter average travel time per route when road users travel with higher speeds. Thus, the average streetlight operation time is reduced and the total energy consumed is also decreased. On average, the adaptive lighting scheme uses 24% less energy compared to the zoning lighting scheme. Compared to multi-sensor scheme, a maximum saving of 89% is achieved with travelling speed of 30 m/s. Based on the simulation results, the performance of the adaptive and zoning lighting scheme is highly influenced by increasing travelling speed compared to multi-sensor lighting scheme. Both lighting schemes show similar trends in energy reduction with increasing travelling speed. The performance of these schemes is almost identical (i.e. a difference of 15 Wh) when evaluated with travelling speeds of 30 m/s. Although it was designed to operate on traffic sensing approach, the multi sensor lighting scheme shows rather consistent energy consumption when travelling speed increased.

4 Lighting management systems, with the potential of connected “intelligent” lighting as an additional energy efficiency tool and a smart city tool

4.1 General Information

Rome was not built in a day, and neither are smart cities. By 2050, nearly 70% of the world's population will live in urban areas, creating both challenges and opportunities for municipalities and industries, leading to a widespread debate about the future of cities. Digital technology functions as a catalyst for urban transformation promising more efficient, livable, “smart” cities that improve the quality of life for citizens and visitors by leveraging smart services, systems, and solutions [11]. As an example, LoRaWAN based street lighting solutions in smart city concept is shown in Figure 10 [12].

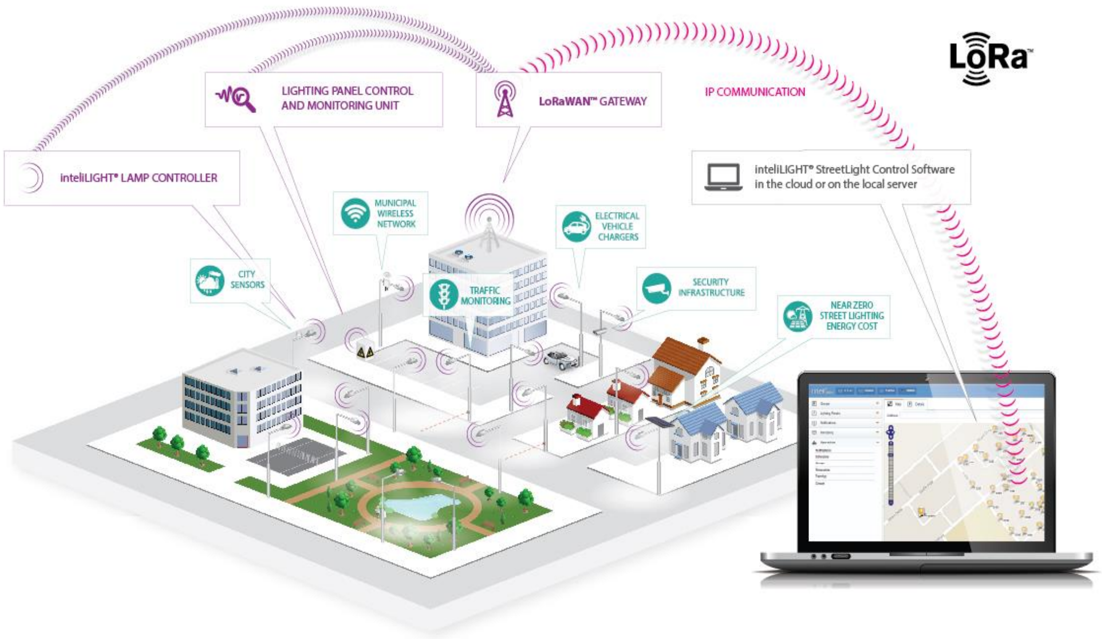


Figure 10: LoRaWAN solution for smart lighting [12]

Smart cities have emerged as a dominant digitization trend in recent years. New products and services enter the market and take off at a much faster pace than in the past, so lengthy discussions and contested agreements, as found in traditional procurement processes, instead hinder innovation. Therefore, smart cities, as a widely adopted buzzword, cited by policymakers, politicians, and companies alike, force us to wonder: are smart cities a true trend for the future or just a hype? To realize the potential of smart cities in the modern, digitized reality, organizations and municipalities must shift their (centralized) mindsets and take actions that go beyond pilot projects, so that they can apply their lessons and innovations on a larger scale. Cities need to focus on designing structures that facilitate innovation ecosystems to be able to create the necessary smart city innovations. To adapt quickly, incumbents need to be able to adopt roles that do not always fit their traditional core competencies. Overall, the future of urban innovations demands collaborations and co-creation with municipalities, incumbents, citizens, as well as competitors across a range of industries [11]. Other trends shaping the lighting industry also have to be considered. The growing global population and increasing urbanization mean that the world needs more light – and it has to be instantly available and reliable. *There is no time for downtime*. Second, we live in a world with significant natural resource challenges, so every product – including lighting components – must be used, recycled and reused efficiently. Third, increasing digitization means that people are becoming accustomed to on the spot, 24/7 access to information – and that is highly relevant to service engineers and lighting installers who need to solve problems on location instantly. A key way forward is to design lighting right from the start so that it is easily serviceable, modular and readily recyclable.

According to the Graduate school of Business of ‘‘Politecnico of Milan”, the market of smart solutions for public lighting has assumed values between € 60 and € 70 million in 2015; furthermore, the difference between the adoption of LED light sources and that of smart solutions is evident. In fact, the latter affected only about 30% of the total number of LED lights installed in 2015 and therefore represents less than 0.5% of the total public lighting infrastructure in the Italian territory. The future use of over 650,000 LED-equipped lights has been estimated by 2020, a notable leap forward (+90%) compared to the 2015 data. In fact, if we consider the overall effect of substitutions and new infrastructures by 2020, the cumulative value of LED solutions in public lighting will be of about three and a half millions of light points: it is estimated that in 2020 the LED light source market stands at € 1.5 billion. As regards investments, it is estimated that in 2020 the smart solutions market stood at around € 195 million; despite the significant growth compared to 2015 (+40%), it is clear that the smart technology market is slower than the one of efficient lighting solutions. The ratio between the two markets was, in 2015, equal to 6.4; the estimate rises only to 7.9 in 2020. In Table 3, the growth prospects of public lighting over the 2015–2020 timeframe can be seen [3].

PUBLIC LIGHTING FORECAST: 2015–2020						
Consump-tion 2015	Saving due to energy efficiency	Saving due to smart techno-logy	Total saving	Total saving	Expected consump-tion in 2020	Expected reduc-tion of CO_2 emission
TWh/year	TWh/year	TWh/year	TWh/year	%/consumption	TWh/year	Mt/year
5.9	-1.42	-0.35	-1.77	30%	4.13	-0.68

Table 3: Public lighting energy consumption (current and expected) [3]

The push for ubiquitous networking and device inter-connectivity in buildings is fueling the development of a new wave of smart devices with embedded electronics, sensors and wireless connectivity that can collect process and exchange data. Commonly known as the Internet of Things (IoT), it encompasses, but is not limited to wireless sensor networks, home automation, mobile devices and lighting control systems. Smart lighting systems are of particular interest as they evolve from traditional lighting control by introducing autonomous control of light through feedback from integrated sensors, user data, cloud services and user input, bringing with it a host of benefits including increased energy savings, enhanced functionality, and user-centric lighting. The study in [13] reviews the current state of the art in smart lighting technology, focusing on energy-saving, commercial, and advanced smart lighting systems. In that study, lighting management system is divided into:

- Occupancy-sensing based systems;
- Daylight-linked lighting control systems;
- Complementary energy saving systems;
- Combined energy-saving smart lighting systems;
- Advanced control schemes related to energy saving.

Figure 11 demonstrates the benefits of smart and sustainable lighting in smart cities.

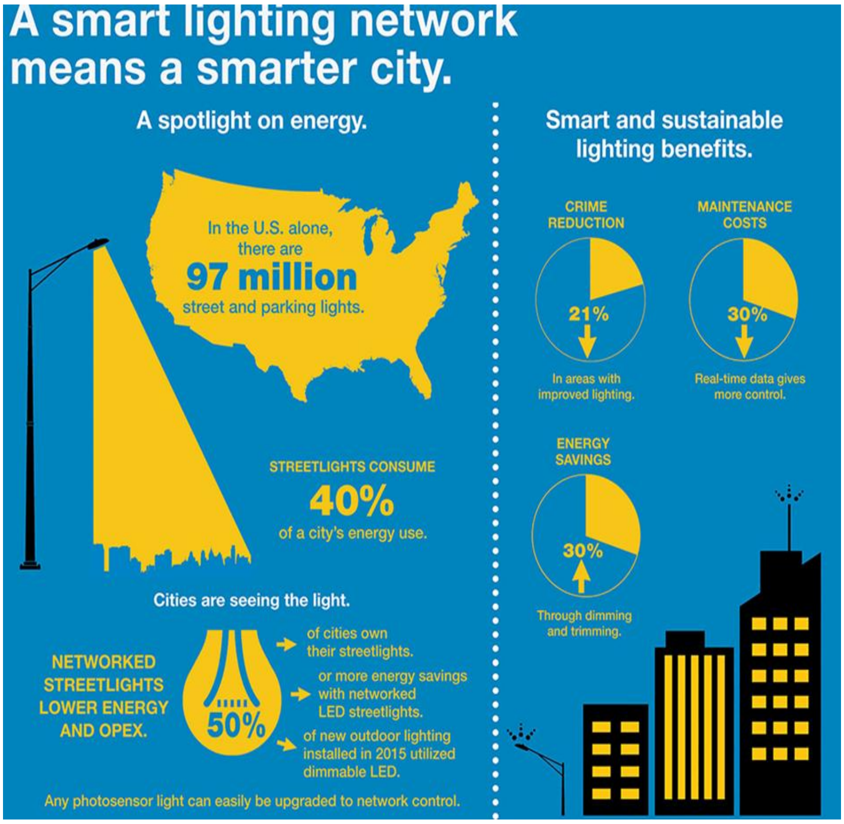


Figure 11: smart and sustainable lighting benefits [14]

The study in [15] concluded that it is very difficult to find prototypes that are based on the historical data of pedestrian and traffic flow to adjust the luminosity of an area. The systems are often reactive, not predictive. The main reason for developing the system is to employ a prediction of pedestrian/traffic flow to generate savings in hardware. Placing a camera in the area for pedestrians and vehicles for a specified period is much cheaper than having a presence sensor in various luminaires that regulates the brightness depending on the passage of pedestrians and vehicles. Moreover, the constant change in light intensity emitted by the luminaires could result in a faster rate of deterioration. Based on new technologies and methods, this work has presented a new system developed under the concept of Smart Cities to provide intelligent lighting systems that can be controlled remotely and, consequently, offer a better quality of life to residents. The new system offers a distributed lighting system to facilitate the implementation of a new infrastructure in a city; in other words, a modular architecture that is fully adaptable to current city's existing lighting systems to optimize energy consumption and its associated costs.

4.2 Case Studies

4.2.1 ENEA Casaccia, Rome, Italy

The aim of the study in [3] is to simulate and compare the energy savings potentially applicable to the consumption data of the Smart Street pilot system located at the ENEA Casaccia R.C. (Rome). The astronomical lighting system energy consumption is compared to the simulation of a pre-defined regulation: it allows the lights dimming (and therefore a reduction of consumptions) based on a statistics averages of the traffic flow rate, differentiated according to the day of the week. Then the baseline consumption is compared to the simulation of an adaptive configuration based on the traffic flow rate. The comparison results are shown in Table 4. The first column shows the type of regulation adopted the second one the total consumption, the third one shows the percent difference between the baselines; the last two columns illustrate the savings in terms of operating costs and the production of carbon dioxide. The great advantage to apply a ''smart'' way of thinking the public illumination is immediately evident.

REGULATION TRADE-OFF [FROM 14/01/2018 TO 07/04/2018]				
Regulation adopted	Total consumption	Total consumption	Cost savings	Reduction of CO_2
Units	kWh	Δ%	€	kg
Baseline	8,055.70	0.00	0.00	0.00
Pre-defined regulation	5,061.73	37.17	538.91	119.772
Adaptive regulation	3,284.05	59.23	858.89	190.855

Table 4: Total consumption trade-off [3]

Figure 12 shows the general architecture of the Smart Street pilot site is located at the ENEA Casaccia R.C. (Rome): the system is a public street lighting line managed in an automatic (programmable) and manual ways. Thanks to the sensors that the system is equipped with, it is possible to program the switching of lights, according to the ephemeris tables (local sunrise and sunset), based on a pre-set and fixed timetable. The system is able to respond dynamically, due to the presence of smart cameras, to the traffic flow rate [3].

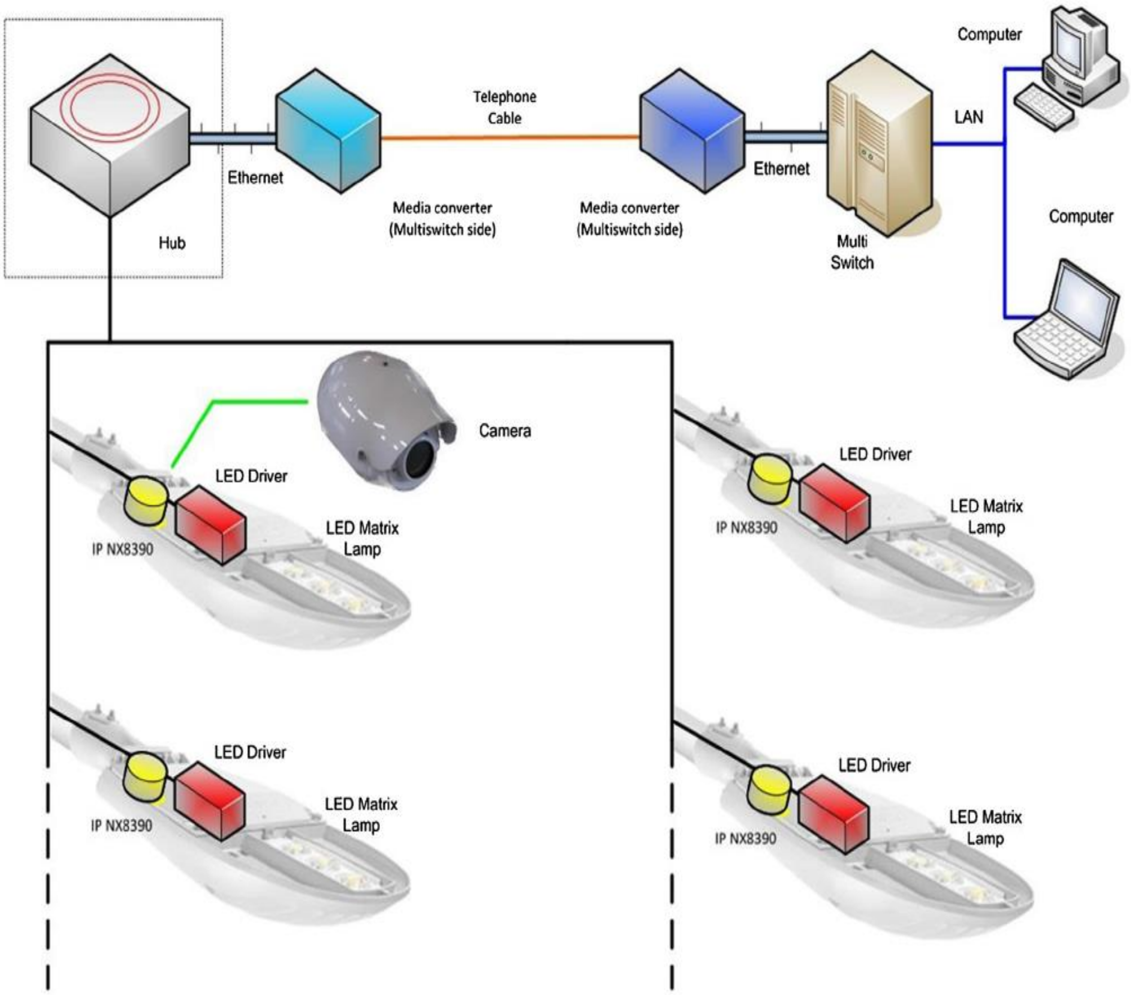


Figure 12: ''Smart Street" pilot site system: general architecture [3]

4.2.2 Bari, Italy

The study in [16] develops a multi-criteria decision making tool to support the public decision maker in optimizing energy retrofit interventions on existing public street lighting systems. The study in [16] proposes a decision-making tool that allows deciding, in an integrated way, the optimal energy retrofit plan in order to simultaneously reduce energy consumption, maintain comfort, protect the environment, and optimize the distribution of actions in subsystems, while ensuring an efficient use of public funds. The presented tool is applied to a real street lighting system of a wide urban area in Bari, Italy. The system is composed of 21 streetlights; every unit has a ''lamp assembly" composed by an IP Node, a LED driver, and a LED matrix lamp. Since each lamp has a unique IP address, it is possible to monitor the individual status and adjust the brightness by operating on the driver that has a specific interface. Several smart cameras provide all the traffic data information, as they are able to record not only the passage of a vehicle or a pedestrian, but also detect its type and speed. All the status information and electric power absorption data are then sent to a hub that takes care to send it to a remote computer system which, moreover, stores the critical data of all the street lamps at 15 min intervals; thanks to a software developed ad hoc, it is possible to run the reverse path to the controls in order to pilot the LED driver. It is therefore possible to receive the telemetry data of each single lamp and consequently send appropriate remote controls that can adjust the brightness from 100% up to the ''off" state.

4.2.3 Southampton, UK

The study in [2] proposes a real-time adaptive lighting scheme which detects the presence of vehicles and pedestrians and dynamically adjusts their brightness to the optimal level. In that study, TALiSMaN, a distributed Traffic-Aware Lighting Scheme Management Network is presented for this purpose. TALiSMaN tailors its operation to different road users, i.e., instead of requiring a centralised controller, TALiSMaN has been designed to operate autonomously over a short-range mesh network (i.e. a network of decentralised and distributed networked streetlights). TALiSMaN is evaluated against existing and state-of-the-art techniques, through the simulation of a scenario using real traffic and geographical data. Results are analysed for both energy consumption and streetlight utility. This is the first work that has used this holistic approach to the evaluation of lighting schemes.

Application-based simulations show that TALiSMaN is able to provide improved or comparable streetlight utility to existing street lighting schemes, but with a significant improvement in energy efficiency (requiring only 1–55% of the energy, depending on traffic volume).

In order to enable progressive control of the streetlight illuminance, based on either the presence detected by local sensors or information relayed by neighbouring nodes, four different operational states are defined in TALiSMaN: 'Lamp on by sensor', 'Lamp on by neighbour', 'Lamp on by delay' and 'Lamp off'. Amongst these operation states, 'Lamp off' and 'Lamp on by sensor' are shared between neighbouring sensor nodes using the on-board wireless communication module. Figure 13 shows the state machine of these operation states during operational hours.

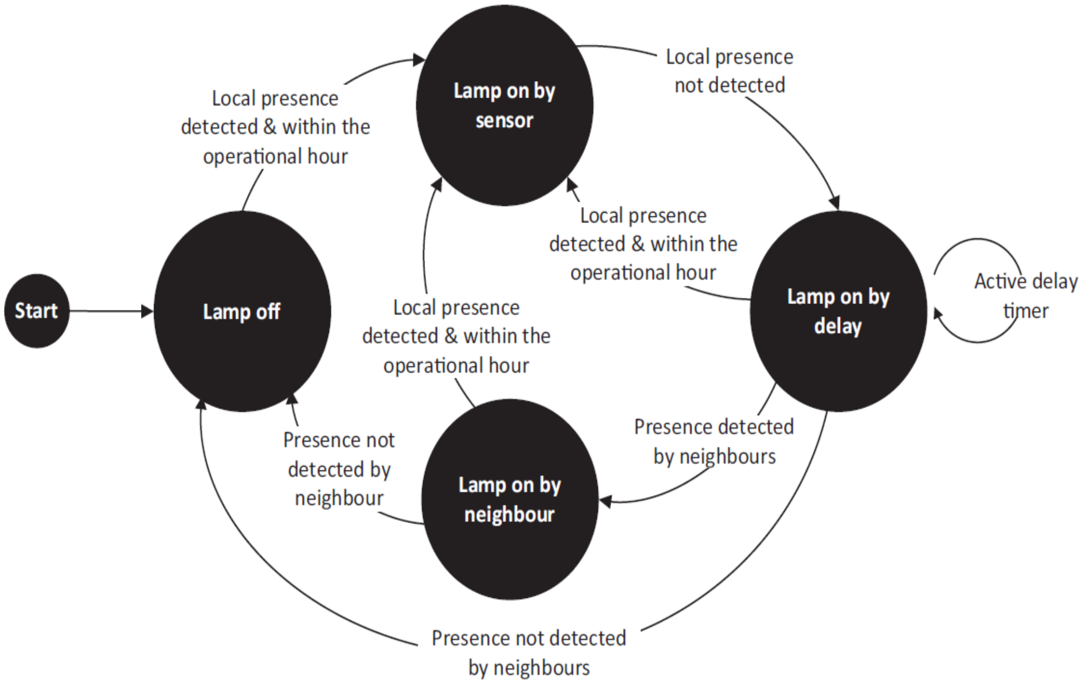


Figure 13: operation state machine during streetlight operational hours [2]

Relationships between a streetlight's proximity to the road user and the desired illuminance is shown in Table 5.

Road user type	Distance from streetlight, d (m)	Illuminance output (%)
Pedestrian	0 ≤ d < 30	100
	30 ≤ d < 60	80
	60 ≤ d < 90	60
	90 ≤ d < 120	40
	120 ≤ d < 150	20
	150 < d	0
Motorist	0 ≤ d 100	100
	150 < d	0

Table 5: The relationship between road users' distance and streetlight illuminance output [2]

Figure 14 shows the development of the required lighting pattern after a pedestrian is detected by a road-user sensor at streetlight s_2. After that, the presence of the pedestrian is shared amongst the sensor nodes at streetlight s_1 to s_8. L_{ped} is the required illuminance of the streetlight based on the approximate relative distance (m) to the detected pedestrian.

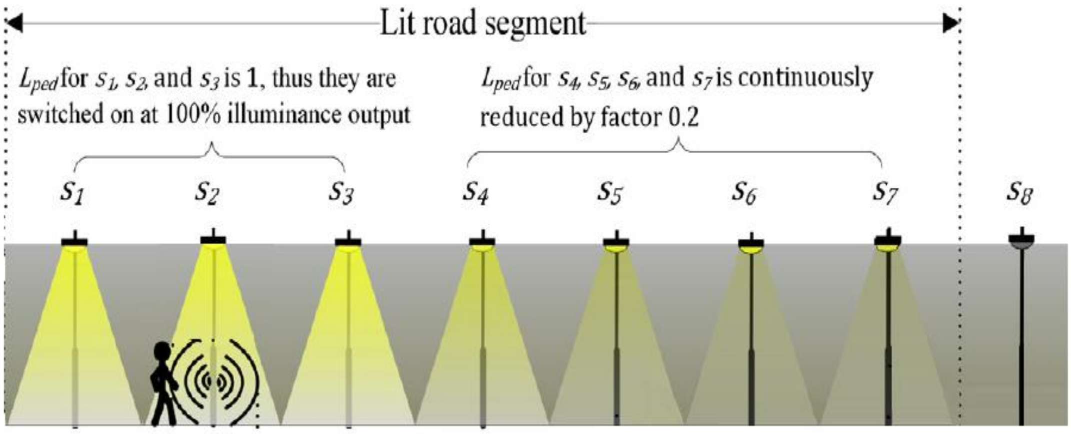


Figure 14: A lit road segment created by streetlight s1 to s7 while operating using the TALiSMaN. This lighting pattern is created based on the approximate relative distance to the detected pedestrian [2]

As the difficulty in detecting potential hazards increases with darker lighting conditions, the streetlight illuminance required by a motorist is always at 100% for a road segment 100 m ahead of them. Since the road-user sensors are assumed unable to detect the direction that the detected motorist is travelling in, both road segments before and after the motorist are lit. Figure 15 illustrates the development of the required lighting pattern upon detection of a motorist by a road-user sensor at streetlight s_1. After that, the presence of the motorist is shared between streetlights s_1 to s_5.

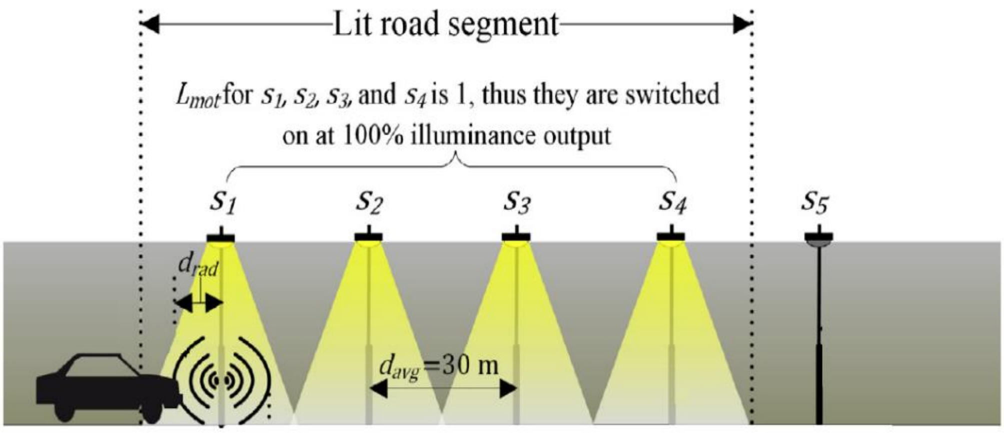


Figure 15: A lit road segment created by streetlight s1 to s4 while operating TALiSMaN. This lighting pattern is created based on the approximate relative distance to the detected motorist [2]

Figure 16 shows the lighting conditions of a road segment at different times t as a result of a simulated pedestrian travelling towards streetlight s_{12}. At t = 2, the presence of the pedestrian is detected by streetlight s_8 and this information is shared between neighbouring streetlights, i.e. s_3 to s_{12}. Upon receiving the information, the brightness levels of these streetlights are adjusted to create the lighting pattern needed by the pedestrian. As the pedestrian travels towards streetlight s_{12}, these optimum lighting conditions are shifted to the right along with the presence detected by streetlight s_9 to s_{12}. Under such lighting conditions, TALiSMaN offered near-optimal streetlight utility to the pedestrian.

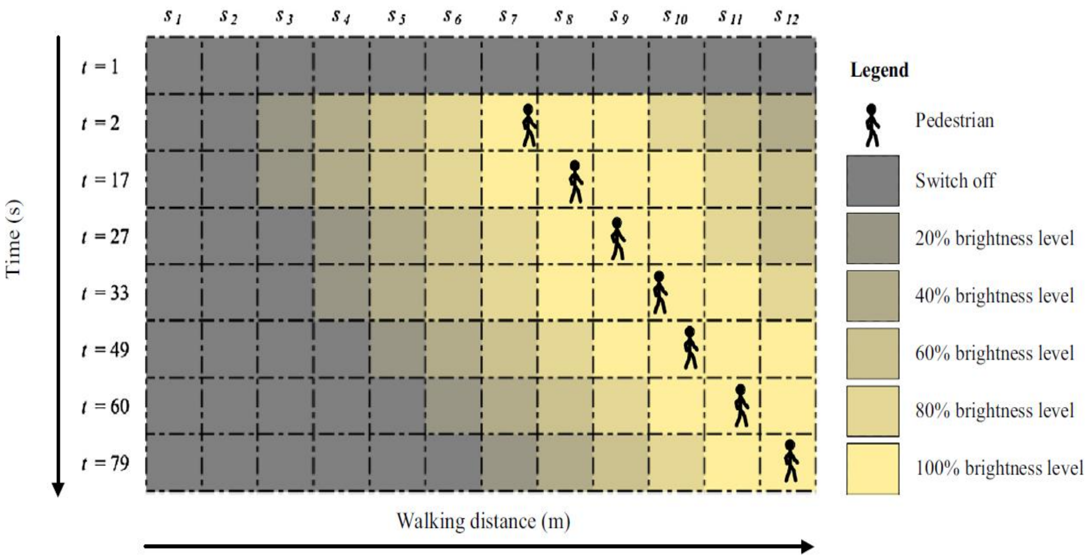


Figure 16: The dynamics of lit road segments (from top view) when a pedestrian travels from left to right [2]

4.2.4 Helsinki

An intelligent LED lighting pilot was carried out along a light traffic route in a housing area in Helsinki [17]. The goal of the research was to develop and test a lighting control system with an optimal lighting behaviour, which saves energy without lessening the safety and security of route users during the dark. The developed lighting control solution was based on tracking route users' movements and location along the route with passive infrared (PIR) sensors. Using this information, the system could create lighting conditions where the illuminated area reaches further in front of the user than behind. This was considered as an optimal solution from the perspectives of energy savings and user comfort.

The control was implemented in a real-life test site used by pedestrians and cyclists consisting of 28 lighting posts with controllable LED luminaires. The recorded PIR data was analysed to evaluate the performance of the developed system in northern outdoor conditions and to compare different lighting control schemes and their influence on energy consumption. The experiences gained during the piloting showed that the system could operate in outdoor conditions, but strong wind in a cold environment caused false sensor activity. The used arrangement of the three PIR sensors with a wide field of view made the system sensitive to false detections, especially as they were installed high in lighting poles surrounded by foliage. The relative energy saving compared to the existing control solution of the area was 60–77% depending on the used smart control scenario and the calendar time.

Figure 17 shows the sensing and control system parts and communication method used to provide adaptive lighting control to the real-life test site. Wired communication is shown with a solid line while wireless communication and Ethernet are indicated with text. The arrowheads show the direction of the communication. For the dynamic behavior of lighting in the networked virtual system, a new methodology was developed. Instead of dynamic computational agents moving from node to node, the lighting intensities are defined as percentages per linearly connected light fixtures down and upstream from triggered sensors. The down and upstream directions are relative to the direction of the user's movement; forward and backward, respectively.

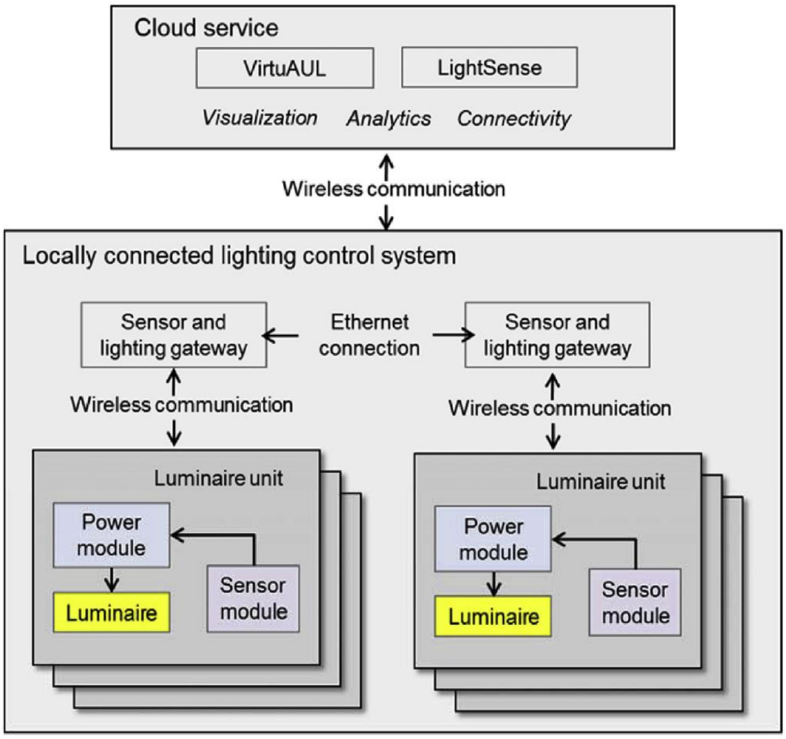


Figure 17: sensing, control system parts, and communication method used to provide adaptive lighting control to the real-life test site [17]

In simulations, three different control scenarios as illustrated in Figure 18 were used. All the scenarios were designed in a way that the adaptive functionality of lighting could not be detected by the road user or was hardly noticeable. In practice, this would mean that the illuminated area on the route would be long enough to cover most of the user's field of vision. With the smart lighting control 1, the lighting was at 100% control level around the route user and two luminaires ahead of him/her. After that, the third luminaire was dimmed to the 50% control level, as well as the luminaire behind him/her. Otherwise, in the area the lighting was dimmed down to the default level of 20%. With the smart lighting control 2, the luminaire by the route user and the two luminaires ahead and behind of him/her were at 100% control level. Beyond the 100% area, the next (third) luminaires in both directions were dimmed to 50% control level and all the other luminaires stayed at the default 20% level. As the illuminated area is symmetric, this control scheme could be realized with standard presence detection without knowing the direction of the movement. With the smart lighting control 3, the illuminated area around the route user was the largest. This time the luminaire by the route user and three luminaires ahead and one luminaire behind of him/her were at full 100% control level. Then, the next luminaires in both directions were dimmed to 75%, and the next luminaires after that were set at 50% lighting level. The default control level beyond the brightened area around the user was 20% in all the control scenarios. As the system was able to track several people at the same time, all the road users could have their own illuminated area and the areas could overlap. The smart lighting control 1 would optimize the energy performance with the smallest illuminated area but would require the lighting system to be able to detect the direction of the movement. The smart lighting control 2 has symmetrical attributes around the road user so it could be realized with standard presence detection technologies.

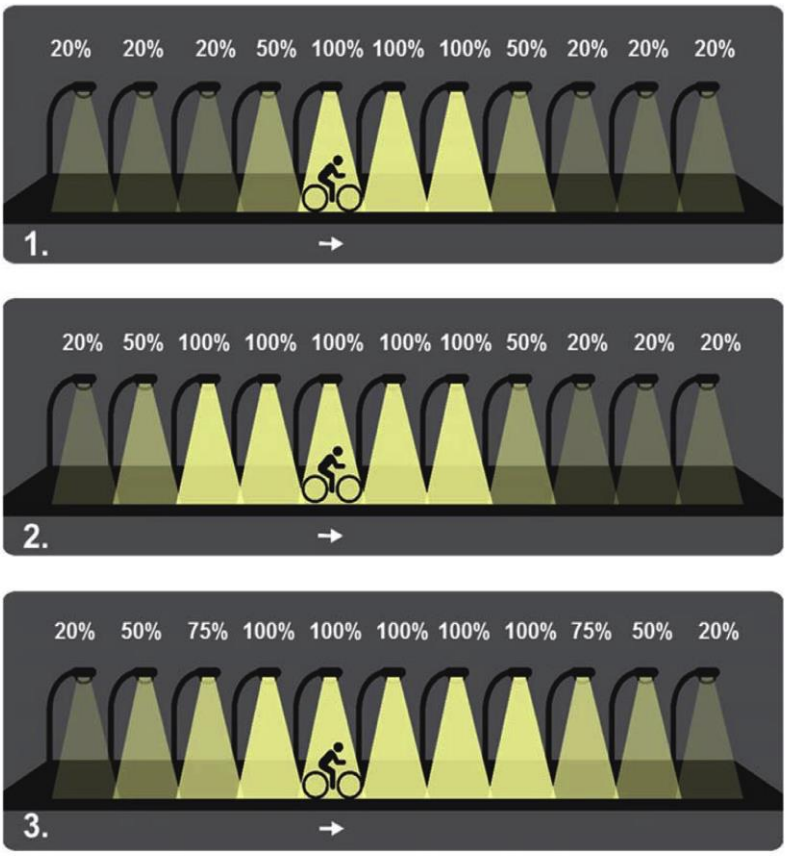


Figure 18: The simulated smart lighting control scenarios with varying amounts of brightened luminaires around the route users. Beyond the brightened area, the luminaires were at 20% control level in all the scenarios [17]

In Figure 19, the dynamic smart lighting control scenarios are compared with normal (static) control of the area in which the lights are off during the bright period of the day, and at 100% control level during the night. The luminaire (Green led Sirius) was measured to consume 6 W at 20% level, 10 W at 50% level, 17 W at 75% level and 27 W at full 100% power. In all simulations, real PIR data collected during 19.4.2017 was used. It can be seen that the smart control generates significant energy savings. This is because of the low default level (20%) and long quiet hours with no or only very few pedestrians at the route overnight. In addition, the overall presence of users on the route is rather low. The relative savings compared to the normal control increase towards the summer with significant amount of natural light in northern latitude. Consequently, artificial lighting is needed only during midnight hours with practically no users. For the same reason, the amount of energy saved with smart control radically decrease towards summer, despite the increasing relative saving. When comparing different smart lighting control scenarios, only little difference between them can be detected. As expected, the highest energy consumption is with the scenario with the largest illuminated area. One of the scenarios (Smart control 2) is such that it could be realized with a simple presence detection. Compared to that, the advanced control able to adapt based on direction of movement provides only small benefit (1–8%). The difference between the smart control schemes reduces towards summer, implying that the low overall presence in the test site contributed to this small benefit. As such, the advanced solution would be more useful in some other applications (with more road users).

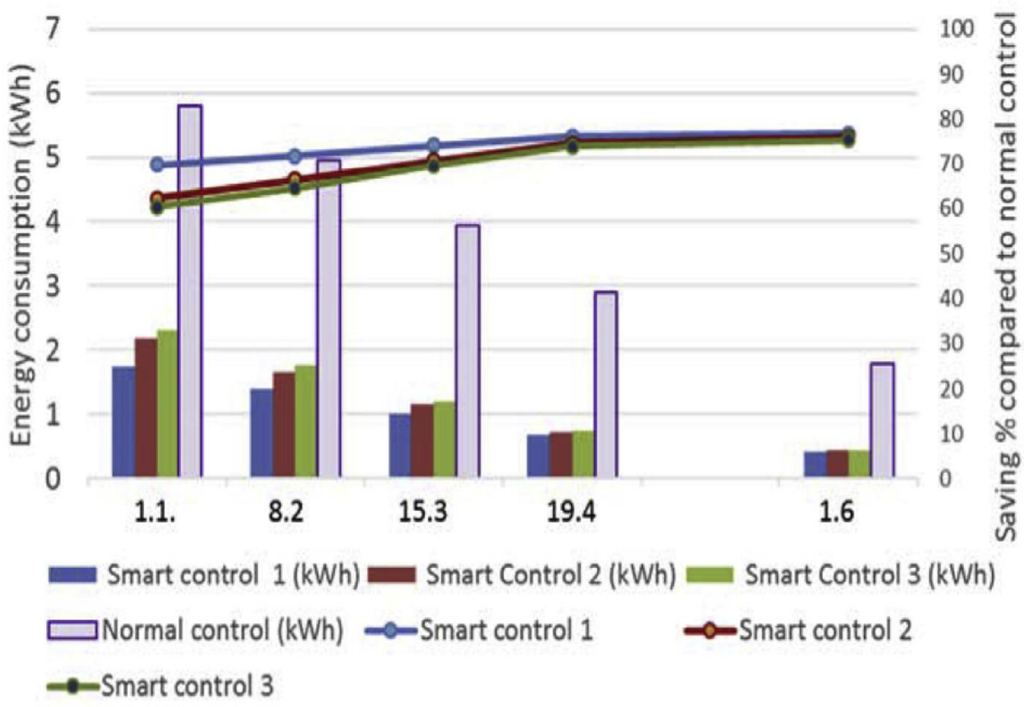


Figure 19: comparison of the dynamic smart lighting control scenarios with normal (static) control of the area [17]

5 Supporting technologies (i.e. integrated renewables and batteries) for lighting systems in areas which are differently used in different times of the year (summer resorts, cottage areas)

The study in [18] investigates the application of solar energy in public lighting for realizing a street lighting subgrid with positive yearly energy balance. The focus is given to the central controller, which ensures the adaptive behaviour of the overall system and provides smart city services to the end users via its web-based user interface. A functionality of the controller of special interest is the optimization of the energy management of the system, i.e., determining when to sell and buy electricity to/from the grid, in order to minimize the cost of electricity (or to maximize the profit) subject to a given, time-of-use variable energy tariff. This requires precise forecasts of the energy produced and consumed, as well as appropriate robust optimization techniques that guarantee that the system bridges potential power outages of moderate duration in island mode. The algorithms implemented in the controller are presented in detail, together with the evaluation of the operation of a deployed physical prototype with 191 luminaries over a horizon of six months, based on the monitoring data collected by the proposed controller.

The management system proposed in [18] provides adaptive, energy-efficient lighting service by applying dimmable LED luminaries, which modulate their light intensity according to the current traffic and environmental conditions. Infrared motion sensors, mounted into the lighting fixtures on each pole, measure the speed and the direction of the motion in the proximity of the luminaries. Smart controllers, in turn, classify these motion signals as vehicle traffic, pedestrian traffic, or no traffic, and adjust their dimming levels to the detected scenario. However, luminaries are not isolated; they inform their neighbours about the detected traffic scenario via wireless communication, enabling the long-range adaptation of the lighting service despite the fact that the motion sensors are dependable only in a shorter range (e.g., 10 neighbors are switched to full intensity in case of vehicle traffic, 4 neighbours in case of pedestrian traffic). Hence, real-time control of the lighting system is achieved by distributed intelligence, eliminating the dependence on communication with the central controller(CC). The energy management system comprises PV panels and inverters for energy generation, batteries for energy storage, as well as the appropriate measurement and control instruments. PV panels have been sized to achieve positive energy balance over a yearly horizon, whereas batteries are used to ensure island mode operation for at least three hours in case of power outages, considering the environmental, meteorological, and traffic conditions of the deployment site. Smart meters and the CC monitor the power flow in the system. The latter also decides when to buy or sell electricity from/to the grid, with the objective of minimizing the costs of energy (or equivalently, maximizing profit) subject to the applied variable energy tariff. The local weather station of the system measures six different weather parameters, which can be correlated to energy production and consumption data in order to evaluate and predict system performance. The signals of the twilight switch in the weather station are used to determine the daily switch on/off times of the luminaires. The central controller of the E+ grid system is in charge of controlling and monitoring the lighting and the energy management system, and it is responsible for delivering smart city information services to the various stakeholders. Technically, it is a web-based software application, hosted on a virtual server in a computational cloud. Such a deployment approach revealed measurable advantages compared to deployment on traditional, physical servers, mainly with respect to augmented scalability and configurability, redundancy of the hardware resources and hence increased dependability, as well as lower energy consumption and investment cost. The architecture of the overall E+ grid system is shown in Figure 20, where the red lines indicate power flow, while green connectors correspond to information flow.

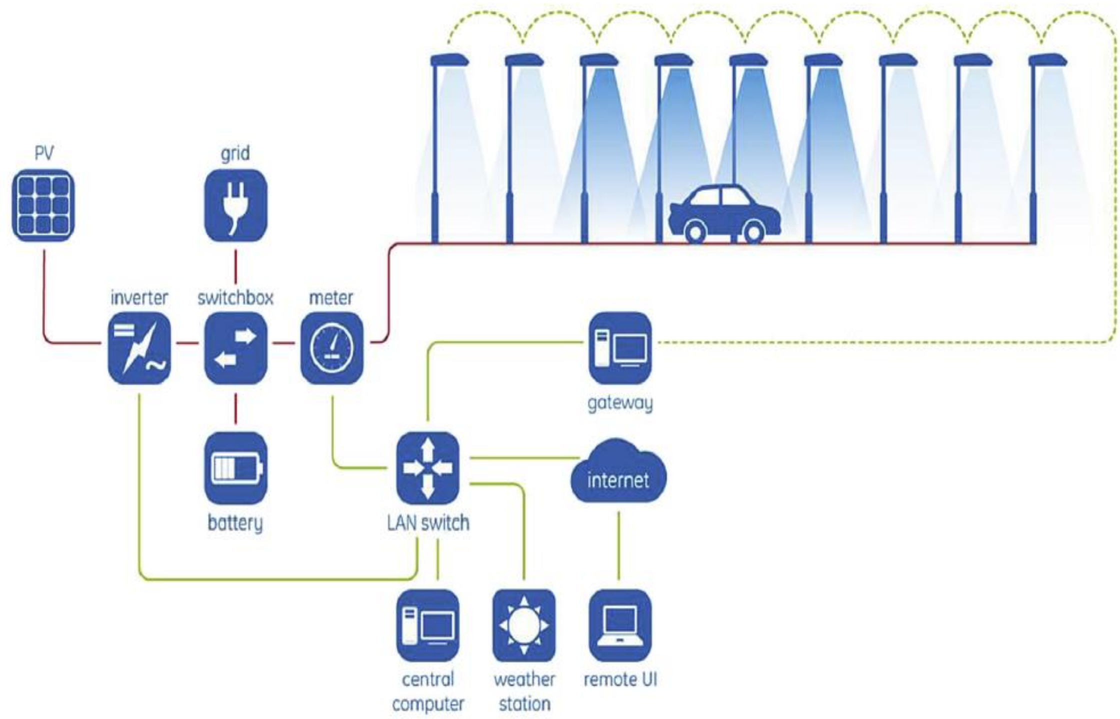


Figure 20: Architecture of the E+ grid system. Red lines indicate power flow, green connectors correspond to information flow [18]

The selection of the solar panels mostly depend on how much power is needed and where they are fitted. The panels not only have to convert the sun's energy into electricity but they may have to withstand the extremes of weather from baking hot sun to freezing cold rain and winds. The batteries need to be able to be charged from the amount of power that will be supplied. It may be that there will be 8 hours of sunlight, but the lighting is only required for 4 hours in the evening. The battery is chosen to provide sufficient electricity for the lighting for the required amount of time.

The control box may be a simple device to interface the solar panels to the battery. In small installations, the solar panels may connect directly to the battery and so protection is required to ensure that the power just flows from the panel to the battery and out to the lighting. A full charging circuit may be required to ensure the battery does not over-charge. The lights also need to be carefully selected. The lower the wattage that can be used to provide the light the better, as the system will be much cheaper for both the panels and the batteries. In addition, the system will more likely be able to provide sufficient power even in times of low sunlight [19].

Off-Grid Systems are sophisticated networks of solar PV panels, batteries, and other electrical devices that take the electrical energy produced by your solar PV panel, and feed it right into LED lighting (Figure 21).

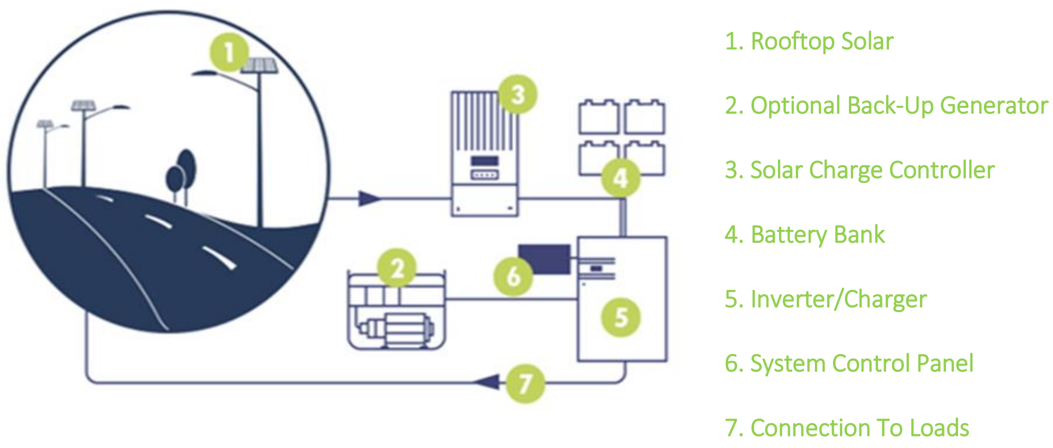


Figure 21: Off grid PV-fed, LED lighting system [20]

A sample of All-in-one solar street and it is main characteristics are shown in Figure 22 [21] [22].

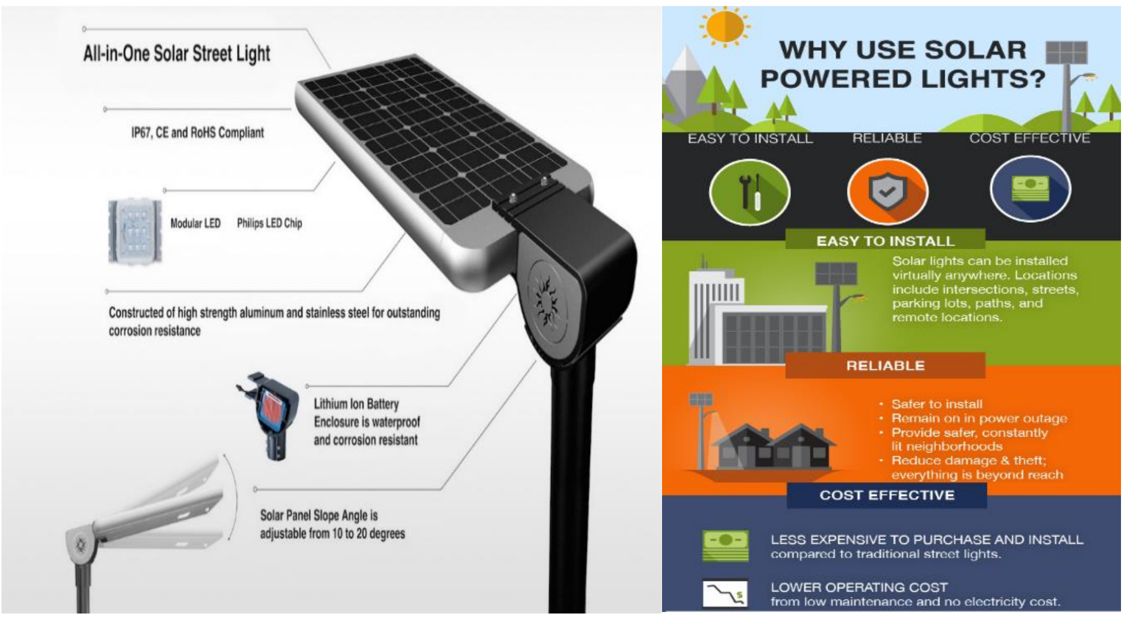


Figure 22: All-in one solar street and it is main characteristics [21][22]

Additional Benefits of Solar Power Lights are:

- **Improved Safety** – Solar power lights do not require connection to an electrical grid. It is safer and easier to install. In the event of a power outage, the light remains on. This reduces the chance of car accidents and the constant light deters theft/vandalism from nearby businesses.
- **Lower Operating Cost** – There is minimal maintenance, and no ongoing electricity cost.
- **Reduced Damage/Theft** – By locating the solar technology directly on the light fixture and placing the battery within the light fixture, the risk of damage, theft or tampering is greatly reduced. There are no wires in the street pole, which means that the wire itself (which exists in regular street lights) cannot be stolen and sold for scrap.
- **No Insect Swarming** – The solar powered street light uses LED street lighting which does not produce infrared light, and therefore does not attract insects (no more moths and other flying insects swarming around the light).
- **Fast Installation** – Since there is no need to trench power lines to the pole, run wires up the pole, connect wires to an electrical grid, or hardwire the street light, the installation is significantly faster. In fact, it can be installed on the pole before it is erected, and thereby reducing a step completely from the process [21].

6 Reliability issues of urban lighting systems and their components

With the increasing complexity of technical equipment, modules or even individual components, the aspects of reliability and lifetime and thus the costs involved with exchange and revision become increasingly more important for the customer. Here, one must consider an optimization between requirements, functions and costs over the lifetime of the product. The single requirement that the device will not fail is no longer sufficient for modern, powerful components or devices. More often, it is additionally expected that they perform their required functions without failure. However, it is only possible to make a prognosis (probability) supported by statistics and experiments as to what extent such requirements can be fulfilled. A direct answer or statement as to whether an individual device or component will operate without failure for a certain period of time cannot be given [23].

6.1 Lifetime of an LED luminaire

Lifetimes of traditional light sources (incandescent, fluorescent, and high intensity discharge lamps) are estimated through industry-standard lamp rating procedures. Typically, a large, statistically significant sample of lamps is operated until 50% have failed; that point, in terms of operating hours, defines the “rated life” for that lamp. Based on years of experience with traditional light sources, lighting experts can confidently use lamp life ratings, along with known lumen depreciation curves, to design the lighting for a space, and to determine re-lamping schedules and economic payback. LED technology changes several aspects of this traditional approach:

- LEDs usually do not fail abruptly like traditional light sources; instead their light output slowly diminishes over time;
- LEDs are often integrated permanently into the fixture, making their replacement difficult or impossible;
- LED light sources can have such long lives that life testing and acquiring real application data on long-term reliability becomes problematic—new versions of products are available before current ones can be fully tested;
- LED light output and useful life are highly dependent on electrical and thermal conditions that are determined by the luminaire and system design.

LED luminaires and replacement lamps available today often claim long life, e.g., 50,000 hours or more, which exceeds the life ratings of nearly all other light sources (except for some electrodeless sources). These claims are based on the estimated lumen depreciation of the LED used in the product and often do not account for other components or failure modes. Life claims by LED luminaire manufacturers should consider the whole system, not just the LEDs [25].

The most important physical influencing factors on the reliability and lifetime of LED light sources include humidity, temperature, current and voltage, mechanical forces, chemicals and light radiation, as shown in Figure 23. These can even lead, in a worst-case situation, to a total failure or influence the aging characteristics in the long term (e.g. brightness), and thus produce a change in the reliability and lifetime.

The study presented in [24] mentions that the lifetime of an LED luminaire is defined as the time when light output of half the product population has fallen below 70% of average initial light output for any reason (B50/L70). This definition includes lumen depreciation of LEDs, depreciation due to interaction with other components within the luminaire and catastrophic failure of any subsystem, ranging from partial failure to total failure of LEDs in providing the desired light output above a specified threshold. Once an LED luminaire's failure criteria are established, the reliability may be expressed in different ways depending on the specific situation.

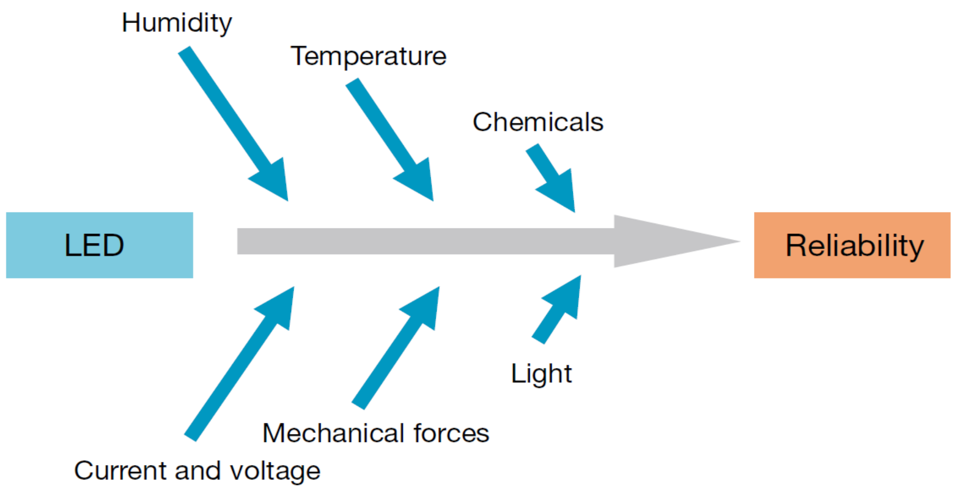


Figure 23: Influencing factors on reliability and lifetime [23]

Reliability may be described as:

1. Mean time-to-failure;
2. Failure rate: Units failed per unit time;
3. Survival probability: LED luminaire will not fail in a time interval [0, t];
4. Probability of service: LED luminaire can function at a given time 't'.

For determining points 1 and 2 from the above list, there is a requirement for testing more than one sample. However, when a single sample is available for testing, points 3 and 4 from the above list are useful. Overall reliability of an LED luminaire can be established using models that describe the essential features of the luminaire, without divulging too many of the actual details. The reliability models need to be derived experimentally and must be verified for correctness using generalized theory. In this work, we propose to model of reliability based on probability of survival or serviceability or remaining useful life (RUL) [24].

6.2 Luminaire reliability

LED lighting products are a mix of different functional subsystems. These subsystems include the optics, drive electronics, controls and thermal design. All subsystems as well as the built-in system of an LED lighting product must have the same long-term reliability for fully utilizing the long LED lifetime. There is an urgent need to address not only the reliability of all the subsystems that make up the LED lighting product; there is also a need to address the transactions between the various subsystems. The study in [24] presents the reliability of LED luminaires and the reliabilities of individual subsystems. The different subsystems in an LED luminaire introduce other potential reliability issues that are critical in deciding the overall system lifetime. The mutual dependency of subsystems and their interactions make the prospect of characterizing LED luminaire reliability challenging. Best design practices ensure that a small number of subsystems, thus reducing the complexity, will decide the overall luminaire reliability.

Novel methodologies are needed to precisely forecast the system-level reliability of LED lighting products. It is also important to understand the different failure mechanisms of LED lighting products, particularly the fundamental physics, if this is to be achieved. The three main subsystems in an LED luminaire are optical, electrical and thermal systems [24].

6.2.1 Optical reliability

The optical system of an LED luminaire comprises of the LED module and optical control elements like diffusers, lens, refractors or reflectors. During the service life, there will be degradation of each component in the optical system. One of the key degradation mechanisms is the yellowing of plastic materials surrounding the LEDs, which results in significant light output reduction and a change in the colour properties of the luminaire. A combination of LED junction temperature and ambient temperature contributes to the yellowing of plastic materials surrounding the LEDs. Temperature is a very influential degradation factor, it is commonly used as an input parameter to predict the reliability and the lifetime of plastic encapsulated LEDs and hence is used to model optical reliability of LED luminaires [24].

6.2.2 Electrical reliability

LEDs contained in a luminaire are powered by drivers based on power electronics, the reliability of drivers is key for luminaires to have a long service life. LED lighting products need to withstand extreme conditions which include temperature cycles and frequent switching during their lifetime. LED drivers need to be designed using robust power conversion topology, given the constraints of cost, size and power consumption. The LED drivers need to be designed for the highest system efficiency, within an inefficient driver component need to operate at a higher temperature, resulting in lower reliability of these components. The power supplied to the LEDs is affected when the output current from the driver reduces because of the driver's case temperature exceeding a normal value, due to which the luminous properties of the luminaire are affected. The lifetime of the LED drivers is closely related to the lifetime of the components that are most likely to have an early failure. Aluminium electrolytic capacitors used for filtering/energy storage and the optocoupler for high voltage isolation and electrical noise rejection between different potentials are the two components that are known to cause wear out mechanisms in LED drivers [24].

6.2.3 Thermal reliability

Thermal interface materials (TIMs) play an important role in the thermal management of LED luminaires by providing a path of low thermal resistance between the LED junction and the heat sink. Some of the common TIM solutions include gels, greases, and pads and solder alloys. However, in extended operation and over time, TIMs can degrade significantly, resulting in a higher thermal resistance between the LED junction and the ambient/heat sink. Luminous flux, colour characteristics and power consumption of an LED luminaire are affected by the LED junction temperature. The primary source of heat in LEDs comes as a by-product of the recombination of electrons and holes at, or near, the p-n junction. This heat needs to be dissipated away from the junction (Figure 24). LEDs will operate at high temperature, thereby reducing their efficiency and leading to premature failure; hence, it is necessary to restrict the junction temperature to a value that will ensure the desired LED lifetime [24].

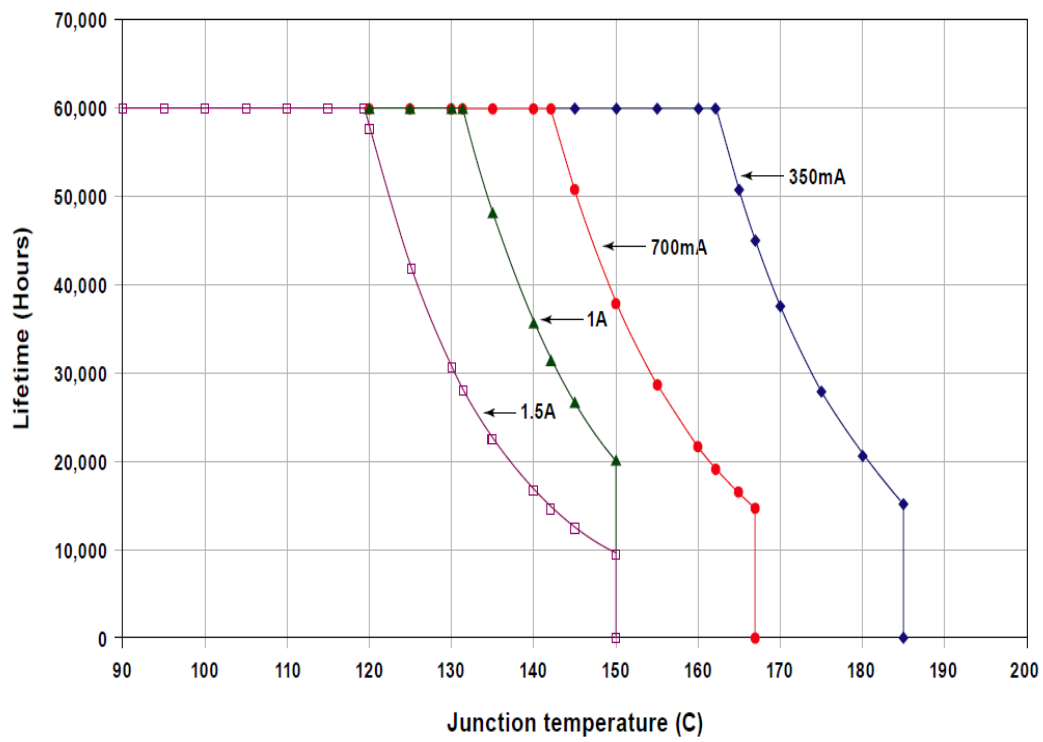


Figure 24: expected LED life based on drive current indicated by each colored line and target LED junction temperatures. Source: Philips Lumileds

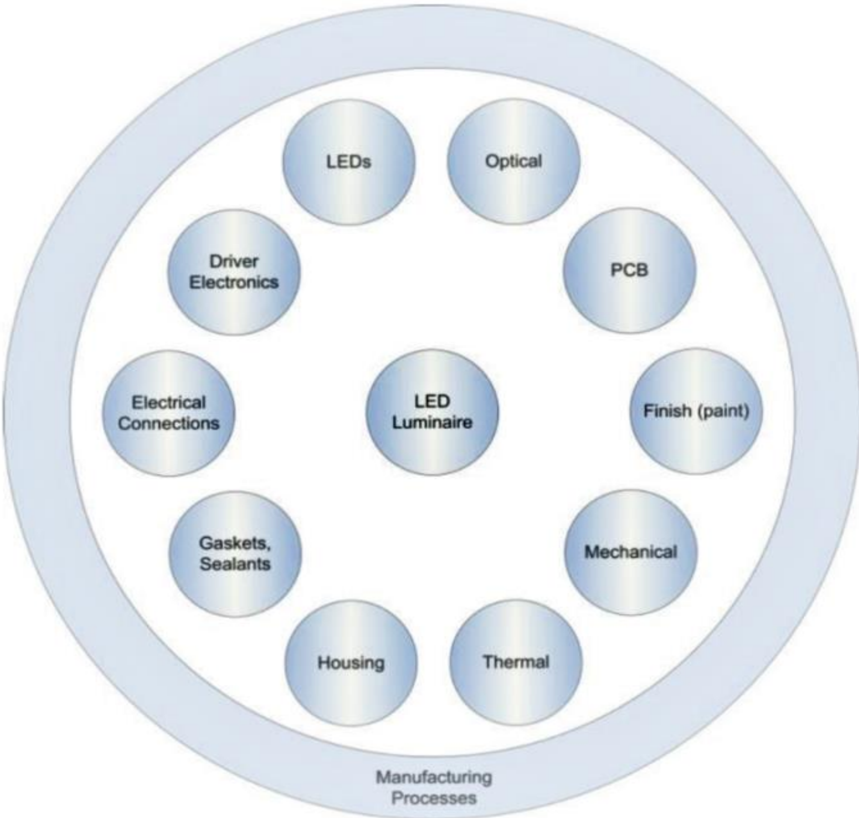


Figure 25: Total system or luminaire reliability [25]

As shown in Figure 25, the total system or luminaire reliability is the product of all of the individual reliability considerations [26]:

$R_{Luminaire} = R_{LEDs} * R_{Optical} * R_{PCB} * R_{Finish} * R_{Mechanical} * R_{Thermal} * R_{Housing} * R_{Gaskets/Sealants} * R_{Connections} * R_{Driver} * R_{Manufacturing}$

In order to accurately characterize the reliability performance of any product, it is important to identify and understand those failure modes that materially affect it. In the case of LED lighting products, lumen depreciation of LED packages is well known; this eventually results in the light no longer being useful. Experience with traditional lighting as well as LED lighting also shows that another gradual change, colour shift, may provide a limit to lifetime as well.

The most commonly observed failures from the LED Systems Reliability Consortium (LSRC) member survey are shown in Figure 26. “Times Referenced” means the number of respondents who cited this failure mode [26].

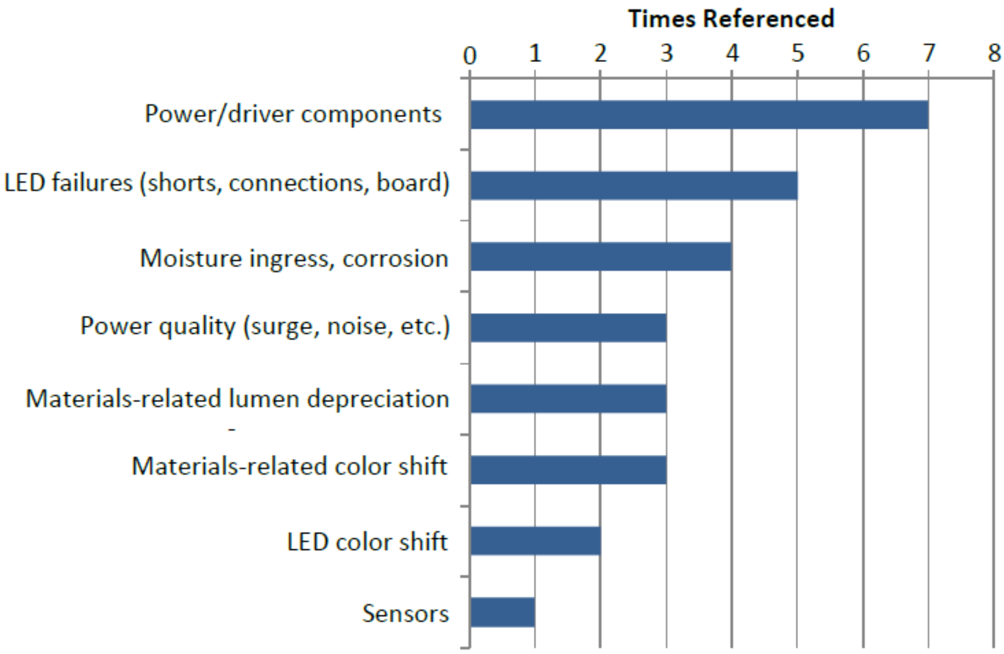


Figure 26: Most-Observed LED System Failures [26]

Figure 27 shows SSL luminaire failure modes, across 212 million field hours. The failure categories in this chart are defined as follows [26]:

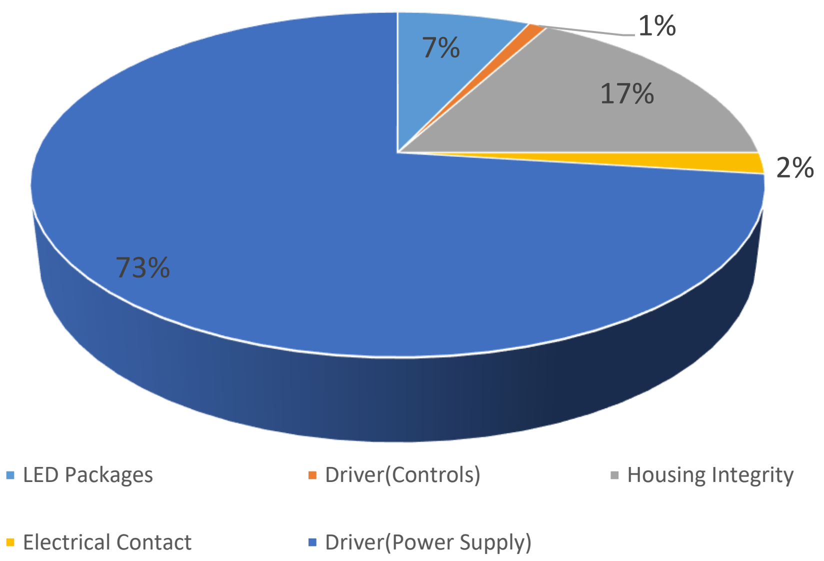


Figure 28: SSL luminaire failure modes, across 212 million field hours [26]

- **Driver (Power Supply)** includes traditional power supplies and contains all failures related to the power supply or its inability to perform as specified by the luminaire manufacturer;
- **Driver (Control Circuit)** includes control board(s) or other control devices, if they are separate and unique from the power supply. These devices are often used to split and/or electronically condition the output of the power supply, and in some cases may also include wireless, wired or other types of controls that monitor and/or manage the luminaire's operational state;
- **Housing Integrity** includes failures from loss of housing integrity, resulting in moisture ingress, debris accumulation, structural failures, etc.;
- **LED Packages** includes traditional end-of-life lumen degradation, chip package failures, significant color shifts, etc.;
- **Electrical Contact** includes wiring and connector failures and any general connectivity issues resulting in failure of the luminaire to light and/or to otherwise operate in a manner that is deemed non-functional.

6.3 Luminaire Reliability Standards

The International Electrotechnical Commission (IEC) standard IEC 62717 recommends "LED Lamp Life" expressed as 'MxFy' and defined as "*length of time during which y% from a population of LED lamps of the same type have either parametrically failed, no longer producing at least x% of their initial luminous flux, or catastrophically failed*'. An LED luminaire comprises several subsystems; failure of any of these can cause system failure. The LED lamp manufacturers currently rely upon a series of 'paired' documents for testing and projecting luminous flux at component level (LEDs and LED modules) and final product level (LED lamps and luminaires). These paired documents are IESNA LM-80 and IESNA TM, IESNA LM-84 and IESNA TM-28, as well as IESNA LM-86 and IESNA TM-29. According to these standards, LED lamp life is derived from lumen maintenance (L70), i.e. the time in hours for the luminous flux to reach 70% of its initial value. However, LED luminaires operate under different environmental conditions and are subjected to switching cycles. The current lighting standards such as LM-80 and LM-84 do not provide accurate lifetime or system reliability information, because these standards recommend continuous operation for testing and projecting L70 values. For LED luminaires, failure modes can be different when subjected to switching cycles in comparison to continuous operation [24].

6.4 Maintenance

On-site maintenance has become a hot topic. Municipalities, authorities and building owners want to fix faulty lights during a single visit to save labour time and costs. This requires the service engineer knowing what the problem is before setting off, taking the correct spare part(s), and being able to fix the problem right away, on the spot. However, to succeed, the engineer needs immediate access to the right information and the right spares.

Signify, an industry leader in LED lighting, has been developing new applications to aid maintenance. One example is Philips' Service tag, which makes components uniquely identifiable with a QR (Quick Response) code, providing instant access to necessary lighting component information at the right time and place. Another one is the Interact sofware application, which, among others allows remote monitoring of light points to enable cities to save on operational costs and prevent issues before they happen.

LEDification is transforming the lighting industry, and Signify is playing its role by simplifying operations, reducing maintenance, ensuring modularity and emphasizing recyclability by enabling more efficient and longer use of components. This all helps make sure customers can enjoy the promised benefits of LED technology [26].

In summary, LED luminaire life is not identical to estimated LED life. LED luminaire life is also a function of the power supply, operating temperatures, thermal management, materials, and electrical and material interfaces. Definitive lifetime ratings will not be possible until more experience is logged with a wide range of LED luminaires in the field.

In the meantime, how can LED luminaire reliability be assessed? Some elements to look for are:

- Use of high-quality LEDs from manufacturers who publish reliability data;
- Luminaire warranty offered by the manufacturer – it should be at least comparable to traditional luminaires used for the application under consideration;
- Luminaire photometric report, based on LM-79-08 test procedure, from an independent testing laboratory;
- Temperature data (for example, board, case, or solder joint tempera-true) for the LEDs when operated in the luminaire in the intended application; and information about how the measured temperature relates to expected life of the system;
- Any test data available about longer-term performance of the LED luminaire [18].

7 Practical Examples

7.1 Municipality of Jimena de la Frontera, Cádiz (Spain)

Jimena de la Frontera is a historic town located in the province of Cadiz, in the southern region of Andalusia, Spain, and has a population of approximately 10,000 people. In July 2009, the municipality expressed its commitment to sustainable development and the creation of a new local energy model by signing the Covenant of Mayors initiative and developing a Sustainable Energy Action Plan (SEAP), with the overall goal of reducing its greenhouse gas emissions (GHG) by 21% before 2020 (compared to 2007 levels). An improvement in the energy efficiency of public outdoor lighting was included in the SEAP as one of the specific areas where actions should be taken. The existing facilities had a need for modernization in order to comply with the latest regulations and achieve significant energy savings and high-energy efficiency of facilities. The contract period was ten years and included the following requirements from the service:

- Energy Management: Energy and administrative management, including a remote-control system and quality control;
- Preventive maintenance and inspection;
- Corrective maintenance with total guarantee of damaged elements in the existing installations during the contract period;
- Improvement works and renovation of facilities with high energy consumption;
- Investments in energy efficiency and savings: Implementation and financing of works for inclusion, upgrading or renewal of equipment or items that promote saving and greater energy efficiency. These works should be considered, presented, implemented and funded by the winning bidder through the savings achieved within the contract period, and have no economic impact on the budget itself. The total estimated value of the contract was 1,461,625.50 Euro (excluding value added tax).

The following improvements have been carried out:

- Less than a year after the contract was awarded, most of the corrective and maintenance actions planned had been carried out, with achievements of 65% savings in total energy consumption;
- Review and renewal of all operation centres included in the contract and introduction of remote control and management systems;
- Replacement of 1,412 low-power compact fluorescent lamps for light emitting diodes (LEDs) integrated into the remote-control system. 1,569 lighting points are managed under the remote-control system;
- Planning of short and mid-term awareness raising campaigns, consisting of regularly publishing information on the Municipality's website and the organization of information days for citizens [27].

7.2 MUNICIPALITY OF CASCAIS, PORTUGAL

In 2005, energy consumption for public lighting in the municipality of Cascais represented 79 percent of total electricity consumed by the local government (for public infrastructure). Cascais' Local Energy Agency took on the task of reforming the criteria used to purchase public lighting technology by means of their involvement in the European project Public Procurement boosts Energy Efficiency (PRO-EE), initiated in November 2008.

Cascais' new energy efficient lighting system was expected to result in a reduction of indirect emissions of 34,600 kg of CO_2 per year in the procurement. The different components of street lighting, that is, the lamp that provides the light, the ballast or control gear that regulates current and the luminaires that direct and shade the light will have different environmental impacts at different stages of the product life cycles. However, an assessment of street lighting as a whole, as part of the Energy Using Products (EuP) study, concluded that energy consumption during the use phase, chiefly by the lamps, but also the optical parts of the luminaires and ballasts, are the most significant causes of greenhouse gas emissions. Figure 29 shows an example of LEDification in Cascais [27].

Figure 29: Cascais, Portugal LED lighting results [28]

7.3 Municipality of Župa Dubrovačka (Croatia)

The Municipality of Župa Dubrovačka is situated in the county of Dubrovnik-Neretva in the south-east of Croatia. Situated on the Mediterranean coast. The Municipality covers an area of approximately 23 km², includes 16 towns and has a population of 6,663 people. In September 2014, the Municipality introduced a Sustainable Energy Action Plan (SEAP) which was established as part of the Covenant of Mayors initiative. The SEAP provides the Municipality with stronger leverage when they wish to implement a green public procurement (GPP) procedure. Figure 30 illustrates lightning at dusk in Župa Dubrovačka.

Figure 30: Župa Dubrovačka [29]

By changing to an LED lighting solution, the Municipality was able to significantly reduce its energy consumption in comparison to the previous street lighting system, where high pressure mercury lamps were used. The municipality calculated the energy and CO_2 emissions saved using the GPP 2020 methodology with an assumed lifetime of 25 years. This calculation was based on the 686 newly installed LED lamps and produced the following results: The new LED lighting solution consumes 210,000 kWh per year and emits 64 tonnes of CO_2 per year. In comparison to the previous system, which was consuming 330,000 kWh and emitting an average of 100 tonnes of CO_2 a year, the new LED lighting solution has reduced the CO_2 emissions (from street lighting) by 36%, saving the equivalent of 900 tonnes of CO_2 over a 25-year period. Financially, the new LED lighting solution is saving the municipality approximately 13,800 Euro a year at today's energy price (currently 0.115 euro per kWh for street lighting). This figure does not include the savings made from the reduced need to service light fixtures. The new solution is programmed so that the lamps do not switch on until visibility reaches the minimum illumination level for street lightning required by law in Croatia. Furthermore, the new solution reduces the power (wattage) and energy consumption in accordance with the intensity of natural lighting by an automatic controller regulation, which is installed in the system [27].

7.4 MUNICIPALITY OF BUDAPEST, HUNGARY

In practice, Liberty Bridge is one of the key crossing points over the Danube, and an iconic site within central Budapest. The city's master lighting plan included the illumination of a number of bridges, in order to allow safe transit while creating visually attractive landmarks at night. In 2009 a procurement process was launched to install lighting that would fit the aesthetics of the bridge, allow for the safe transit of trams, cars and pedestrians and withstand humidity and heavy vibrations. The sustainability and cost of the lighting solution were key concerns for the city.

Figure 31: Budapest [30]

More than 800 light fittings were installed to provide Liberty Bridge's ornamental lighting (see Figure 31), 584 of which are LED lights. This amounts to installed power of 40.7 kilowatts, of which the LEDs account for 13.1 kilowatts. The project was carried out in 2009 at a cost of €1.66 million. The estimated life expectancy of the ornamental lighting installed is 15 years and 30 years for the street lighting. This longer lifespan means lower replacement rates, bringing considerable direct and indirect economic benefits and reduced waste. Replacing the lamps is difficult and costly due to their mounting on the bridge and the disruption to traffic, and these costs have been avoided. The savings on electricity compared with the original concept (which used halogen lighting) are estimated at 40,000 Euros per annum, with total savings of 100.000 Euro per annum [27].

7.5 City of Rotterdam (The Netherlands)

The City of Rotterdam (see Figure 32) is the second largest city in The Netherlands and has a population of approximately 610,000 people. The city has a lighting plan in place since 2012. The primary task of public lighting is to guarantee traffic safety on the streets and community safety in the public domain. The lighting plan accommodates the following three specific policy ambitions of the municipal government:

1. To achieve a better design-quality of both dayscape and nightscape in order to improve public space;

2. To achieve more efficient maintenance by introducing standardization in lighting equipment and poles;

3. To reduce energy levels and light pollution by applying technological innovations which contribute to sustainability on a citywide scale.

Figure 32: Rotterdam [31]

The City of Rotterdam published a tender in 2012 for the purchase of standard lighting fixtures for the whole city for the period 2013 to 2020. After the registration and evaluation of the delivered documents and samples, six suppliers were admitted to the e-auction. The result of this tendering procedure with an e-auction was that contracts were concluded with two suppliers (one supplier won two lots). The prices of the LED fixtures were almost the same as previously paid for conventional light fittings, with the advantage of providing optimum performance in the field of lighting, energy consumption and social return. Energy savings will depend on the deployment of the fixtures across the city, with priority given to replacing existing sodium fixtures with higher energy consumption where the savings can be up to 35%.

Depending on the use of the fixtures and deployment, the contract value will be between 8-10 million euros. From 2012 (the baseline year before the framework agreement began) to 2015, the energy consumption from street lighting reduced from 25.6 million kWh per year (2012 baseline figure) to 23.2 million kWh per year, resulting in a cumulative saving of 1,262 tonnes of CO_2e in the period [27].

References

[1] Lighting Europe Secretariat, "Strategic Roadmap 2025 of the European Lighting Industry," 2016.

[2] Sei Ping Lau , Geoff V. Merrett, Alex S. Weddell, Neil M. White, "A traffic-aware street lighting scheme for Smart Cities using autonomous networked sensors," *Computers and Electrical Engineering,* vol. 45, p. 192–207, 2015.

[3] Enrico Petritoli , Fabio Leccese , Stefano Pizzuti , Francesco Pieroni, "Smart lighting as basic building block of smart city: An energy performance comparative case study," *Measurement,* vol. 136 , p. 466–477, 2019.

[4] Suntiti Yoomak, Chaiyan Jettanasen, Atthapol Ngaopitakkul, Sulee Bunjongjit,, "Comparative study of lighting quality and power quality for LED andHPS luminaires in a roadway lighting system," *Energy and Buildings,* vol. 159, p. 542–557, 2018.

[5] UN Environment – Global Environment Facility | United for Efficiency (U4E), "Accelerating the Global Adoption of ENERGY-EFFICIENT LIGHTING," U4E POLICY GUIDE SERIES, 2017.

[6] "www.warehouse-lighting.com," 2018. [Online]. Available: www.warehouse-lighting.com/how-does-led-lighting-reduce-co2-emissions.aspx. [Accessed 11 2 2019].

[7] "https://www.hinton.ca/890/LED-Streetlights," [Online].

[8] "https://blog.energytrust.org/cities-take-savings-to-the-streets/," [Online].

[9] Premium Light pro Consertium, "LED Street Lighting Procurement & Design," Österreichische Energieagentur – Austrian Energy Agency, 2017.

[10] Sei Ping Lau ; Geoff V. Merrett ; Neil M. White, "Energy-efficient street lighting through embedded adaptive intelligence," in *International Conference on Advanced Logistics and Transport*, Sousse, Tunisia, 2013.

[11] Kati Brocka, Elke den Ouden, Kees van der Klauw, Ksenia Podoynitsyna, Fred Langerak, "Light the way for smart cities: Lessons from Philips Lighting," *Technological Forecasting & Social Change,* pp. article in press, https://doi.org/10.1016/j.techfore.2018.07.021, 2018.

[12] "https://intelilight.eu/worlds-first-lora-street-lighting-control-solution-released-flashnet/," [Online].

[13] "Smart lighting: The way forward? Reviewing the past to shape the future," *Energy and Buildings,* vol. 149 , p. 180–191, 2017.

[14] "https://sensus.com/solutions/smart-lighting-infographic/," [Online].

[15] Juan F. De Paz , Javier Bajo b, Sara Rodríguez , Gabriel Villarrubia , Juan M. Corchado, "Intelligent system for lighting control in smart cities," *Information Sciences ,* vol. 372 , p. 241–255, 2016.

[16] Raffaele Carli , Mariagrazia Dotoli , Roberta Pellegrino, "A decision-making tool for energy efficiency optimization of street lighting," *Computers and Operations Research ,* vol. 96, p. 222–234, 2018.

[17] Eveliina Juntunena, Esa-Matti Sarjanoja, Juho Eskeli,, "Smart and dynamic route lighting control based on movement tracking," *Building and Environment,* vol. 142, p. 472–483, 2018.

[18] Andras Kovacs a,Roland Batai b, Balazs Csanad Csaji a, Peter Dudas b, Borbala Hay, "Intelligent control for energy-positive street lighting," *Energy,* vol. 114, pp. 40-51, 2016.

[19] "http://www.maceraoyunlari.org/solar-panel-lights/," [Online].

[20] "http://conxcorp.com/off-the-grid-program/," [Online].

[21] "https://dx3solarlighting.com/why-solar/," [Online].

[22] "http://conxcorp.com/off-the-grid-program/," [Online].

[23] Lutz Thomas , Ritzer Markus, "Reliability and lifetime of LEDs," Osrom optp Semicpnductors, 2018.

[24] KR Shailesh , CP Kurian , SG Kini, "Understanding the reliability of LED luminaires," *Lighting Res. Technology,* vol. 50, p. 1179–1197, 2018.

[25] Next Generation Lighting Industry Alliance LED Systems Reliability Consortium, "LED LUMINAIRE LIFETIME: RECOMMENDATIONS FOR TESTING AND REPORTING," U.S. Department of Energy, THIRD EDITION, SEPTEMBER 2014.

[26] "http://www.lighting.philips.com," 11 02 2019. [Online].

[27] "http://ec.europa.eu/environment/gpp/case_group_en.htm," [Online]. [Accessed 31 03 2019].

[28] "https://www.arquiled.com/en/project/led-street-lighting-cascais-boardwalk/," [Online].

[29] "https://www.jetsetter.com/," [Online]. [Accessed 04 08 2020].

[30] Yong Hwi Kim, Yong Yi Lee, Bilal Ahmed, Moon Gu Son, Junho Choi, Jong Hun Lee, Kwan H. Lee, "MudGet: Reproduction of the desired lighting environment using a smart-LED," *Journal of Computational Design and Engineering,* vol. 4, p. 231–237, 2017.

[31] Francesco Marinoa, Fabio Leccesea, Stefano Pizzutib, "Adaptive street lighting predictive control," in *8th International Conference on Sustainability in Energy and Buildings*, Turin,Italy, 2016.

[32] M Indra al Irsyad , RabindraNepal, "A survey based approach to estimating the benefits of energy efficiency improvementsinstreetlightingsystemsinIndonesia," *Renewable and Sustainable Energy Reviews ,* vol. 58, p. 1569–1577, 2016.

[33] Raffaele Carli, Mariagrazia Dotoli, Edmondo Cianci, "An optimization tool for energy efficiency of street lighting systems in smart cities," in *IFAC*, 2017.

[34] Wojnicki, Leszek Kotulski, Adam S¸edziwy, Sebastian Ernst, "Application of distributed graph transformations to automated generation of control patterns for intelligent lighting systems," *Journal of Computational Science,* vol. 23, p. 20–30, 2017.

[35] Dong Jina, Christopher Hannona, Zhiyi Li, Pablo Cortes, Srinivasan Ramaraju, "Smart street lighting system: A platform for innovative smart city applications and a new frontier for cyber-security," *The Electricity Journal ,* vol. 29 , p. 28–35, 2016.

[36] A. Peña-García, Hurtado, Aguilar-Luzón, "Impact of public lighting on pedestrians' perception of safety and well-being," *Safety Science,* vol. 78, p. 142–148, 2015.

[37] M. Beccali , M. Bonomolo , F. Leccese, D. Lista, G. Salvadori, "On the impact of safety requirements, energy prices and investment costs in street lighting refurbishment design," *Energy ,* vol. 165 , pp. 739-759, 2018.

[38] Dong Jina, Christopher Hannon, Zhiyi Li, Pablo Cortes, Srinivasan Ramaraju, "Smart street lighting system: A platform for innovative smart city applications and a new frontier for cyber-security," *The Electricity Journal ,* vol. 29, pp. 28-35, 2016.

[39] Jiahong Liua, Chao Mei, Hao Wang, Weiwei Shao, "Powering an island system by renewable energy—A feasibility analysis in the Maldives," *Applied Energy ,* vol. 227, p. 18–27, 2018.

[40] "http://gmk.com.sg/blog/impact-and-facts-led-lights/," [Online]. [Accessed 1 4 2019].

[41] "LED Luminaire Reliability," US Department of Energy, Energy Efficiency and Renewable Energy, 2018.

[42] "https://www.eprmagazine.com/features/powering-the-smart-cities-with-intelligent-lighting/," [Online].

[43] Hsueh-Ming Wang, Oleg Bukhtiyarov, Jimmy Chen, "Reliability analysis of LED based streetlights on the temperature effect".

[44] "https://www.iluxz.com/blog/led-luminaire-reliability/," [Online].