UNIVERSIDADE DE LISBOA
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Lumisol: a contribution to solar street lighting in developing countries

Rita Hogan Teves de Almeida

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Dissertação de Mestrado Integrado em Engenharia da Energia e do Ambiente

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Trabalho realizado sob a supervisão de

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Abstract

In 2011, 1.3 billion people did not have access to electricity, mainly in Sub-Saharan Africa and South Asia. In addition, in Sub-Saharan Africa, around 75 million people lived with an unreliable grid. This thesis intends to contribute positively to the development of these regions through the introduction of street lighting systems in these low income communities.

Two products were developed: a stand-alone street light system (suitable for off-grid population) and a grid connected system (to overcome the problem of grid unreliability). Both systems were developed according to European Street Lighting Standards through the use of DIAlux software. The "worst month" method was used to size the stand-alone system. For grid connected systems, a daily failure of 3 hours was considered. All the components used in both systems are available in the Portuguese market. Regarding stand-alone system a prototype has been tested since late July at Faculdade de Ciências, Universidade de Lisboa. Additionally, a performance analysis across the African continent was done. The stand-alone prototype has been working in accordance with our expectation. The grid connected system has not been tested, however it has a high potential to overcome the problem of unreliable grid despite entailing a higher investment than the one corresponding to typical luminaires.

Concerning the marketing plan, an extrapolation from Bambadinca, Guinea-Bissau, was done. Accordingly, the needed number of poles per person ranges between 0.18 and 0.26, while the needed number of poles per household ranges between 1.14 and 1.64. Considering a market share of 5% in Guinea-Bissau, Mozambique and Uganda, the number of necessary poles ranges between 482.3 and 693.0 thousand. In addition, taking also into account 2% of Kenya and Tanzania markets, the number of poles for the cheapest option increases to 754.6 thousand poles and for the most expensive option to 1,084.2 thousand poles.

Keywords: Street lighting systems, EN 13201, Developing countries, PV solar energy, Rural electrification

Resumo

Em 2011, 1.3 mil milhões de pessoas não tinham acesso à eletricidade, principalmente na África Sub-Sahariana e no Sul da Ásia. Adicionalmente, na África Sub-Sahariana, cerca de 75 milhões de pessoas vivem com uma rede elétrica pouco confiável. Esta tese pretende contribuir positivamente para o desenvolvimento destas regiões através da introdução de sistemas de iluminação pública nestas comunidades.

Dois produtos foram desenvolvidos: um sistema de iluminação pública isolado da rede (ideal para populações sem acesso a esta) e um sistema para conexão à rede (para solucionar o problema de fiabilidade). Ambos os sistemas foram desenvolvidos de acordo com as Normas Europeias de Iluminação Pública através do uso do software DIAlux. O método do "pior mês" foi utilizado no dimensionamento do sistema isolado. No caso do sistema conectado à rede considerou-se uma falha diária de 3 horas. Todos os componentes utilizados em ambos os sistemas estão disponíveis no mercado português. Em relação ao sistema isolado, um protótipo está a ser testado desde o final de Julho na Faculdade de Ciências, Universidade de Lisboa. Adicionalmente, uma análise de performance ao longo do continente africano foi feita. O protótipo tem estado a trabalhar de acordo com o esperado. O sistema conectado à rede não foi testado, porém tem um elevado potencial para superar os problemas de falta de fiabilidade da rede, apesar de implicar um elevado investimento quando comparado com luminárias típicas.

Em relação ao plano de mercado, uma extrapolação de Bambadinca, Guiné-Bissau, foi realizada. O número de postes por pessoa varia entre 0.18 e 0.26, enquanto o número por casa varia entre 1.14 e 1.64. Considerando uma quota de mercado de 5% na Guiné-Bissau, Moçambique e Uganda, o número de postes varia entre 482.3 e 693.0 mil. Se se acrescentar 2% do mercado do Quénia e da Tanzânia, este valor irá aumentar para 754.6 mil, para a opção mais barata, e para 1,084.2 mil postes, para a mais dispensiosa.

Palavras chave: Sistemas de iluminação pública, EN 13201, Países em desenvolvimento, Energia solar fotovoltaica, Eletrificação rural

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List of Acronyms

AC	Alternate Current
CEN	European Committee for Standardization (Comité Européen de Normalisation, in French)
CFD	Compact Fluorescent Lamp
CIE	International Commission on Illumination (Commission Internationale de L'Eclairage, in French)
D	Power Density
DC	Direct Current
DOD	Deep of Discharge
ECly	Energy Consumption Indicator
EN	European Standards
FCUL	Faculty of Sciences, University of Lisbon
GMF	Global Maintenance Factor
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HID	High-intensity Discharge
IDE	Energy Development Index
IEA	International Energy Agency
IP	Ingress Protection
LED	Light Emitting Diode
MEPI	Multi-dimensional Energy Poverty Index
MFL	Maintenance Factor of Luminaire
MFLB	Maintenance Factor of Lamp Brightness
NGO	Non Governmental Organization
PV	Photovoltaic(s)
PVGIS	Photovoltaic Geographic Information System
PWM	Pulse-Width Modulation
RGB	Red, Green and Blue
RoHS	Restriction of Certain Hazardous Substances use
RTC	Real Time Clock
RVE.Sol	Rural Village Energy Solutions
SFL	Survival Factor of Lamp
SHS	Solar Home System
SLS	Street Lighting Systems
SOC	State of Charge
SWOT	Strengths, Weaknesses, Opportunities and Threats
UF	Utilization Factor
VRLA	Valve Regulated Lead-Acid

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1 Introduction

Access to modern energy is vital to achieve many development goals related to poverty, health, education, equality and environmental sustainability. However, in 2011, 1.3 billion people (or 18% of the world population) did not have access to electricity, and 95% of this total was from Sub-Saharan Africa and developing Asia (Table 1) [1].

The New Policies Scenario projects that the number of people without access to electricity will decline to around 970 million in 2030 (12% of the world population), as can be seen in Table 1. Sub-Saharan Africa is the only region where the number of people without access to electricity will increase between 2011 and 2030, as a consequence of the simple fact that electrification rate is, in general, lower than population growth rate in the countries located in this region. This will happen because in these low income countries development policies are not so effective as in other countries such as China (that has several electrification projects) or Brazil (that has a National Program called "Luz para Todos" or Light for All, which pretends to achieve universal access in the next few years). By 2030 Middle East, Latin America and China are expected to have universal access to electricity and by the previous reasons it is believed that China and Brazil will achieve this target earlier. In what concerns sub-Saharan Africa electrification rate will probably be a little bit higher than 50% by 2030 [1].

	Number of people without access to electricity (million)		Share of population without access to electricity (%)	
	2011	**2030**	**2011**	**2030**
Developing countries	1257	969	---	---
Africa	600	645	---	52
Sub-Saharan Africa	599	645	---	52
Developing Asia	615	324	---	---
China	3	0	~100	100
India	306	147	75	87
Latin America	24	0	95	100
Middle East	19	0	90	100
World	1258	969	---	---

Table 1 - Number of people (million) and share of population without access to electricity by region in the New Policies Scenario, 2011 and 2030 (adapted from [1])

To accomplish the previous projections, a combination of on-grid, mini-grid and off-grid solutions are considered. In each region the decision about the most suited solution is based on regional costs and consumer density to determine regional costs per megawatt-hour. On-grid is in general the cheapest option but grid extension and transmission losses must be taken into account. This study concludes that grid extension is the most suitable solution for all urban areas and around 30% of rural areas. The remaining rural areas are expected to be better served by mini-grids (65%) and off-grid solutions (35%) [1].

In addition, United Nations created a Programme, Sustainable Energy for All, focused on the goal of achieving three objectives: universal energy access, renewable energy and energy efficiency. This programme was signed by 80 countries with the more ambitious goal of achieving universal access to modern energy by 2030 [2].

Sub-Saharan Africa deserves a special attention in this context since, as mentioned above, this region is expected to be the last one in the world that will be fully served by electricity. In this region by 2010 589 million people had no access to electricity, corresponding to an electrification rate of about 32% (about 64% in urban areas and 13% in rural areas) [3]. Although, even in this region, different electrification realities occurred by 2010 (Figure 1). For example, while Mauritius had almost universal electricity access, Malawi and Uganda had electrification rates lower than 10%. If we look for rural electrification, only Mauritius and South Africa surpass a rate of 50% and almost half of the countries have rural electrifications rates below 10%. It can be seen that rural electrification rate is lower than urban in all cases, and that the majority of the countries had electrification rates below 50% (exceptions are Cote d'Ivoire, Gabon, Ghana, Mauritius, Nigeria, Senegal and South Africa).

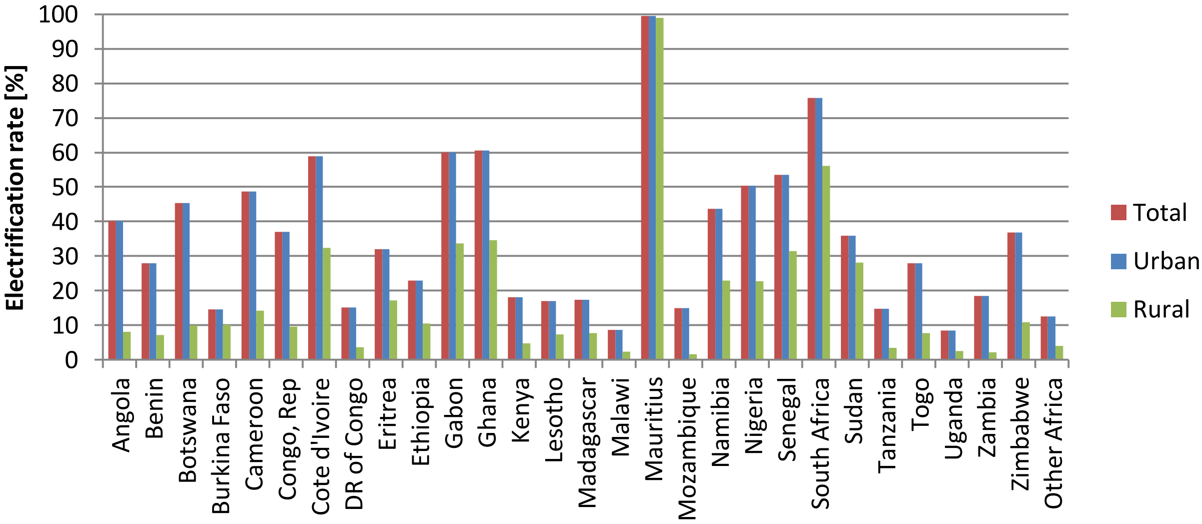

Figure 1 - Electrification rate in Sub-Saharan Africa countries, in 2010 (adapted from [3])

Two additional sets of data related to energy access in sub-Saharan Africa are available through United Nations' inter-agency mechanism on energy issues: Multi-dimensional Energy Poverty Index (MEPI) and Energy Development Index (EDI) [4]. The first one is a tool to evaluate energy related deprivations, which is composed of two components: a measure of the incidence of energy poverty[1], and a quantification of its intensity. EDI, developed by International Energy Agency (IEA) may be used to understand the role energy plays in human development, measuring energy development at household level (access to electricity and to clean cooking facilities) and community level (modern energy use in public services, such as schools, hospitals and street lighting), as can be seen in Figure 2. Available data shows that sub-Saharan Africa countries dominate the lower half of the ranking. These countries have a low contribution from clean cooking and public service indicators [5].

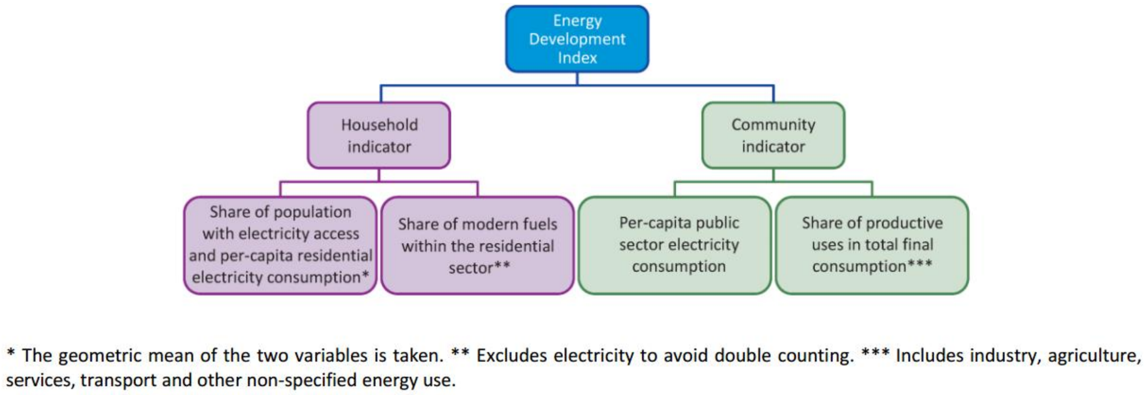

Figure 2 - Components of the Energy Development Index [5]

As previously mentioned, EDI calculation for each country or region takes into account street lighting. This shows that street lighting may be considered a measure of the quality of life [5],

[1] Energy poverty is a lack of access to modern energy services

[6] and this is one of the motivations for this work, that is focused on low cost street lighting specially suited for low income countries. In this context, our main goal was the development of two products: a stand-alone solar street light (based on a previous one developed at FCUL [7]) and a grid connected street light that includes an energy storing system, to overcome the problem of grid unreliability that is typical in these regions.

This document includes: *i)* a brief review of street lighting state the art (chapter 2) *ii)* a stand-alone solar street light product development, which include remote monitoring, cost and economic analysis and product performance analysis across Africa (chapter 3) *iii)* a grid connected street light system (chapter 3) *iv)* a market plan for both products (chapter 4) and *v)* conclusions and recommendations for future work (chapter 5).

2 Street Lighting

Street lighting is a public good benefit that enhances safety, comfort, commercial prosperity, and socialization [8]. Safety and security increase not only because criminal activities are easily detected and prevented but also because traffic accidents decrease. Commercial prosperity occurs as a consequence of higher productivity and extension of marketplace hours. Socialization will also increase with street lighting because an illuminated village invites people to the streets and contributes to a decrease of rural exodus.

There are 3 main objectives to achieve with street lighting [9]:

1. To allow all street users to proceed safely (motorised traffic vehicles, slow moving vehicles, cyclists, pedestrians and animal drawn vehicles)
2. To allow pedestrians to see hazards, orientate themselves, recognize other pedestrians and give them a sense of security
3. To improve day and night time appearance of the environment

Usually, street lighting is supported by a public entity (government, municipality, or other) that should purchase the equipment. Users have the responsibility of using it properly and report operational issues to the contractor [8]. In some countries, street lighting is a public responsibility while in others all the taxpayers contribute to street lighting, and finally in others just some of them pay for it. For example, in Portugal, municipalities have to pay for street lighting [10], in Ghana urban communities and companies contribute with some extra payments or taxes for street lighting (as well as rural electrification projects) [11], and in Sudan the group of families in the vicinity of each light are supposed to cover their cost (if not, the light is moved) [12].

Street lighting systems consumes 43.9 billion kWh of electricity every year all over the world [13]. For example, Peninsular Malaysia used 876.3 GWh of power for public lighting during 2006 (which corresponds to 1.07% of Peninsular Malaysia electric demand) [6]. Regardless of who pays for street light, a bet in energy efficiency is essential because energy efficient technologies and designs can reduce street lighting costs substantially. This may help municipalities to expand their services by providing lighting in low income and other underserved areas [14].

Some recommendations related to street light strategies should help to accomplish optimal lighting solutions [15]. These recommendations are divided in recommendations for energy savings and recommendations resulting from user needs.

The first group of recommendations are [15]:

1. Prior to reconstruction of street lighting a choice between an upgrade and redesign should be made.
2. Special attention should be paid to the determination of the street lighting class.
3. Measurements for determining the road surface reflection properties are recommended.
4. If high-pressure sodium (HPS) lamps are applied, they should be used with improved photometric and technical characteristics.
5. Luminaires which are efficient, easy to handle, and with the degree of protection of at least IP65[2] are recommended.
6. It is very important to use the correct value of maintenance factor in the design process.
7. Luminaires characterized by a power factor of at least 0.95 are recommended.
8. The use of dimming system is recommended .

[2] IP stands for Ingress Protection. An electrical equipment often has an IP rating. The numbers after it gives information about the amount of protection that each product has against dust (first digit) and fluid (second digit). In this case, number 6 means dust-tight and number 5 means protected against water jets (“AXIS Communication,” [Online]. Available: http://www.axis.com/products/cam_housing/ip65.htm. [Accessed 24 6 2014])

Recommendations resulting from user needs are [15]:

1. Places where people gather and places with intensive pedestrian activity should be illuminated by white light sources characterized by excellent colour rendering.
2. Dark areas should be avoided.
3. The effects of obtrusive light should be minimized.
4. Position, size and design of the pole and luminaire should not stand out from the environment.
5. Full galvanized steel poles should be used instead of painted ones.

In all street lighting systems (SLSs) the lamp is the main component. Different light sources can be used in SLS, that can be divided into 4 groups [16]: incandescent, fluorescent, high-intensity discharge (HID) and light emitting diode (LED) lamps. In street lighting HID (which includes HPS), induction and LED lamps are the most commonly used [17]. In the next subchapter an introduction to HID and LED lamps will be presented.

The type of connection and energy source is also an important aspect. SLSs can be on-grid or off-grid. The first one is the most commonly used in the world (mainly in developed countries). Off-grid or stand-alone street lighting appears to fulfil and be the best solution to rural or remote areas needs. In these places, a grid connection does not exist, grid extension cost is exorbitant, and inaccessibility is a huge problem. A World Bank study proves that on rural electrification programs the average cost of grid extension varies between US$5,000 and US$10,000 per km in "normal" terrains and between US$19,000 and US$22,000 per km in difficult terrains [6]. This is obviously a huge contribution to street lighting investment costs in remote areas.

In addition to this cost in developing countries the majority of SLSs are assembled with poor quality components, and no lighting requirements are taken into account. This usually results in oversizing, no maintenance, vandalism and poor lighting. These facts, combined with unstable and limited diesel powered grids, high environmental temperatures and low electrification levels, offer several challenges to this market [18].

Different energy sources are used to power street lighting. In grid connected systems, the energy used comes from the grid. In stand-alone systems, photovoltaic, wind and diesel generators are the most commonly used energy sources. Each one of these sources may be used alone or in a combination that includes two or three sources. Models based on renewable energy sources are the ideal ones because they contribute to the sustainability lowering the running costs and being environmentally friendlier. In these regions it is especially important that running costs (like fuel) are minimized, or even eliminated, if one expects any kind of maintenance to be done. The main drawbacks of these systems are: the fact that renewable energy sources always present a variability; the correct choice of the best solution in a given place must be accessed through a careful analysis of local conditions[3]; and also the fact that energy production will not be in general synchronized with demand and thus a battery bank is always necessary for energy storage.

2.1 Types of Light Sources

As mentioned above, different types of light sources are available on the market. For street lighting applications the most commonly used are HID and LED. These two types of light sources will know be briefly presented.

High-intensity discharge light sources can be divided in four types: metal halide, high-pressure sodium, low-pressure sodium and mercury vapour. The light production technique is similar to

[3] For example in Peninsular Malaysia, PV systems work better than PV/wind ones because wind resource is limited [6]. On the other hand, in hybrid systems that had been tested in Denmark it is possible to see that the wind component is much more important than the solar one [58].

the one used in fluorescent lamps but here visible light is produced, and so there is no need for the phosphor coating. The bulb is made from a quartz or ceramic glass envelope (Figure 3). This envelope provides a stable thermal environment for the arc tube, and the atmosphere inside it prevents the electrodes oxidation, and also reduces the amount of UV radiation emitted by the lamp [16],[19].

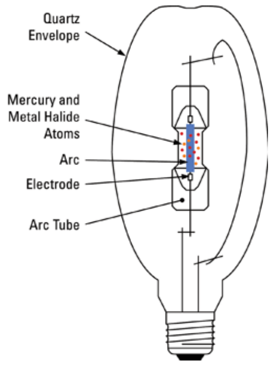

Figure 3 - HID lamp [19]

HID bulbs produce light when an electric arc passes between the electrodes in the pressurized arc tube, causing metallic additives to vaporize. Arc tube contains a mixture of argon, mercury, and metal halide salts. A high voltage pulse is applied to the electrodes to ionize the gas. When the gas is fully ionized, an arc is created and current (limited by the ballast) flows across the tube. As the pressure and temperature inside the tube increase, the materials within the arc tube vaporize, and light is emitted in the form of visible light (and UV). Because HID lamps require a high voltage for ignition, a current limitation during warm-up, and a constant power while running, the existence of electronic ballast is needed. Ignition time ranges between 1 and 15 microseconds. After ignition the lamp voltage drops quickly due to low lamp impedance after discharge starting, whilst the current increases to a significant value (ballast avoids a short circuit occurrence). During the period of lamp warming up (the warm up time ranges between 1 and 4 minutes for pulse-start technology and 2 and 15 for probe-start), the current decreases and the voltage increases. This second effect is bigger than the first one resulting in a power increase during this period. Eventually lamp voltage reaches its nominal value and the power is regulated to a constant level (see Figure 4) [16], [19], [20].

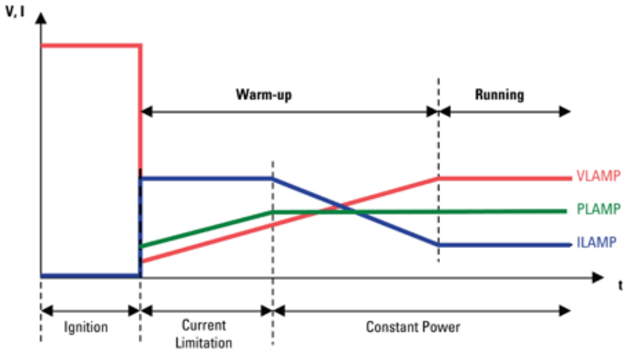

Figure 4 - HID lamp mode [19]

These HID lamps have long lifetime and are extremely energy efficient, but they do not produce pleasing light colours (exception for metal halides). They are most commonly used for outdoor security and area lighting [16].

Light Emitting Diodes (LED) as well as organic light-emitting diode (OLED) and polymer light-emitting diode (PLED) belong to the group of solid-state lighting (SSL). SSL systems produce light when current is passed through a pn junction, causing electrons and holes to recombine and generate the emission of photons. The radiation emitted in this process in a given pn junction is essentially monochromatic, presenting a colour that depends on the energy gap through which the electron-hole recombination process occurs. LEDs are commonly made from aluminium-gallium-arsenide (AlGaAs) based pn junctions [16], [17], [21]. White LED light can be obtained in two different ways: by a combination of phosphor excited by blue or UV LED emission, or by a mixture of multi-colour LEDs (RGB[4]). The last option has a lower efficiency due to the power loss in the down conversion process [22]. A single light LED bulb is a combination of different LEDs [16]. In the present work, LEDs will be used mainly because they are the most energy efficient light source, and because these light sources are easily controlled through dimming.

LEDs are on the streets since the early 90s, when cities throughout Europe and USA started replacing incandescent-based traffic lights by LEDS. The market share of LEDs has continued to grow in the field of street lighting, and it is expected that this type of light source will dominate in the future, at the expense of high intensity discharge street lamps [23]. If properly used, LEDs present lifetimes of 10 to 15 years, which is equivalent to more or less 60,000 working hours (that is at least 3 times higher than current technologies), offer energy savings that can achieve 50%, and have a low environmental impact (it is a RoHS[5] compliant product). They also reduce light pollution (better light distribution by the ability to precisely control light direction through optical optimization), have better colour rendering and colour temperature, and lower power consumption (higher efficacy (in lm/W), more lux per Watt). Moreover, LEDs have a lower operating and maintenance cost (O&M) mainly because they offer a reduction in energy use as well as a higher lifetime. Thus, the return on investment (ROI) for new equipment based on this technology will be faster, even with higher initial cost as still happens today.

It is important to stress that accomplishing the standard regulations for luminance level and uniformity is easier to achieve using LED street lamps than with conventional lamps. LEDs have also a dimming option that allows an adjustment of power using intelligent systems, which will reduce, even further, energy consumption and light pollution, as well as a quick turn on/off (because the problem with hot ignition is eliminated) [24]. With respect to nocturnal insects, LEDs have also a big advantage: LEDs emit light in a small peak in a blue range and smaller than conventional light sources in the green range; since insects are attracted to the emission of UV-blue and green light they will be less attracted by a LED light source. In addition, as LED can reduce power consumption in lighting, cooper wire of transmission lines can also be reduced [23], [24], [25].

Nevertheless, LEDs also have some disadvantages, namely, high investment cost, the need for a driver and for a heat sink [20]. These needs appear because LEDs are greatly influenced by electric failures and temperature [17]. Furthermore, failures have been identified in at least one of four functional aspects of luminaire design and manufacturing using this type of light sources: power management, thermal management, optical management and luminaire assembly integrity. Power management should ensure that the power delivered to the LED is appropriately sized and filtered. Thermal management should guarantee that heat generated by 1the LED is removed in order to keep the pn junction temperature within the acceptable range. Optical management should ensure that light output is correctly shaped and directed through the desired surface. Assembly integrity should ensure that luminaire housing design and materials must provide sufficient protection for the LEDs according to the anticipated working environments [26].

In the next figure it is possible to see the frequency of different failures that have been documented for a family of outdoor luminaires. 5,400 systems were analysed and the number of failures was 29 (the systems have not yet reached its lifetime) [26].

[4] **R**ed, **G**reen and **B**lue

[5] Restriction of Certain Hazardous Substances use

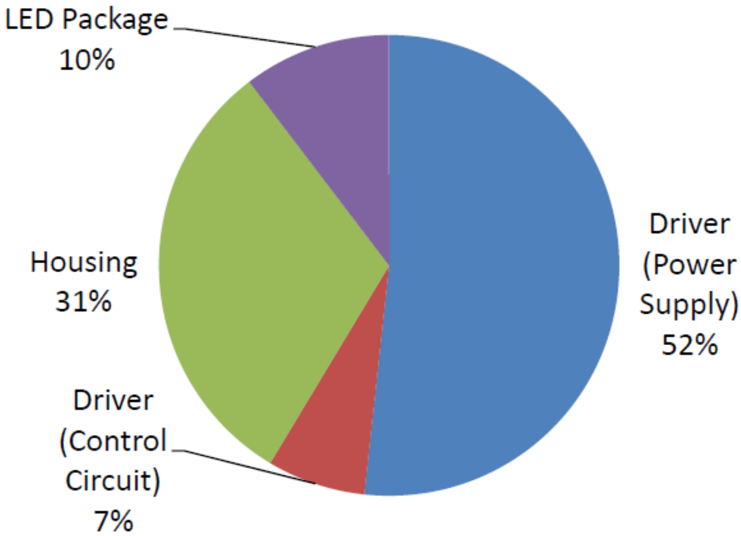

Figure 5 - Distribution of the 29 failures in 34,000 operating hours for a family of outdoor luminaires [26]

The result of comparative studies on energy efficiency use by LED/mercury lamps and LED/sodium lamps is summarized in Table 2 [25].

Table 2 - Energy saving: LED vs. sodium and LED vs. mercury lamps [25]

Brand new performance	Sodium	LED	Mercury	LED
1. Lamp efficacy, η_L (lm/W)	120	72	65	72
2. Luminaire efficiency, η_F = η_2 × η_p	0.595	0.72	0.595	0.72
-secondary optics efficiency, η_2	0.7	0.85	0.7	0.85
-power supply efficiency, η_p	0.85	0.85	0.85	0.85
3. Lighting-to-target effectiveness, η_R	0.4	0.85	0.4	0.85
4. overall lighting efficiency for brand new luminaire, e_o = η_L × η_F × η_R (lm/W)	28.6	44.2	15.5	44.2
-power consumption per net illuminance to target, p_o = 1/e_o (W/lm)	0.035	0.023	0.065	0.023
Energy saving = [p_o(HID) − p_o(LED)]/ p_o(HID)	–	35.4%	–	65.0%
Lifetime performance				
5. luminaire maintenance factor, Cm	0.7	0.8	0.7	0.8
6. Lifetime decayed illuminance, η_D	0.4	0.7	0.4	0.7
-lifetime, yr	3	10	3	10
-lifetime-average light decay, η_Da = η_D + (1 − η_D)/2	0.7	0.85	0.7	0.85
7. Lifetime-average overall lighting efficiency, e_LCYC = e_o × Cm × η_Da (lm/W)	14.0	30.1	7.6	30.1
-lifetime-average power consumption per net illuminance to target, p_e = 1/e_LCYC (W/lm)	0.071	0.033	0.132	0.033
Lifetime energy saving = [p_e(HID) − p_e(LED)]/p_e(HID)	–	53.5%	–	74.8%

It can be seen that the energy savings of LEDs lamps is mainly due to its lighting-to-target effectiveness and low light degradation over lifetime. LEDs can save about 75% energy when compared to mercury lamps.

The same study [25] includes an installation cost comparison of 10 km roadway lighting with 2 lanes installed 30 m apart in tow staggered rows for LED using grid and solar-powered, and a grid-powered mercury lamp.

Table 3 - Installation cost comparison of 10 km roadway lighting

Roadway distance (km)	10					
Number of lamps installed	667, 30 m apart in tow staggered rows					
Type of lighting design	Grid-powered LED		Mercury lamp		Solar-powered LED	
	Unit price, $	subtotal	Unit price, $	subtotal	Unit price, $	subtotal
Lamp cost, $	1000	666,667	60	40,000	1000	666,667
Power generator cost, $	$400/kW	30,651	$400/kW	93,333	0	0
Power line cost, $		448,000		608,000		100,000
PVC pipe cost, $		180,000		180,000		40,179
Transformer station cost, $	11,000	29,700	11,000	59,400	0	0
Light pole, $	300	200,000	300	200,000	300	200,000
Solar PV per W LED, Wp	–		–		2.5	
Total solar PV installation, kWp	–		–		167	
Solar PV price, $/Wp	–		–		5	
Total solar PV module cost, $	–		–		833,333	
Battery cost, $	–		–		300	200,000
Controller cost, $	–		–		500	333,333
PV module poles, $	–		–		300	200,000
Civil construction and installation, $	1000	666,667	1000	666,667	700	466,667
Other, 2%	2%	17,767	2%	22,815	2%	34,137
Freight, 1%	1%	8844	1%	11,407	1%	16,667
Total installation cost, USD	2,248,335		1,881,622		3,090,982	

It is possible to see that the total installation cost for grid-powered LED is 2.248 million USD, while for solar-powered LED is 3.091 million USD. Mercury lamp has the lower installation cost, 1.882 million USD, due to LED lamp and solar PV costs. In the next table a cost/effectiveness comparison is done. The payback time for the excess investment of LED solutions is 2.2 years for grid-powered LED and 3.3 for solar-powered.

Table 4 - Cost/ effectiveness comparison of 10 km roadway lighting

Roadway distance (km)	10		
Number of lamps installed	667, 30 m apart in tow staggered rows		
Type of lighting design	Grid-powered LED	Mercury lamp	Solar-powered LED
Lighting power per lamp, W	100	400	100
Total power consumption, kW	77	267	67
Total installation cost, USD	2,248,335	1,881,622	3,090,982
Maintenance and lamp replacement saving			
Maintenance cost per year, $/yr	3% 47,450	3% 55,249	3% 72,735
Lamp replacement time, yr	10	2	10
Lamp replacement cost, $/yr	0	36,667	0
Net maintenance saving, $/yr	44,465	–	19,181
Overall cost/effectiveness			
Power saving, kW	190	–	267
Lighting hours, h/day	12		
Electricity price, $/kWh	0.3 (fixed price) (in remote island)		
Yearly total energy saving, kWh/yr	832,368	–	1,168,000
Yearly total energy saving, $/yr	249,710	–	350,400
Net maintenance saving, $/yr	44,465	–	19,181
Additional investment for LED, $	366,713	Base	1,209,360
Payback time (LED additional investment/ total yearly saving), yr	1.2	–	3.3
Side benefit of LED lighting			
CO_2 emission reduction, kg/yr	549,363	–	770,880

In addition, it is expected that in the next few years LED advantages will increase due to developments in the field of semiconductor, electronic and housing technologies [24]. For example, current LEDs lamps are currently used with constant current sources to drive the LEDs, and a new LED lamp control architecture based on pulse width modulation signal that regulates the current applied according to the LED lamp temperature will lead to an increment in lifetime expectation of 25% [27].

2.2 Photovoltaic Street Lighting

The main quality criterion for PV stand-alone systems is reliability [27].

PV powered lighting systems have existed for many years but they have a high initial cost and low conversion efficiency which makes them difficult to accept. However, in the past 20 years photovoltaic solar electricity production has grown by 20 to 25% per year. This grow has been driven by an increase in efficiency of solar cells, and mostly by lowering the production cost through improvements in manufacturing technologies and economies of scale [28].

PV technology incorporated on SLS has been improving because of their sustainable and environmentally advantages when compared to conventional energy powered systems. On the other hand, PV systems have a higher price than conventional grid electricity and it is necessary to store energy (because production is during the day and consumption overnight) [13]. PV SLS (as street lighting systems in general) can be off-grid or on-grid. In both cases different configurations can be used. The next figures include the main components of a PV SLS for grid connected street light with AC load with or without storage capacity (Figure 6 and Figure 7, respectively), grid connected street light with DC load (Figure 8), off-grid street light with AC load (Figure 9) and off-grid street light with DC load (Figure 10).

As can be seen all the systems include a PV module (which convert sunlight into electricity) and a load (in this case the lamp). All cases except the first one include a storage capacity (battery) and a charge controller to prevent battery overcharging and over discharging. The first one does not have storage capacity and PV generation goes directly to the inverter. In grid connected PV systems electricity grid is obviously a component, as well as an inverter (which is also used in off-grid systems if load is an AC lamp).

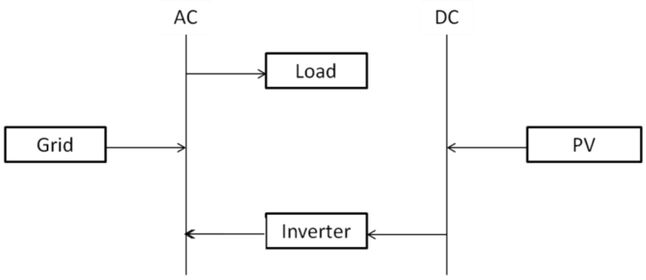

Figure 6 - Configuration of grid connected street light with AC load, without storage capacity

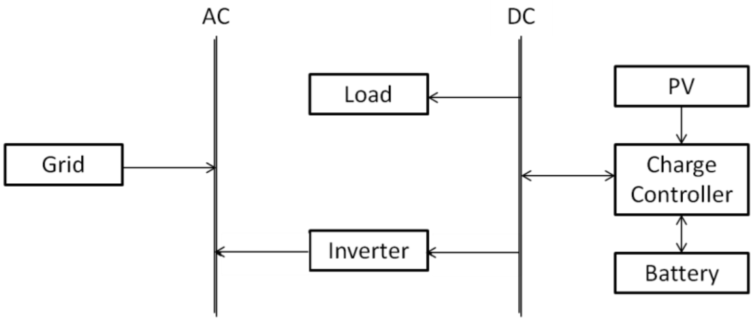

Figure 7 - Configuration of grid connected street light with AC load, with storage capacity

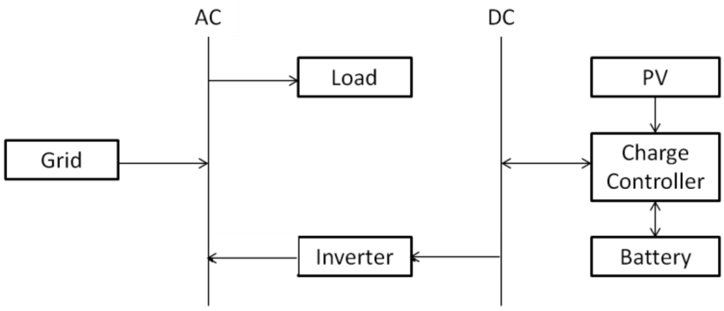

Figure 8 - Configuration of grid connected street light with DC load, with storage capacity

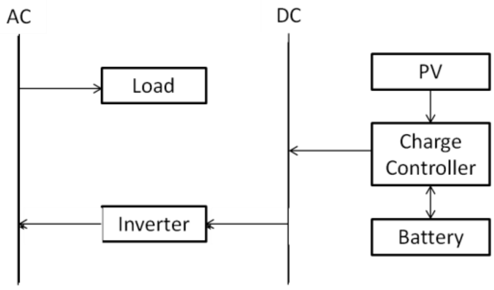

Figure 9 - Configuration of off-grid street light with AC load

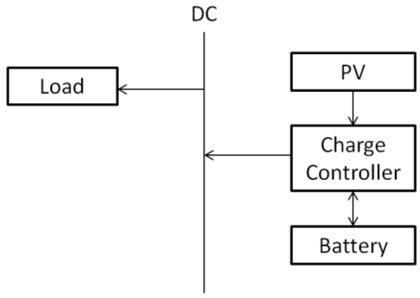

Figure 10 - Configuration of off-grid street light with DC load

Considering that different options are available it is important to discuss the main advantages and disadvantages of each solution.

The first option (grid connected street light with AC load, without storage capacity) does not have storage capacity and if the electricity supply is secure and efficient this will be the best solution. In grid connected PV systems with battery (Figure 7 and Figure 8), it is important to note that the grid can, like the panel, charge the battery. In fact, the least reliable component is the battery and based on it, a system without it can be a good solution, but if the electrical grid is weak and has higher failures the use of the battery can compensate it.

About the load, it can work in direct or alternate current. In on-grid systems the inverter is always necessary and therefore the load can be AC or DC (because grid works at AC and PV and battery at DC).

About off-grid systems the difference between them are the load. If all the components can work at DC, a DC lamp will be the best solution because the inverter is needless. According to that off-grid street light with DC load are the best option (Figure 10).

It is also important to understand in which cases on-grid and off-grid systems are the best solution. If the national grid or mini-grid is available on-grid solution are cheaper than off-grid [13]. On-grid can contribute to a less installed PV capacity, lower battery size or higher lifetime of battery and inverters. As already mention if the electricity supply is efficient battery is not necessary and these systems will be cheaper and more reliable than the one with storage capacity. And according to [13] in China, when a PV module and a battery is installed on each pole, the cost of electricity is cheaper than the use of conventional grid. When grid does not exist the cost of its extension is often more expensive than the use of isolated systems. The cost of off-grid systems is 2 to 4 times higher than on-grid solutions [13].

One of the main advantages of solar lighting is that grid extension (overhead or underground) and therefore distribution grid costs are not required [8]. All advantages described for street lighting is also true for photovoltaics' case.

About systems components different types of PV modules, batteries, lamps and charge controllers are available in the market. A briefly analysis of its components will be done in the next paragraphs.

About the PV technology that should be used, a study which analysis technical, economic and environmental indicators proves that when monocrystalline and polycrystalline silicon were compared, the first one has a large power generation, less CO2 emissions (because this study is for grid connected systems) and higher environmental performance, however the polycrystalline is cheaper than monocrystalline [13].

About batteries, they represent the storage capacity of the system. Batteries used in PV systems should be stationary, require little maintenance (should consume little water), operate at different charge states (being able to work well at higher states of charge and from time to time on a lower), and need a good protection for overloads (because in a stand-alone system, the size is often based on the worst month) [29].

In stand-alone applications batteries known as OpzS are the best option. Although these batteries have a high price, a low availability and it is necessary to verify electrolyte level twice a year. To avoid these valve regulated lead-acid (VRLA) batteries are commonly used. VRLA can be AGM (absorbed glass mat) or GEL. In grid connected systems lithium-ion, molten/ sodium salt and vanadium redox [29].

In a photovoltaic street lighting system, as well as in any street lighting system, LED seems to be the best solution. Furthermore, if an off-grid system is considered, DC load is the best solution, and LED meets this requirement. Beyond that, it reduces power consumption, battery capacity (if needed) and accordingly loss of load power (LLP) [25].

After knowing the ideal characteristics of a solar street lighting system, the knowledge of street lighting standards is also necessary.

2.3 Street Lighting Standards

The main standards related to street lighting are EN 13201, EN 12665, CIE 115:1995 and CIE 115:2010 (revision and update of CIE 115:1995).

International Commission on Illumination (CIE, Commission Internationale de L'Eclairage, in French) is responsible for CIE 115:1995 and CIE 115:2010. On the other hand, European Committee for Standardization (CEN, Comité Européen de Normalisation, in French) is responsible for EN13201 and EN12665. A detailed analysis of both updated documents (EN13201 and CIE 115:2010) will be done in the next subchapters. A previous explanation of the Portuguese "Reference Document for Street Lighting Energy Efficiency" will also be done.

Before this it is essential to introduce some lighting concepts, namely: luminous flux, luminous intensity, luminance, illuminance, threshold increment and surround ratio. Luminous flux (ϕ) is the quantity derived from radiant flux by evaluating the radiation according to the spectral sensitivity of the human eye [30], i.e. is the quantity of light emitted in all directions by a light source [31]. It is calculated by the following equation (1) and is measured in lumen.

$$\phi = K_m \int_0^\infty \frac{d\phi(\lambda)}{d\lambda} V(\lambda)\, d\lambda \qquad [lm] \qquad (1)$$

Where K_m is the photopic vision, $\frac{d\phi(\lambda)}{d\lambda}$ is the spectral distribution of the radiant flux and $V(\lambda)$ the spectral luminous efficiency.

Luminous intensity of a source in a given direction (I) is represented by the quotient of the luminous flux ($\partial\phi$) leaving the source and propagating in the element of solid angle containing the given direction, by the element of solid angle ($\partial\Omega$), as can be seen in the next equation [30]. It is measured in candela (cd), which may be defined as the luminous intensity, in a given direction, of a light source that emits monochromatic radiation of 540×10^{12} Hz, with an energetic intensity on that direction of 1/683 Watts per steradian [31]. For an isotropic source, 1 cd is equivalent to lm/sr.

$$I = \frac{\partial \phi}{\partial \Omega} \qquad [cd] \qquad (2)$$

Luminance (L) is the luminous intensity of the light emitted or reflected in a given direction from an element of the surface, divided by the area of the element projected in the same direction. So, luminance in a given direction, at a given point of a real or imaginary surface is given by the following equation [30]:

$$L = \frac{\partial \phi}{\partial A \times \cos\theta \times \partial \Omega} \qquad [cd\ m^{-2}] \qquad (3)$$

Where $\partial \phi$ is the luminous flux transmitted by an elementary beam passing through the given point and propagating in the solid angle $\partial \Omega$ containing that direction, ∂A is the section of that beam containing the given point, and θ is the angle between the normal to that section and the direction of the beam [30].

Average luminance (L_{avg}) is the luminance averaged over the specified area, minimum (L_{min}) and maximum (L_{max}) luminance are the lowest and highest possible value of luminance in any of the points in the specified surface. Maintained illuminance (L_m) is the value below which the average luminance on the specified area should not fall [30].

Luminance uniformity or overall uniformity (U_o) is the ratio of minimum luminance to average luminance (Equation 4) [30].

$$U_o = \frac{L_{min}}{L_{avg}} \qquad [\%] \qquad (4)$$

Longitudinal uniformity (U_L) is the ratio of minimum luminance to maximum luminance [31], as can be seen in Equation 5 in a given surface. It can be adopted to road surface luminance of a driving lane (with this ratio found in a line in the centre of the road surface along a driving lane) and to road surface luminance of a carriageway (as the lowest of the longitudinal uniformities of the driving lanes of the carriageway) [32].

$$U_L = \frac{L_{min}}{L_{max}} \qquad [\%] \qquad (5)$$

Illuminance at a point of a surface (E) is the quotient of the luminous flux incident on an element of the surface containing the point, by the area of that element [30]. It is measured in lux, which corresponds to one lumen per square meter.

$$E = \frac{\partial \phi}{\partial A} = \int_{2\pi\ sr} L \times \cos\theta \times \partial \Omega \qquad [lx] \qquad (6)$$

Where L is the luminance at the given point in the various directions of the incident elementary beams of solid angle ($\partial \Omega$), and θ is the angle between any of these beams and the normal to the surface at the given point.

The definitions of average (E_{avg}), minimum (E_{min}), maximum (E_{max}) and maintained (E_m) illuminance are identical the corresponding ones for luminance.

Four different illuminance concepts are essential: spherical (E_0), hemispherical (E_{hs}), cylindrical (E_z) and semi-cylindrical (E_{sz}).

Spherical illuminance is calculated by the following equation [30].

$$E_0 = \int_{4\pi\, sr} L \times d\,\Omega \qquad [\text{lx}] \qquad (7)$$

Where dΩ is the solid angle of each elementary beam passing through the given point and L its luminance at that point.

Hemispherical illuminance it the total luminous flux falling on the curved surface of a very small hemisphere located at the specified point divided by the curved surface area of the hemisphere (the base of the hemisphere is taken to be horizontal unless stated otherwise) [30].

Cylindrical illuminance is defined by the following equation [30].

$$E_z = \frac{1}{\pi} \int_{4\pi\, sr} L \times sin\varepsilon \times d\,\Omega \qquad [\text{lx}] \qquad (8)$$

Where dΩ and L is the same as before and ε is the angle between it and the given direction.

Semi-cylindrical illuminance (Esc) is the total flux falling on the curved surface of a very small semi-cylinder located at the specified point, divided by the curved surface area of the semi-cylinder (the axis of the semi-cylinder is taken to be vertical unless stated otherwise and the direction of the curved surface should be specified) [30].

Illuminance uniformity or overall uniformity (U_{avg} or U_o) is the ratio of minimum illuminance to average illuminance (Equation 9) [30].

$$U_0 = \frac{E_{min}}{E_{avg}} \qquad [\%] \qquad (9)$$

Threshold increment (TI) measures the loss of visibility caused by the disability glare of the luminaires of a road lighting installation [32] and can be calculated as follow [33].

$$\mathrm{TI} = \frac{65}{\left(\mathrm{L_{avg}}\right)^{0.8}} \mathrm{L_v} \qquad [\%] \qquad (10)$$

Where L_v is the veiling equivalent luminance, which can be calculated by the following equation.

$$\mathrm{L_v} = 10 \sum_{k=1}^{n} \frac{\mathrm{E_k}}{\mathrm{E_k^2}} \qquad [\text{cd m}^{-2}] \qquad (11)$$

Where E_k is the illuminance produced by the k-th luminaire on a plane normal to the line of sight at the height of the observer's eye (1.5 m above road level).

Surround ratio (SR) is the ratio of the average illuminance on the two longitudinal strips each adjacent to the two edges of the carriageway (and lying off the carriageway) by the average horizontal illuminance on two longitudinal strips, each one adjacent to the two edges of the carriageway (lying on the carriageway) [33].

According to [33] SR can be expressed by Equation 12 in accordance with Figure 11. The width of the four strips shall be the same and the minimum of the following options: 5 meters (Figure 12), half the width of the carriageway (Figure 14), or width of the unobstructed strip lying off the carriageway (Figure 14) [33].

$$SR = \frac{E_1 + E_4}{E_2 + E_3} \qquad [lx] \qquad (12)$$

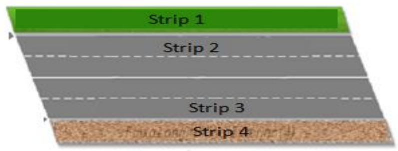

Figure 11 - Location of different strips [31]

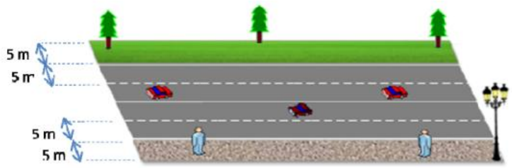

Figure 12 - Width of strip equal to 5 meters [31]

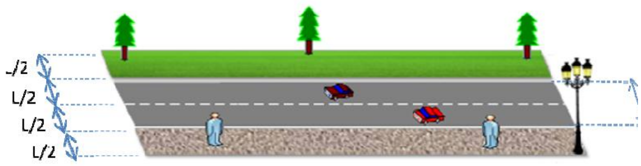

Figure 13 - Width of strip is equal to half the width of the carriageway [31]

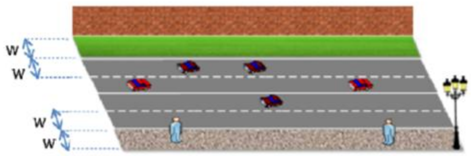

Figure 14 - Width of the unobstructed strip lying off the carriageway [31]

2.3.1 EN13201

Current European Street Lighting Standards were defined in July 2004 by CEN members. This European Standard is known as EN 13201 and is divided in four parts [34]:

1. CR 13201-1: Road lighting - Part 1: Selection of lighting classes [34]
2. EN 13201-2: Road lighting - Part 2: Performance requirements [32]
3. EN 13201-3: Road lighting - Part 3: Calculation of performance [33]
4. EN 13201-4: Road lighting - Part 4: Methods of measuring the light performance of installations [35]

In addition, a draft of "Road lighting - Part 5: Energy performance indicators" is also available [36].

According to [34] a step by step selection procedure may be followed in order to determine lighting class. Based on the typical speed of main user and on user type (which define public traffic area) the sets of lighting situations are described in the forward table.

Table 5 - Grouping of lighting situations [34]

Typical speed of main user [km/h]	User types in the same relevant area: Main user	Other allowed user	Excluded user	Sets of lighting situations
>60	Motorised traffic		Slow moving vehicles; Cyclists; Pedestrians	A1
		Slow moving vehicles		A2
		Slow moving vehicles; Cyclists; Pedestrians		A3
>30 and ≤60	Motorised traffic; Slow moving vehicles	Cyclists; Pedestrians		B1
	Motorised traffic; Slow moving vehicles; Cyclists	Pedestrians		B2
>5 and ≤30	Cyclists	Pedestrians	Motorised traffic; Slow moving vehicles	C1
	Motorised traffic; Pedestrians		Slow moving vehicles; Cyclists	D1
		Slow moving vehicles; Cyclists		D2
	Motorised traffic; Cyclists	Slow moving vehicles; Pedestrians		D3
≤5	Motorised traffic; Slow moving vehicles; Cyclists; Pedestrians			D4
	Pedestrians		Motorised traffic; Slow moving vehicles; Cyclists	E1
		Motorised traffic; Slow moving vehicles; Cyclists		E2

After this first classification a further detailed assessment is necessary. The main parameters that need to be analyzed are described in the next table.

Table 6 - Specific parameters [34]

Parameters		**Options**
Area (geometry)	Separation of carriageways	Yes No
	Types of junctions	Interchanges Intersections
	Interchange spacing, distance between bridges	>3 km ≤3km
	Intersection density	<3 intersections/ km ≥3 intersections/ km
	Conflict areas	No Yes
	Geometric measures for traffic calming	No Yes
Traffic use	Traffic flow of vehicles per day	<4,000 4,000 to 7,000 7,000 to 15,000 15,000 to 25,000 25,000 to 40,000 >40,000
	Traffic flow of cyclists	Normal High
	Traffic flow of pedestrian	Normal High
	Difficulty of navigation task	Normal Higher than normal
	Parked vehicles	Not present Present
	Facial recognition	Unnecessary Necessary
	Crime risk	Normal Higher than normal
Environmental and external influences	Complexity of visual field	Normal High
	Ambient luminance	Rural Urban City centres
	Main weather type	Dry Wet

Taking into account the decisions from the previous table, the lighting class is defined. The next table shows the relationship between sets of lighting situations (from A1 to E2) and lighting classes (ME, MEW, S and CE).

Table 7 - Relationship between sets of lighting situations and lighting classes [34]

Sets of lighting situations	**Lighting classes**
A, B	ME/MEW
C	S
D	CE
E	S, CE

This document [34] also define the procedures that should be followed to relevant areas determination for different lighting situation sets, conflict areas, traffic calming measures and pedestrian crossing. Road authority is the responsible to define and analyze specific parameters and to consider the various traffic areas. If a public area has more than one different traffic area each one should be defined separately.

European Standard EN 13201-2 [32] defines photometric requirements for each lighting class. The main classes considered are ME, MEW, CE, S, A, ES, EV. The ME and MEW classes are intended for drivers of motorized vehicles for users on traffic routes, and in some countries also residential roads, allowing medium to high driving speeds. The next tables present the photometric requirements for ME and MEW classes (Table 8 and Table 9, respectively). These classes are based on the road surface luminance. The parameters of the next tables may be calculated (and measured) in accordance with [30], [33] and[35].

Table 8 - ME-series of lighting classes [32]

Class	Luminance of the road surface of the carriageway for the dry road surface condition			Disability glare	Lighting of surroundings
	L_{avg} [cd m^{-2}] (minimum maintained)	U_0 (minimum)	U_L (minimum)	TI [%] (maximum)	SR (minimum)
ME1	2.00	0.40	0.7	10	0.5
ME2	1.50	0.40	0.7	10	
ME3a	1.00	0.40	0.7	15	
ME3b	1.00	0.40	0.6	15	
ME3c	1.00	0.40	0.5	15	
ME4a	0.75	0.40	0.6	15	
ME4b	0.75	0.40	0.5	15	
ME5	0.50	0.35	0.4	15	
ME6	0.30	0.35	0.4	15	No requirement

Table 9 - MEW-series of lighting classes [32]

Class	Luminance of the road surface of the carriageway				Disability glare	Lighting of surroundings
	Dry condition			Wet condition		
	L_{avg} [cd m^{-2}] (minimum maintained)	U_0 (minimum)	U_L (minimum)	U_0 (minimum)	TI [%] (maximum)	SR (minimum)
MEW1	2.00	0.40	0.6	0.15	10	0.5
MEW2	1.50	0.40	0.6		10	
MEW3	1.00	0.40	0.6		15	
MEW4	0.75	0.40	No requirement		15	
MEW5	0.50	0.35	No requirement		15	

The CE classes are intended for drivers of motorized vehicles, pedestrians and pedal cyclists, on conflict areas such as shopping streets, road intersections of some complexity, roundabouts and queuing areas. Here the classes are based on the illumination of the road area (see Table 10).

Table 10 - CE-series of lighting classes [32]

Class	Horizontal illuminance E_{avg} [lux] (minimum maintained)	Horizontal illuminance U_o (minimum)
CE0	50	0.4
CE1	30	
CE2	20	
CE3	15	
CE4	10	
CE5	7.5	

The S and A classes are intended for pedestrians and pedal cyclists for use on footways and cycle ways, emergency lanes and other road areas lying separately or along the carriageway of a traffic route, residential roads, pedestrian streets, parking areas, schoolyards and so on. These classes reflect different priorities to the road lighting, and are defined based on the illumination of the road area, horizontal illuminance for S classes (Table 11) and hemispherical illuminance for A classes (this classes value will not be presented here but can be found in [32] because they will not be considered in this work).

Table 11 - S-series of lighting classes [32]

Class	Horizontal illuminance E_{avg} [lux] (minimum maintained)	Horizontal illuminance E_{min} (minimum)
S1	15	5
S2	10	3
S3	7.5	1.5
S4	5	1
S5	3	0.6
S6	2	0.6
S7	Performance not determined	

The ES and EV classes are additional classes. The first one is for situations where the public lighting in pedestrian areas is necessary to identify persons or objects and in roads with higher crime risk than normal. EV classes are used in situations where vertical surfaces (such as toll stations or interchange areas) need to be seen. ES classes are based on semi-cylindrical illuminance and EV class on the vertical plane illumination, and for the same reason as A classes the correspondent values can only be found in [32]. This document [32], also has a brief chapter about appearance and environmental aspects.

European Standard EN 13201-3 [33] defines the conventions and mathematical procedures in the calculation of photometric quantities explained before (such as luminance and illuminance) and quality characteristics (for example, average luminance, uniformity, threshold increment and surround ratio).

European Standard EN 13201-4 [35] specifies the procedures to measure installed street lighting systems (annex A of this fourth part has a template to the test report). During these measurements, the following conditions should be taken into account:

1. Stabilization after switch-on: the measurement should be done after stabilization (it is important, for example, in discharge lamps);
2. Climate conditions: extreme temperatures or atmosphere light transmission can influence the measurement;
3. Extraneous light and obstruction of light: it is essential to know if measurements are intended to record direct or reflect light, or unobstructed light, for example;

4. Measurements taken from a moving vehicle: it is necessary to know the coordinates of the vehicle in each measurement point, to minimize, for example, shadow effects, light reflection or electronic noise from the vehicle. Measurements must be made using equipment with photometric heads conforming to the requirements.

Non-photometric measurements should also be considered. The main important are [35]:

1. Geometric data;
2. Electric voltage supply: should be measured continuously at a significant point in the electric installation during the measurements;
3. Temperature: should be measured one meter above ground level and recorded at intervals of 30 minutes.

European Standard EN 13201-5 is still a draft document and introduces two metrics: the power density (D) and the energy consumption indicator (ECly). The first one estimates the energy needed for a road lighting situation ensuring that the design criteria specified in Part 2 are fulfilled. ECly determines the energy consumption during the year, even if the relevant lighting requirements change during night for different seasons. These indicators only allow comparisons between projects with the same road geometry and lighting requirements due to the fact that energy performance is influenced by these indicators [36]. This European Standard will be used in the present work.

2.3.2 CIE 115:2010

In order to simplify road's classification EN13201, CIE 115:2010 was created. This report is a revision and update of CIE 115:1995, and includes a model developed for the selection of lighting classes (M, C or P) based on the luminance and illuminance concepts [9]. This new document gives much more attention to power consumption and environmental aspects than the 1995 one. The higher performance of the light sources now available (specially due to the introduction of electronic control mechanisms) leads to the introduction of the concept of adaptive lighting. Changes in the average lighting level cannot affect the other quality criteria outside the limits given in each class. A reduction in light output of every lamp by the same amount using dimming techniques will not affect luminance or illuminance uniformity, or the object contrast, but the threshold contrast will increase. On the other hand, switching off some luminaires will not fulfil quality requirements and is not recommended [9]. CIE115:2010 gives a "weight factor" to the EN13201 questions and in the end the sum of these gives the lighting class.

2.3.3 Reference Document for Street Lighting Energy Efficiency

In Portugal, the Reference Document for Street Lighting Energy Efficiency (Documento de Referência para a Eficiência Energética na Iluminação Pública) defines a set of technical parameters that should be used in streetlight. The main goals of this document are increasing energetic efficiency and decreasing CO_2 emissions [31]. An energetic class will be defined based on the energy efficiency of each project.

The streets can be classified in functional streetlight or decorative lighting but this document is only about the first one. Lighting class determination is done based on CIE 115:2010. Energy Efficiency is analyzed based on a utilization factor (UF) and a maintenance factor (MF), which depends on the energy efficiency of the source and accessories (in lm/W), and photometric characteristics. Utilization Factor is the ratio of luminous flux received by the area that should be illuminated to the sum of luminous flux of each individual light source [31].

Luminous flux decreases over time and it will depend on light source and ballast or driver. The following table has the Maintenance Factor of Lamp Brightness (MFLB), which can be defined as the ratio between luminous flux at an instant t and initial luminous flux [31].

Table 12 - Maintenance Factor of Lamp Brightness according to lifetime of different light sources (adapted from [7])

	Lifetime [khours]					
Source of Light	**4**	**6**	**8**	**10**	**12**	**65**
Sodium Vapour High Pressure	0.98	0.97	0.94	0.91	0.90	-
Metal Halide Lamp	0.82	0.78	0.76	0.74	0.73	-
Sodium Vapour Low Pressure	0.98	0.96	0.93	0.90	0.87	-
Compact Fluorescent Lamp	0.91	0.88	0.86	0.85	0.84	-
Light Emitting Diode	-	-	-	-	0.95	0.70

Survival Factor of Lamp (SFL) is the probability of the lamp to work for a certain time. It depends on the type of the source light, power applied to the lamp, switching frequency, and ballast or driver. Table 13 include SFL for different light sources [31].

Table 13 - Survival Factor of Lamp according to lifetime of different light sources (adapted from [31])

	Lifetime [khours]					
Source of Light	**4**	**6**	**8**	**10**	**12**	**65**
Sodium Vapour High Pressure	0.98	0.96	0.94	0.92	0.89	-
Metal Halide Lamp	0.98	0.97	0.94	0.92	0.88	-
Sodium Vapour Low Pressure	0.92	0.86	0.80	0.76	0.62	-
Compact Fluorescent Lamp	0.98	0.94	0.90	0.78	0.50	-
Light Emitting Diode	-	-	-	-	0.95	0.70

Maintenance Factor of Luminaire (MFL) is defined as the ratio between current light output ratio and the initial light output ratio. Light output ratio is the ratio between luminaire luminous flux and the sum of individual light sources of the luminaire. It can be defined by luminaire IP and pollution level according to the following table. Pollution level should be considered as "high" when smoke surround the luminaires [31].

Table 14 - Maintenance Factor of Luminaire (adapted from [31])

	Pollution Level	Lifetime [khours]		
		4	**8**	**12**
IP55	Low	0.92	0.80	0.71
Plastic diffuser	High	0.97	0.71	0.61
IP65	Low	0.95	0.84	0.76
Plastic diffuser	High	0.89	0.76	0.66
IP65	Low	0.97	0.90	0.82
Glass diffuser	High	0.94	0.84	0.76
IP66	Low	0.95	0.87	0.81
Plastic diffuser	High	-	0.81	0.74
IP66	Low	0.97	0.93	0.88
Glass diffuser	High	-	0.88	0.83

Finally, the Global Maintenance Factor (GMF) is calculated according to the following equation. A three year period may be considered (12000 hours) [31].

$$GMF = MFLB \times SFL \times \mathrm{MFL} \qquad [\,] \qquad (13)$$

To evaluate the energy efficiency (ε) of a street lighting installation (Equation 14) it is necessary to know the total illuminated area (S), which is represented by the product between inter distance of lighting sources and total road width (in an urban environment from façade to façade), the average level of illuminance (E) and total power of luminaires plus auxiliary lights (P).

$$\varepsilon = \frac{S \times E}{P} \qquad [\,] \qquad (14)$$

This value of energy efficiency determines the energetic class as can be seen in Table 15. A is the most efficient class and G the less efficient.

Table 15 - Relationship between energetic class and energetic efficiency[6] [31]

Energetic Class	Energetic Efficiency
A	$\varepsilon > 40$
B	$40 \geq \varepsilon > 35$
C	$35 \geq \varepsilon > 30$
D	$30 \geq \varepsilon > 25$
E	$25 \geq \varepsilon > 20$
F	$20 \geq \varepsilon > 25$
G	$\varepsilon \leq 25$

If the power is not constant all over the night, an energy saving should be presented. Consumption in different periods of night should be considered (for a night of 12 hours) and if a sensor exists this savings should be defined based on lowest and highest power.

2.4 Africa Street Lighting Market

Currently, information about street lighting in developing countries is poor and market knowledge does not exist. A lot of documents about electrification and lighting were done by international groups such as World Bank, International Energy Agency, or Lighting Africa but the main concern of these authors is always focused on solar home systems and smaller lighting systems like solar portable light (SPL) or pico-powered lighting systems (PLS).

In a recent past, several African governments have acknowledge the growing importance of modern lighting devices and are gradually putting in place policies and regulations to promote their adoption and usage among off-grid communities instead of investing in both grid extension and kerosene subsidies. To address this issue, governments have different available options [37]:

1. Incorporate off-grid solutions in rural electrification programs: for example, the promotion of PLS is a faster and cheaper alternative than national grid extension. Liberia has an interesting programme, Lighting Lives programme, created by the Rural and Renewable Energy Agency (RREA), with World Bank cooperation. One of this programme primary goal is to facilitate the creation of a viable market for PLS. RREA is supporting a pilot project that matches high-quality manufacturers of PLS with 6 retail partners in order to distribute these products to rural markets. A part of the sales revenues will be used to create a Rural Energy Fund, to expand the programme to other communities [37].
2. Fiscal incentives - taxes, duties and subsidies: several governments have provided fiscal incentives to supply barriers and encourage demand for PLSs. For example, in Kenya, all imported LED lighting equipment and solar components are exempt from taxation; in Ethiopia solar products are not subjected to inland duties and surtaxes; and in Uganda, the Government implemented a 45% subsidy on all solar equipment. However,

[6] Definition of energetic classes E, F and G are meaningless, however this information is in the Reference Document for Street Lighting Energy Efficiency

in other countries, taxes and tariffs can add 5 to 30% to the final retail price (Figure 15). In addition some of them also have a subsidy for kerosene. For example, in Cameroon kerosene is exempt of all taxes (as in Ethiopia) [37].

3. Quality control: to prevent market spoilage and poor quality products some countries (like Tanzania and Kenya) are instituting strict quality-control frameworks [37].
4. Business development assistance: For example, in Tanzania, Ministry of Energy and Minerals (with the Swedish International Development Agency) is providing business development services for solar lighting companies, awareness programs for consumers and networking among solar industry stakeholders [37].

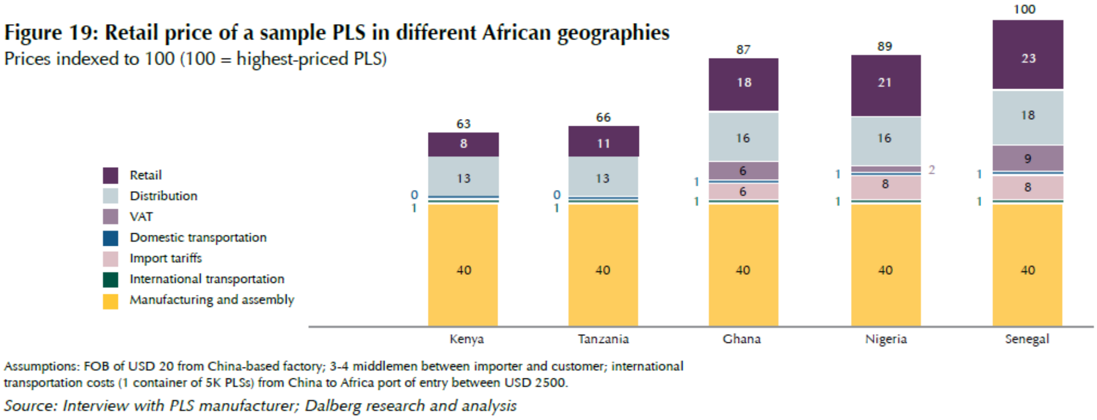

Figure 15 - Retail price for a sample PLS in different African geographies

Various channels are used to reach PLS consumers: standard retail and dealer-distribution networks, MFIs and NGOs, institutional (including governmental and corporate partnerships), micro-franchise, rental and proprietary/ own distribution [37].

To reach street lighting consumers these channels are not equal. Standard retail and dealer-distribution can be an alternative, but the best ones are MFIs, NGOs and institutional partnerships. Rental can also be an alternative but it is impossible to cut the street lighting for a family and keep it working for its neighbour. Partnerships with all kinds of community-based organizations could also be a good practice.

According to [8] African leadership must make the commitment to provide solar powered systems to the nation's people to increase productivity, living standards and empower the people. When a government pays for light, more jobs are created, commerce expands, and more taxes can be collected. In the specific case of street lighting, accidents will decrease, resulting in a lower hospital running cost, less injuries and deaths. Welfare increases and migration of populations to over-crowded cities also decreases.

Nevertheless, a mixed history of successes and failures with respect to any kind of solar projects in Africa can be found. The following examples show the importance of street lighting as well as its difficulties. In 2010 an electrification project was implemented in the Subue village, Mozambique. After FUNAE[7] selected this village, SDPI[8] identified beneficiaries' priorities: house light was the first priority and street light was the second [38]. Unfortunately, only a school and PV street lamps were installed, and when a lamp was broken and no one knew who was responsible for maintenance [38]. In Sukatani, Indonesia, 15 street lighting systems were installed in 1988. In 1993, all systems were operating (in 8 the original batteries had been replaced by locally produced car batteries). In 1997, 9 systems were working although one lights a nearby household instead of the street (all systems have a broken time control unit, which cannot be replaced because local manufacturers could not supply it in such a small

[7] Fundo de Energia, in Portuguese

[8] Secretaria de Desenvolvimento e Promoção do Investimento, in Portuguese

quantity). From the remaining 6, 3 had been converted to solar home systems and 3 were out of order (one because PV module was broken and the other 2 because battery was broken) and village co-operative did not have any money for maintenance. Villages, however, still considered that SLS are very useful and necessary. Three factors are highlighted: lack of infrastructure or the supply of spare parts, lack of financial support, and need for domestic light apart from outdoor [39]. In Ghana, most of the solar street lighting systems installed in urban centres have never worked because of inadequate feasibility study of the installed systems. Most battery banks were placed underground and during rainfall these batteries were flooded and damaged. The current capacity installed is low but with the increase of government support this systems will also increase [11]. In 2009, according to Electoral Commission of Ghana, 60kW of grid connected solar SLS are available, as well as 30 kW of stand-alone street lighting [11].

Different SLSs already exists on the market. In order to achieve the best solution it is necessary to know the current available products. A briefly characterization of the most important ones will be done next.

2.4.1 Competitors

As previously mentioned, the majority of SLSs in developing countries are assembled with poor quality components and lighting requirements are not considered in the projects. In addition to dozens of Chinese products, the most relevant street lighting systems that can compete with the products that will be developed in this work are from COVIMED, Fosera, Philips, Sunna, Uniglobe and ZYLED.

COVIMED has different solar street lighting systems. Two of them will be analysed here: COVIMED 560 and COVIMED 518. The first one, with 3.80 m in height, has a 15W power lamp, a battery capacity of 65 Ah and a PV module of 40 W_p [40]. The second one is higher (6.20 m), has a 35 W power lamp, 150 Ah of battery capacity and a PV module of 120 W_p [41]. Both work at 12V nominal voltage, have 36 hours of autonomy, and work from 10 to 12h per night [40],[41]. Their prices range between 1,364.88 (COVIMED 560) and 3,105.32€ (COVIMED 518) [42].

Figure 16 - COVIMED 518 [42]

Fosera has three different Commlight products: Commlight 400, Commlight 800 and Commlight 800 XL. All systems have a 10W_p PV module, a system voltage of 3.2V, 3 to 10 days of autonomy, and 2 to 5 years of warrantee. The PV module can be installed with an angle of 12 or 78 degrees. In addition, the system has a dimming control with motion sensor. All systems use LiFePO4 batteries, the first system with 12.8 Ah capacity, the second one with 25.6 Ah and the last one with 64.0 Ah. The first system as an illuminance of 400 lm and the others 800 lm, and they all are integrated systems similar to the one presented in the image of Figure 17. On the left side of the pole a "normal" system is presented and on the right side it is possible to see a new PV module that can be installed according to the user needs in the 800 lm options. The Commlight 800 can have an additional 10 W_p PV module, while the Commlight 800 XL can have a bigger one (27 W_p). In Figure 17 it is possible to see the illumination of the system as a function of the distance from the lamp. It is also important to note that this system can be sold in different places across African continent [43].

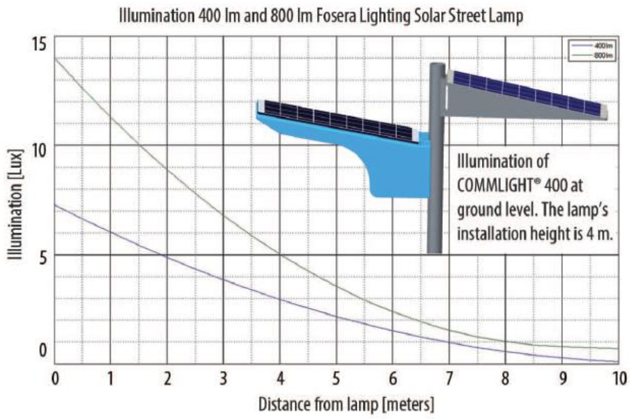

Figure 17 - Illuminance for different distances from Fosera Light's lamp [43]

According to information obtained via email, the cost of each system varies between 344€ and 600€ (without pole, assembly, transport and clearing at the border) in Mozambique. In Kenya and Uganda, the price of Commlight 800 with additional PV module and pole is almost 500€ (more than 100 units), while the price of Commlight 800 XL with additional PV module and pole is around 600€ (more than 100 units). In these last countries, transport and clearing at the border (relevant for Uganda) still needs to be added.

Philips has several solar powered LED street lighting solutions. According to [44] Philips offer affordable price, high quality of light, reliable and robust systems and easy installation and maintenance. The following figures represent the system components (Figure 18) and systems installed in Africa (Figure 19).

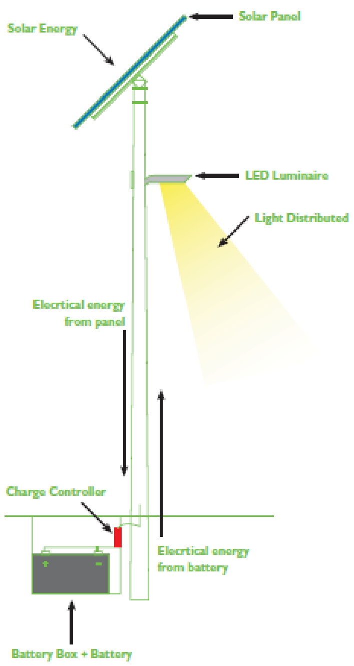

Figure 18 - Philips solar street lighting system [44]

Figure 19 - Philips solar street lighting systems installed in Africa [44]

Philips systems can use lead acid or crystal gel batteries and pretend to use lithium ones in a near future, different PV technologies (silicon, organic materials and cadmium telluride), a

Philips LED module (which includes LEDs, driver, heat sink, optics and cables), and a Philips charge controller. Different combinations can be done and some are currently working across Africa [44]. According to [45] one hundred community light centres are being installed across Africa.

Each project is done individually to fulfil user needs. The design is made in 4 steps: definition, agreement and validation of functional requirements (based on application, required light levels, uptime and dimming possibilities); creation and validation of the light plan; designing of the matching power system; and designing of the project plan [44].

Because prices information about solar powered LED street lighting solutions are not available, different emails were send to Philips Lighting Portugal, Philips Lighting South Africa and Philips Lighting Offices Middle East and Africa. Only one answer was obtained, from Philips Portugal. Even so, because this product is not available in Europe, it was impossible to obtain such information.

Since 2012 Philips has a yearly Cairo to Cape Town Road show (Figure 20 is the plan for the current year). With this Philips aims to be engaged in a dialogue with customers, governments, NGOs and media and present healthcare and lighting solutions to all of them [45].

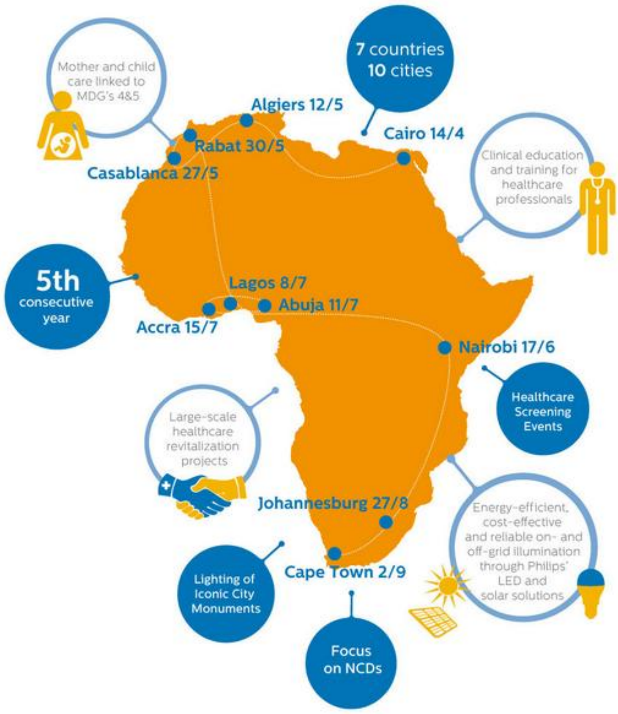

Figure 20 - Philips Cairo to Cape Town Road Show 2014 [45]

Sunna has a solar street light specifically adapted to hot and tropical environmental conditions. It has own quality components and includes an energy management system (which ensures batteries' protection), NiMH batteries and LED module (with dimmable mode available). According to them, their products have the lowest total cost of ownership. Sunna sold one thousand products in 2013 in a dozen countries and expects to achieved 10 thousand in 2014/2015 with project partners [18], [46].

Sunna has 2 main products: ISSL + Sunna and Up2 Sunna. The first one has a LED power between 10 and 20W, a 120 Wh battery and a 35 W_p PV module. Up2 Sunna has a LED power between 20 and 40W, a 240 Wh battery and a 75 W_p PV module. Both products have a lifetime between 8 and 12 years and a 3 to 5 years of warranty [18]. According to information obtained via email, for S4 class with ISSL+, the installed price for final customer in developing costumer is below 1500€.

Uniglobe has a Ceramic Discharge Metal-Halide (CDM) Solar Street Light. It has a two 120 W_p or one 135 W_p PV module, a 120 or a 200 Ah battery and a 35W Philips lamp with ballast [47].

According to a quotation obtained from RVE.SOL in August of 2013, 235 units will cost US$283,175 (approximately US$1,200/unit). The unitary cost is presented in the next table. It is important to note that in this quotation battery capacity is 120Ah and PV module has 130Wp.

Product	Price (US$)
CDM Solar Street Lighting System, lamp fixture set, CDM 35W lamp, built-in-ballast and reflector	500
DC charge controller	275
Monocrystalline solar module	200
Silicone Gel Battery	230

Table 16 - CDM Street Light system components

ZYLED-SL-AC-DC-4 is also a photovoltaic street lighting system, which is available in Portugal through Soltuga company. Four different products are available: ZYLED-SL-AC-DC-18W, ZYLED-SL-AC-DC-36W, ZYLED-SL-AC-DC-50W, and ZYLED-SL-AC-DC-70W. The number on the name is the nominal power of each system. All of them have a lifetime of 35,000 hours and work at 12V nominal voltage. Both the first and the third have a 90W PV module, while the second one is equipped with a 130W PV module. The fourth includes two 100W PV modules. The first one includes a 100 Ah battery, others a 150 Ah. Acording to the manufacturer they present 4.5, 3.5, 2.5 and 2.5 days of autonomy, respectively [48].

2.5 First Generation Prototype developed at FCUL

As previously mentioned, a first prototype has been developed at FCUL in 2012. This system is an intelligent stand-alone photovoltaic street light system. It includes an ATmega328 microprocessor, a sensor to detect ambient light at the sky level, and a pyroelectric sensor to detect people's movement. The system is programmed in order to obtain a significant increase of daily operation time for the same battery capacity and photovoltaic installed power. For example, when no presence is detected the system enters a stand-by mode corresponding to about 20% of its maximum power, and only when people's movement are detected the LEDs fade up to maximum power [7].

The system main components are a 50Wp PV module, a 24Ah battery, and a 23W LED lamp. It has 2 says of autonomy, fulfil European standards for class S and the total cost (for this unit alone, meaning without any type of scale gain) was about 594€/ unit [7]. The system is presented in Figure 21 (electrical circuit) and Figure 22 (photography). The cost structure of the system is presented on Figure 23.

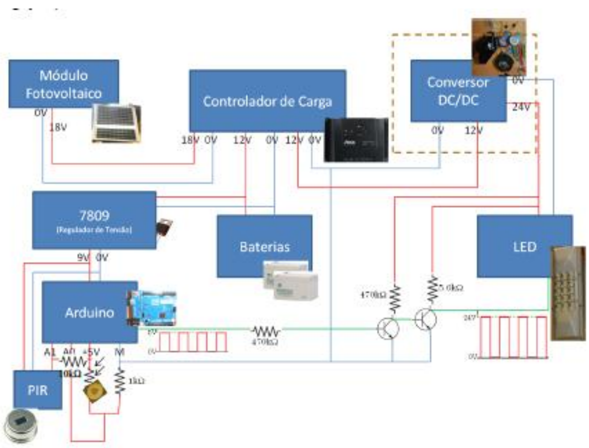

Figure 21 - Electrical circuit of FCUL's prototype [7]

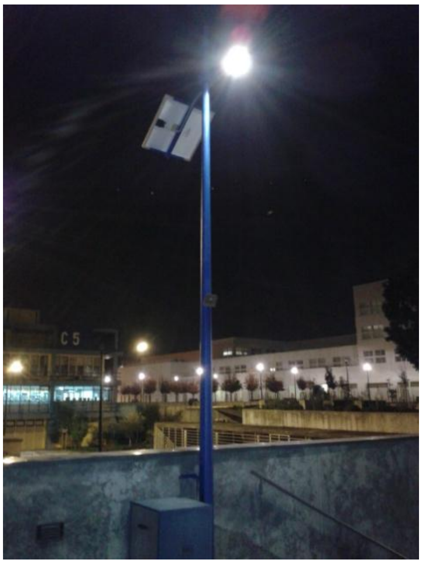

Figure 22 - Installed FCUL's prototype [7]

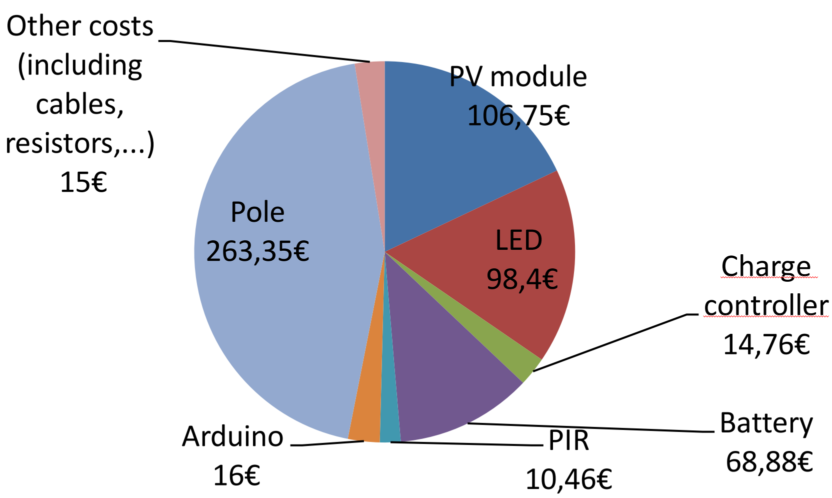

Figure 23 - Cost of the components of FCUL's prototype [7]

3 Second Generation Prototypes

The main goal of this work is the development of two products: a stand-alone photovoltaic street lighting system and a grid connected street lighting system with storage capacity. Both systems should fulfil street lighting standards for ME, CE and S classes (according to EN13201). Based on this a determination of each subclass will be done, followed by the definition of the ideal lamp. Finally, both systems will be presented.

3.1 Determination of Lighting Situations and Classes

Only available on confidential document.

3.2 Lighting Plan

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3.3 Stand-alone Solar Street Light

Stand-alone street light system will be developed based on the first generation prototype.

3.3.1 Sizing of stand-alone PV systems

The system sizing will be done in accordance with "worst month" method [49]. As daily energy requirements are identically over the year in our target region, system specifications need to be defined in the month that has lower solar resource availability (month with the bigger ratio of demanded energy versus available energy [49]).

In order to choose the components and main characteristics of a stand-alone photovoltaic system the following steps should be followed [50]: define load, location and inclination; determine irradiation; calculate installed power to fulfil load; calculate number of modules; and define the remaining system specifications (battery, charge regulator, inverter).

Firstly, it is necessary to define the maximum number of days of autonomy (n), which is the maximum number of days that the system should work without receiving solar radiation. This number should take into consideration the meteorological conditions in the place, the type of installation, the overall costs, or its social relevance [49]. Before being able to size a PV system, it is also essential to define the nominal voltage of the installation (V_N), which should be 12 or 24V for small systems [49]. Then, solar energy available (the resource) should be obtained, and electrical energy required (the demand) and system sizing (the result) is calculated [49].

The available solar energy depends on local latitude and modules orientation. This orientation is defined by azimuth (α) and inclination or elevation (β) angles. Although PV module produces more energy if it is able to follow the sun's path during the day using a solar tracking system, system cost will increase and the moving parts (tracker) will contribute to a lower system robustness, which can lead to a higher operation and maintenance cost. In a fixed system the module should be turned towards the terrestrial equator (facing south in the north hemisphere and north in the south hemisphere). In what concerns inclination, it is recommended that this angle should range between the absolute value of the latitude of the place minus 10º and plus 10º ($|latitude|-10º < \beta < |latitude|+10º$), according to the energy consumption over the year. Nevertheless, this value should always be higher than 15º (to prevent dust or water accumulation) [49].

Considering local coordinates (latitude) and module orientation, the next step consists in getting information about the solar resource. The most common sources for this are Photovoltaic Geographical Information System (PVGIS) [51] and NASA Surface Meteorology and Solar Energy [52]. Both sources have lots of information but the most relevant for sizing are monthly irradiation on horizontal plane ($G_{dm}(0)$) and monthly irradiation on chosen angle plane ($G_{dm}(\beta)$), measured in daily Wh/m^2.

To compute the energy demand (load), it is necessary to know the total daily load. Each equipment has its own load that may be calculated multiplying the nominal power of operation (P_l) by the daily time of use (t_l). The total daily load is simply the sum of the daily load for each one of the n pieces of equipment that are supposed to be locally used.

$$Total\ daily\ load = \sum_{i=1}^{n} P_{l(i)} \times t_{l(i)} \qquad [\text{Wh/day}] \qquad (15)$$

Taking into account the solar energy available (in the "worst month") and the electrical energy required, the following parameters may be calculated: current that the array of modules needs to provide (and number of modules), battery bank capacity (and number of batteries), electrical characteristics of the charge controller (and inverter if necessary) and length and sections of cables [49], [50]. With installed power to fulfil load and other system specifications sizing is complete.

The installed power (P_{peak}) should be calculated considering total daily load, peak solar hours (PSH) and required PV power (P_{pv}) in accordance with Equation 16 [50].

$$P_{peak} = \frac{P_{PV}}{PSH} \qquad [\text{W}_\text{p}] \qquad (16)$$

The required power is calculated using the next equation, where components efficiency are considered.

$$P_{PV} = \frac{Total\ daily\ load}{\eta_{cables} \times \eta_{charge\ controller} \times \eta_{battery} \times \eta_{inverter}} \qquad [\text{Wh/day}] \qquad (17)$$

Once the worst month production and total daily load are known, some additional calculations need to be done in order to choose the most suitable system components (PV module, battery, charge controller and inverter). In what concerns PV modules, one may choose among the options available taking also into account that three different types of connections between them can be used: series, parallel or mixed. This allows the system to be designed in order to fulfil the desired power, voltage and current. The modules should have a V_{max} a bit higher than the nominal voltage of the system (V_{DC}) and battery. To calculate the number of modules in series (N_s), in parallel (N_p) and the total number (N) the following equations should be used (on Equations 18 and 19, the lowest superior integer must be used) [50].

$$N_S = \frac{V_{DC}}{V_{max}} \qquad [\ ] \qquad (18)$$

$$N_p = \frac{P_{peak}}{P_{módulo} \times N_s} \qquad [\ ] \qquad (19)$$

$$N = N_s \times N_p \qquad [\ ] \qquad (20)$$

The necessary area for PV module(s) may be calculated using equation 21. Of course, in small scale applications like the one we are interested in, in general, only one PV panel will be needed.

$$A_{necessary} = A_{1module} \times N \qquad [m^2] \qquad (21)$$

The capacity of the battery is determined using the next equation. The maximum deep of discharge (DOD_{max}) is essential because it is not recommended fully to discharge the battery.

$$C_B = \frac{\frac{n \times Total\ daily\ load}{V_{DC} \times \eta_{cable}}}{DOD_{max}} \qquad [Ah] \qquad (22)$$

If more than one battery is necessary, the number of batteries in series (N_{bs}) is calculated by the upcoming equation, where V_{Nbat} is the nominal voltage of the battery. It is important to mention that special care is recommended when batteries are connected in parallel, namely, one should never use different battery types in such of associations, since they will in general have different voltages or, more importantly, different charge rates and capacities, thus resulting in a shortened life span.

$$N_{bs} = \frac{V_{DC}}{V_{Nbat}} \qquad [\ ] \qquad (23)$$

The charge controller (or regulator) has its own characteristics: input (I_{in}) and output (I_{out}) current, as well as output power (P_{out}). These values can be calculated by Equations 24, 25 and 26, accordingly [50].

$$I_{in} = \frac{P_{peak}}{V_{DC}} \qquad [A] \qquad (24)$$

$$P_{out} = P_{load} \qquad [W] \qquad (25)$$

$$I_{out} = \frac{P_{out}}{V_{DC}} \qquad [A] \qquad (26)$$

Lastly, it is necessary to select the appropriate cables. The length should be known and the section is calculated by the following equation (where S is the section, r is the resistivity, L the length and $\%V_N$ the voltage drop in the cables).

$$S = \frac{r \times L \times I_{mMax}}{V_{DC} \times \%V_N} \qquad [mm^2] \qquad (27)$$

Besides considering the previous equation, S should be chosen according to the cables available in the market. The immediately superior cross section available may be used (the smaller the section, the smaller the losses by Joule effect). It is also important to consider, for safety reasons, that the minimum cross section for cable between module and battery should be $6mm^2$ and for the rest of the system $4mm^2$ [49].

The typical acceptable voltage drops in cables are shown in the next table.

Table 17 - Typical acceptable voltage drops in cables, according to [49]

Section of PV System	Voltage drop (% of V_N) [%]
Panel Array-Battery	1
Battery-Converter	1
Main line	3
Main line (illumination)	3
Main line (equipment)	5

3.3.2 Lumisol Sizing and Components

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3.3.3 System Design

The most important decisions related with the system design are the options related to the location of the PV module and the battery. In what concerns battery location different options were considered: underground, ground, middle of the pole and top of the pole. The underground solution has a better temperature performance, but flooding may be a huge problem; both ground and middle of the pole solution may present problems related to safety, since batteries are in general problematic targets for thefts in these regions; taking this into account top of the pole installation seems to be the most reliable and safe solution. In what concerns the PV module top of the pole installation was also the option since it minimizes shadows on the PV module and also provides a good shadow under the panel for the installation of the battery box. It is also important to note that the box has ventilated holes. In Figure 24 the final solution for the system is schematically represented. Detailed drawings of the different parts are presented in Appendix 7.1. A dynamic flow simulation was done with SolidWorks' software in order to test system stability.

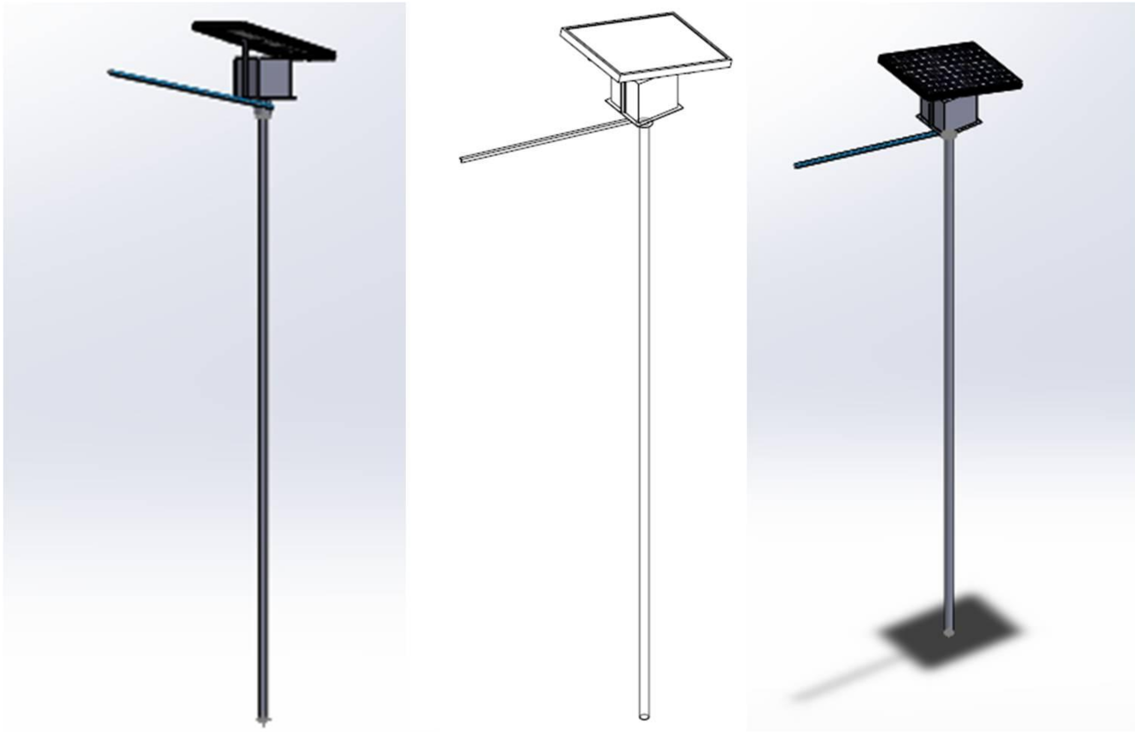

Figure 24 - System Design (obtained in SolidWorks)

3.3.4 Remote Monitoring

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3.3.5 Costs and Economic Analysis

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3.3.6 Product Performance Analysis Across Africa

PV sizing was done for Uganda and system components were chosen based on this assumption. To eliminate sizing costs and thus achieve scale economies a performance analysis across Africa will be presented, in order to evaluate if the designed solutions may be used across Africa. Five additional places will be considered (Table 18): an island in the equatorial Atlantic (São Tomé and Príncipe), a place in the Tropic of Capricorn (Botswana), a place in the Tropic of Cancer (Niger), one of the most southerly places (South Africa) and one of the most northerly places (Tunisia).

Table 18 - Coordinates of all considered countries

Country	Latitude	Longitude
Uganda	00°25'27" North	33°12'15" East
São Tomé and Príncipe	00°00'25" South	06°31'20" East
Botswana	23°00'00" South	26°00'00" East
Niger	23°00'00" North	12°00'00" East
South Africa	34°35'49" South	19°54'26" East
Tunisia	37°18'57" North	09°44'26" East

First of all, it is necessary to know daily consumption. It will depend on night time and number of hours at different power levels (Table 19).

Table 19 - Night time, number of working hours at different power and daily consumption (night time data from [51])

Country	Night time (maximum) [h]	Number of hours at			Daily consumption [Wh]
		Maximum Power	50% of Maximum Power	20 % of Maximum Power	
Uganda	12	4	3.5	4.5	95.2
São Tomé and Príncipe	12	4	3.5	4.5	95.2
Botswana	14	4	4	6	100.8
Niger	14	4	4	6	100.8
South Africa	15	4	4	7	103.6
Tunisia	14.5	4	4	6.5	102.2

With the information from the previous table, PVGIS was used to determine PV potential and stand-alone PV estimations. Firstly, it is necessary to know the irradiance on a fixed plane. This plane was defined as 15º N and 15ºS for all countries and absolute value of latitude plus 10º for countries that are not in Equator line, north oriented for south hemisphere countries and south oriented for north hemisphere countries. Since PV modules should be towards equator it is expected that in Botswana and South Africa PV modules should be north oriented and in Niger and Tunisia south oriented. Prototype can have 2 orientations so in Botswana and South Africa, all modules should be north oriented and in Niger and Tunisia all should be south oriented.

As can be seen in Figure 25, in Tunisia (47N) and Tunisia (15N), South Africa (44S) and South Africa (15S), Niger (33N) and Niger (33S) battery becomes fully discharged in more than 25% of days. In addition, in Tunisia (15S) and South Africa (15N) battery becomes fully discharged in 2% and 1% of days, respectively. This means that if the prototype is installed in these places, maximum depth of discharge will not be taken into account in all days, and battery lifetime will decrease.

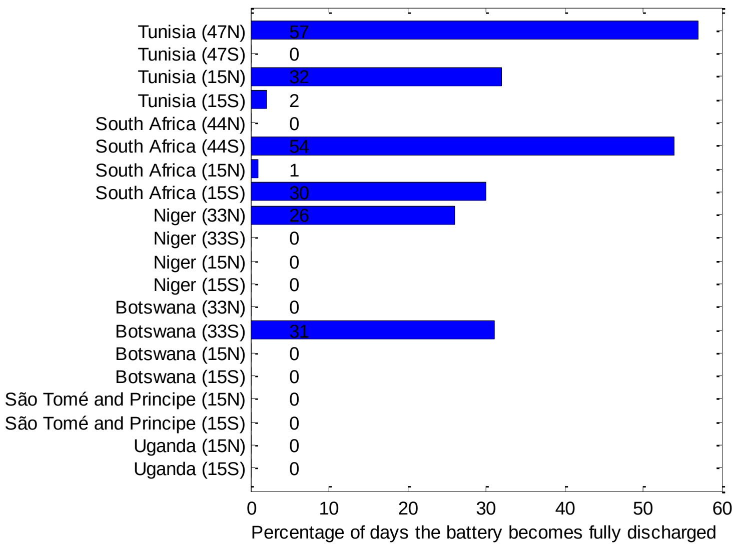

Figure 25 - Percentage of days the battery becomes fully discharge (data from [51])

Based on the previous data, from now on, 15S and 15N will be considered in Niger, Botswana, São Tomé and Príncipe and Uganda; 47S and 15S in Tunisia; and 44N and 15N in South Africa. Figure 26 has the percentage of days with fully charged battery.

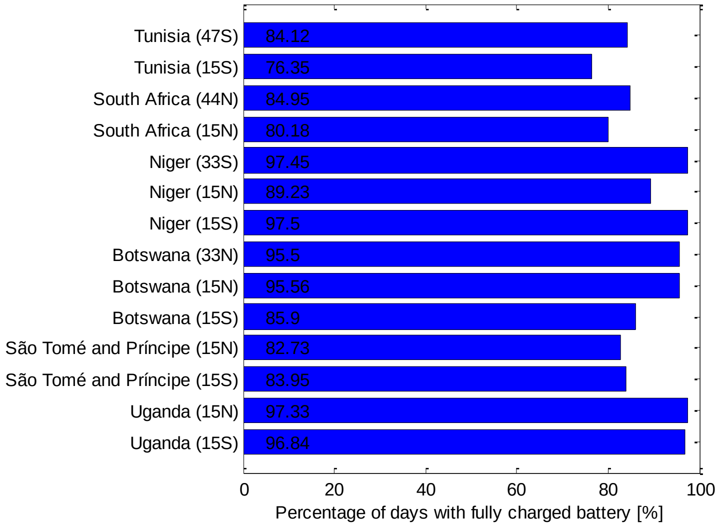

Figure 26 - Percentage of days with fully charged battery (data from [51])

As expected, higher values correspond to Uganda case, as well as Niger (south oriented) and Botswana (north oriented). In Tunisia and South Africa system has a better performance with inclination equal to latitude plus ten, although even here 15S or 15N has more than 75% of days with fully charged battery. A more detailed analysis of battery state of charge status is available in Table 20.

Table 20 - State of charge (data from [51])

Country		Percentage of days with each state of charge [%]									
State of charge		50 to 55	55 to 60	60 to 65	65 to 70	70 to 75	75 to 80	80 to 85	85 To 90	90 to 95	95 to 100
Uganda	**15S**	0	0	0	0	0	0	1	30	16	50
	15N	0	0	0	0	0	0	1	30	16	51
São Tomé and Príncipe	**15S**	0	0	0	0	1	1	4	34	16	41
	15N	0	0	0	0	1	2	4	34	16	41
Botswana	**15S**	0	0	0	0	1	1	7	27	14	45
	15N	0	0	0	0	0	0	5	28	13	51
	33N	0	0	0	0	0	0	5	28	13	50
Niger	**15S**	0	0	0	0	0	0	3	31	13	50
	15N	0	0	0	1	1	1	4	30	13	46
	33S	0	0	0	0	0	0	3	32	13	49
South Africa	**15N**	0	0	1	1	2	2	8	27	13	41
	44N	0	0	0	0	1	2	9	28	13	43
Tunisia	**15S**	1	1	1	2	2	3	6	27	13	39
	47S	0	0	0	1	1	2	7	29	13	42

As expected, Uganda has the better performance, as well as north oriented cases in Botswana and south oriented in Niger, followed by São Tomé and Príncipe, South Africa (44N), and Botswana (15S). Tunisia (15S) is the worst case, but even here the system works perfectly.

In Table 21 we present the comparison between energy production in both cases: 15º inclination angle and the ideal ones (for each location). It can be seen that the differences are not greater than 4%. In Botswana and Niger, if all systems are oriented 15º to equator, energy production is equal to the one produced in the ideal orientation.

Table 21 - Percentage of average energy production per day when compared to ideal case, with latitude plus ten, equator oriented (data from [51])

	Botswana		Niger		South Africa	Tunisia
	15S	**15N**	**15S**	**15N**	**15N**	**15S**
Jan	100	100	100	101	100	99
Feb	100	100	100	100	100	100
Mar	100	100	100	100	100	100
Apr	99	100	100	100	100	100
May	101	100	100	100	98	100
Jun	99	100	100	100	99	99
Jul	101	100	100	100	100	100
Aug	100	100	100	100	101	100
Sep	100	100	100	100	100	100
Oct	100	100	100	100	100	100
Nov	100	100	100	100	100	100
Dec	100	100	100	97	100	96

Based on the previous calculations it is possible to conclude that a 15º tilt may be used in all cases. In Niger and Botswana, if the system is oriented towards equator, differences are not significant. In South Africa and Tunisia, some little problems appear: energy production is not completely sufficient and battery capacity is lower than the ideal one. Energy production deficit means that PV module is not the ideal one, but the maximum losses are 2% in South Africa winter (May) and 4% in Tunisia winter (December) as can be seen in Table 20. In what concerns battery, for Tunisia and South Africa there are days (maximum 2%) in which the battery will become fully discharged (Figure 25) and SOC can be 50% or lower in Tunisia and 60% in South Africa. The last situation should not be considered to be a problem because 60% is a reasonable value for SOC (Table 20).

3.3.7 FCUL Prototype

A second generation prototype compatible with scenario B was developed at FCUL. Since a pole was not available the prototype was installed in a building roof (Figure 27). Despite not being in accordance with ideal inclination for Lisbon, PV module was installed as it should happen in African locations (15º). Due to time limitations the battery used was an AGM type (instead of GEL) and has a lower capacity (26 Ah).



Figure 27 - Street lighting system installed at FCUL

According to a PVSyst[9] simulation done for Lisbon, using a 50Wp PV module and a 26Ah battery capacity the following data is expected: yearly available solar energy of about 71 kWh; energy losses due to full battery about 34 kWh; missing energy about 0.8 kWh; solar fraction about 98%. In November, December and January solar energy available is not expected to be enough (missing energy occurs only in these months). Solar fraction, as expected, is lower in December (82.6%). In January this value is 91.7% and in November 97.2%.

This system was installed with the remote monitoring system previously described (**Error! eference source not found.**), and data was obtained during a period of about one month (July/August). Typical obtained data will be analysed below. Figure 28 includes the four analyzed parameters for three consecutive days (from 2nd to 4th August): from top to bottom, LDR measurement, voltage between PV module and battery negative terminal, battery voltage, and temperature inside the box.

[9] PVSyst is a software used to analyze and size PV systems

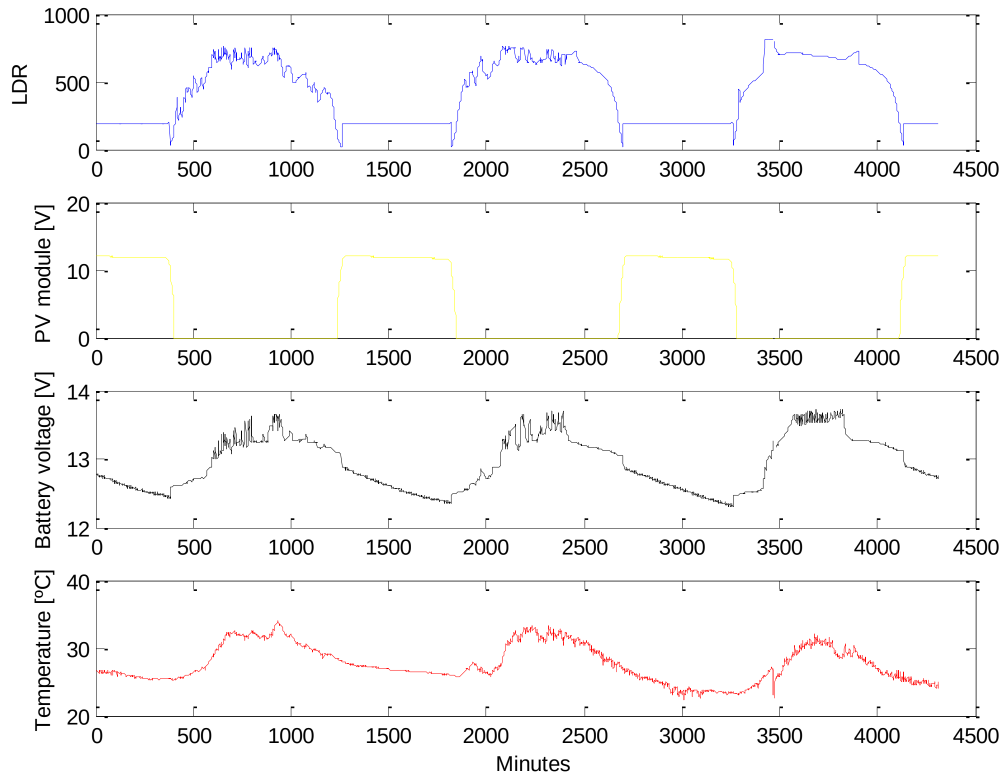

Figure 28 - Monitoring results for 2nd, 3rd and 4th August

It can be seen that all parameters have identical daily profiles. The results obtained with the LDR have a problem because this sensor cannot detect LED power changes, both because it was not installed in the better position, and mainly because the LDR resolution was set to detect daytime light. It is also important to note that in this setup it is only possible to measure the voltage between both PV module and battery negative terminal and not the module voltage by itself. However, despite not being possible to know PV module voltage, measured data clearly shows that the solar panel may be used as a night-time controller, hence avoiding the use of any other type of detector (like the LDR), and, in fact, the implemented code uses this voltage to detect day/night transitions and thus control the light output. As expected, the battery voltage increases during daytime and decreases during night-time. It will be interesting to further analyse this data in order to indirectly measure the instantaneous battery state of charge. The temperature inside the box ranges between 28 and 32ºC. Daily profiles of environmental and box temperatures, as well as their variations (Equation 28) will be further analyzed below.

$$\Delta T = T_{box} - T_{env} \qquad [ºC] \qquad (28)$$

Figure 29, Figure 30, and Figure 31 are representative of the daily temperature profiles obtained through the whole month. Higher grow rates occur between sunrise and 10am. During this period differences between environmental and box temperature are minimum, and sometimes box temperature is lower than environmental temperature (Figure 29). Differences during daytime can be explained by different solar radiation conditions. In a clear sky day the box receives direct solar radiation while in a cloudy day this does not happen. Hence, in the first case, temperature inside the box tends to increase more than in the second one. According to battery voltage and LDR measurements along the day it is possible to conclude that Figure 30 represents a cloudy day and Figure 29 and Figure 31 a clear sky day. Thermal inertia also plays an important role in this system. As can be seen, during night-time differences between environmental and box temperature increase, which means that environmental temperature fluctuation is higher than box temperature fluctuation.

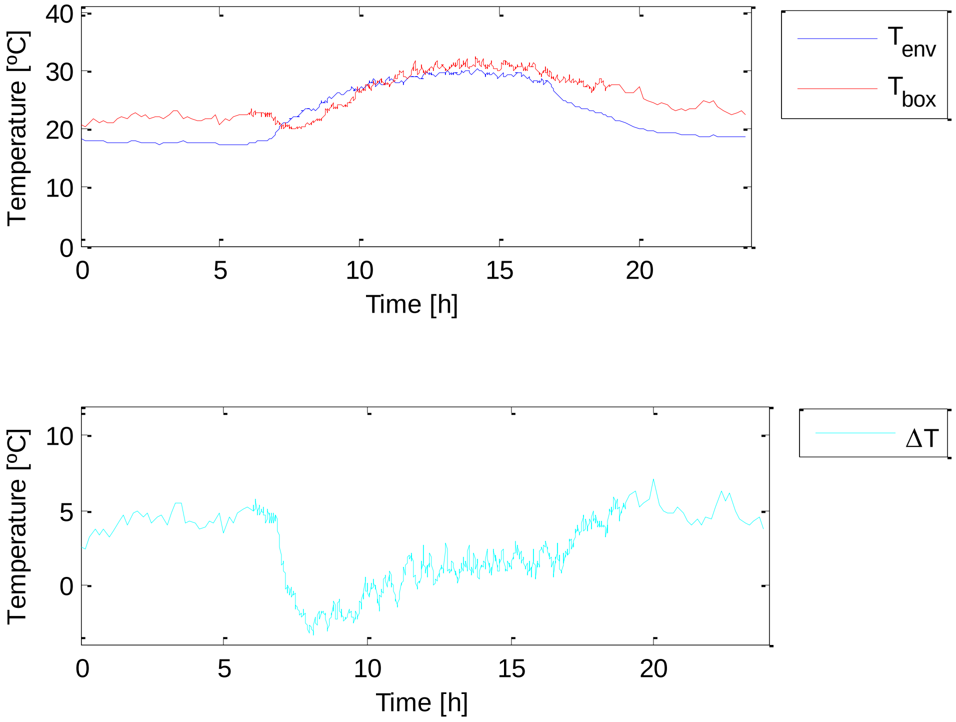

Figure 29 - Daily profile of environmental and box temperatures and their variation (15th August)

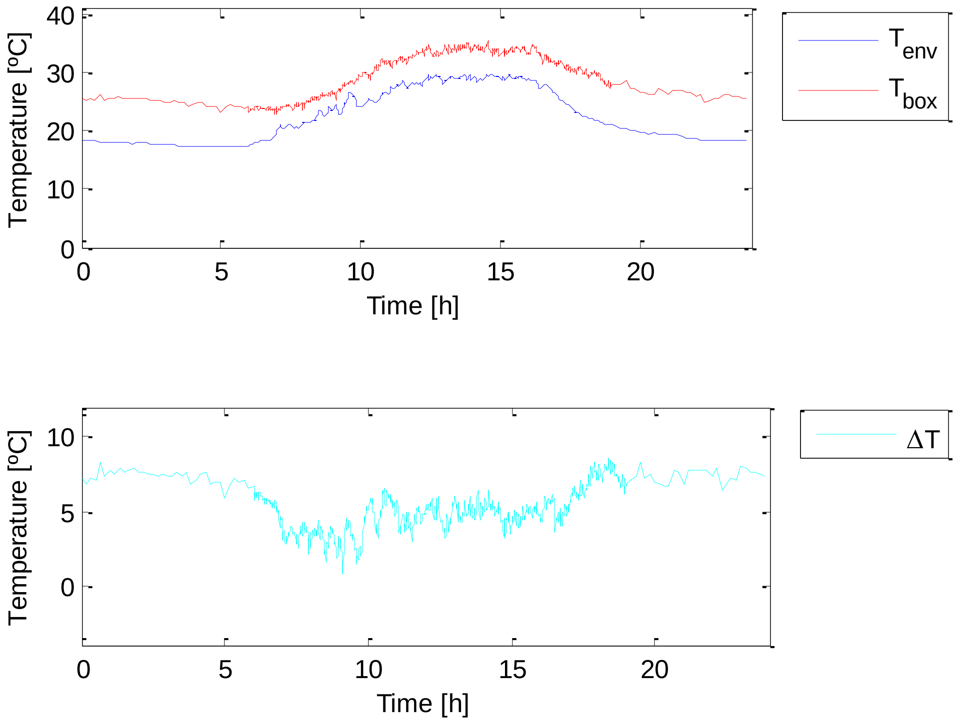

Figure 30 - Daily profile of environmental and box temperatures and their variation (21st August)

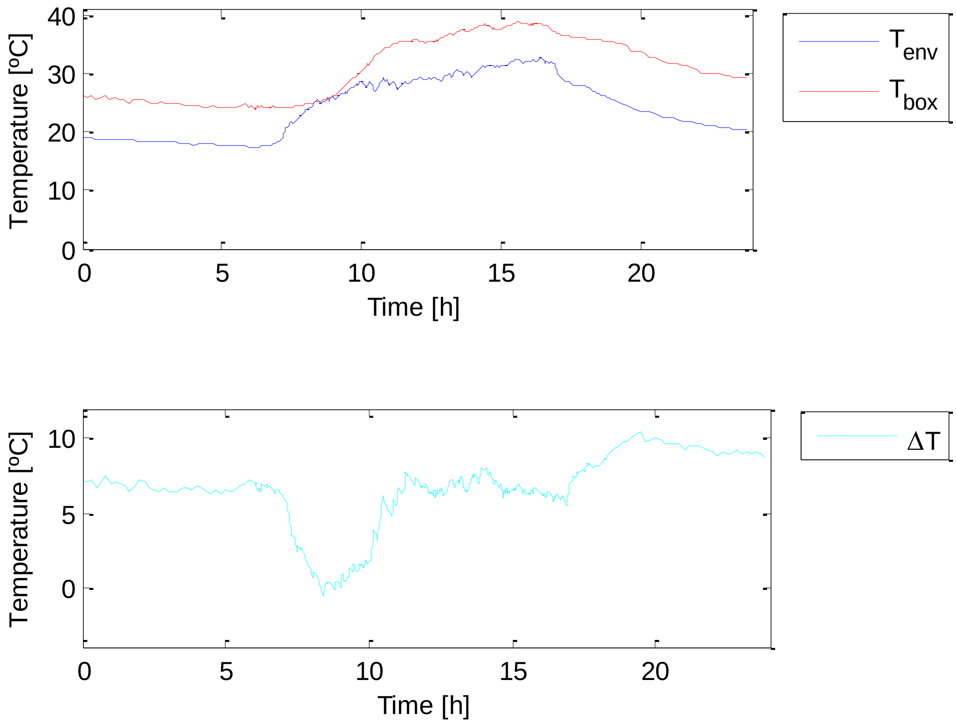

Figure 31 - Daily profile of environmental and box temperatures and their variation (31st August)

The following figure represents daily maximum and minimum temperatures for box and environment.

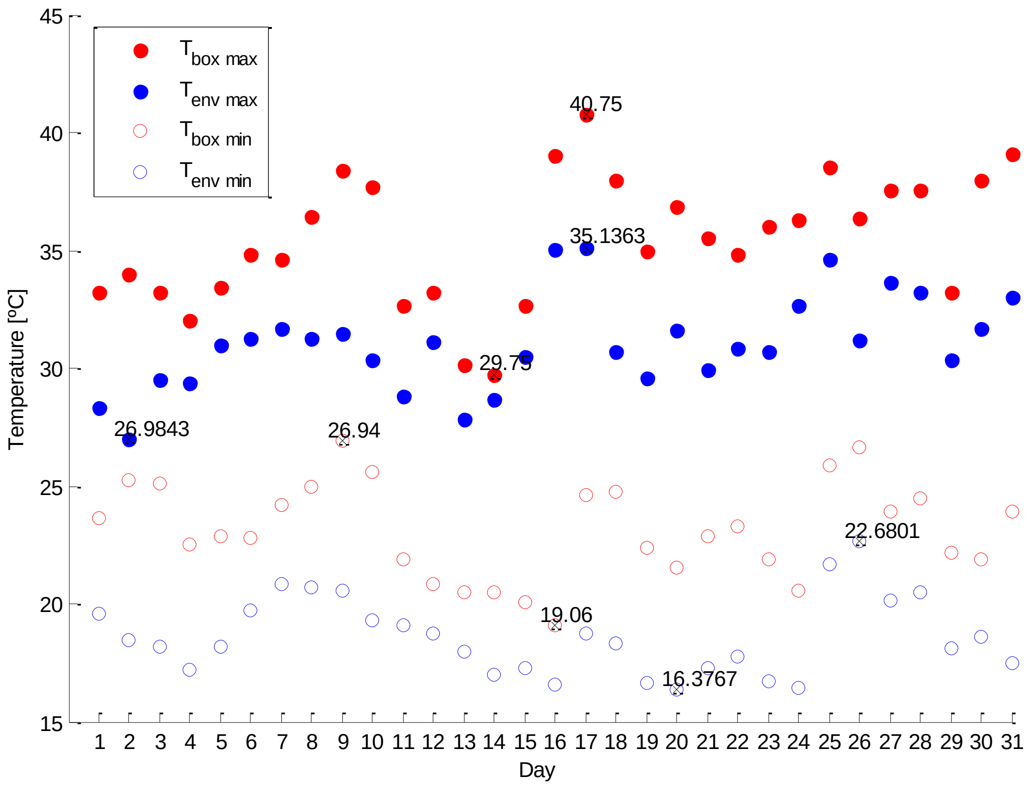

Figure 32 - Box and environmental maximum and minimum daily temperature (August 2014)

Average daily temperature is 24.8ºC, while average box temperature is 29.3ºC or 4.5ºC higher than daily temperature. This difference is probably the most relevant indicator for the present analysis. Average maximum and minimum environmental temperature are 31.0ºC and 18.6ºC. Average maximum and minimum box temperature are 35.5ºC and 23.2ºC. As can be seen, maximum temperature for box and environment occurs on 17th August (40.8ºC and 35.1ºC respectively). Environmental temperature ranges between this last value and 16.4ºC, and minimum temperature occurs in different days along the month. Minimum temperature inside the box is 19.1ºC (16th August) while the highest minimum temperature is 26.9ºC (9th August).

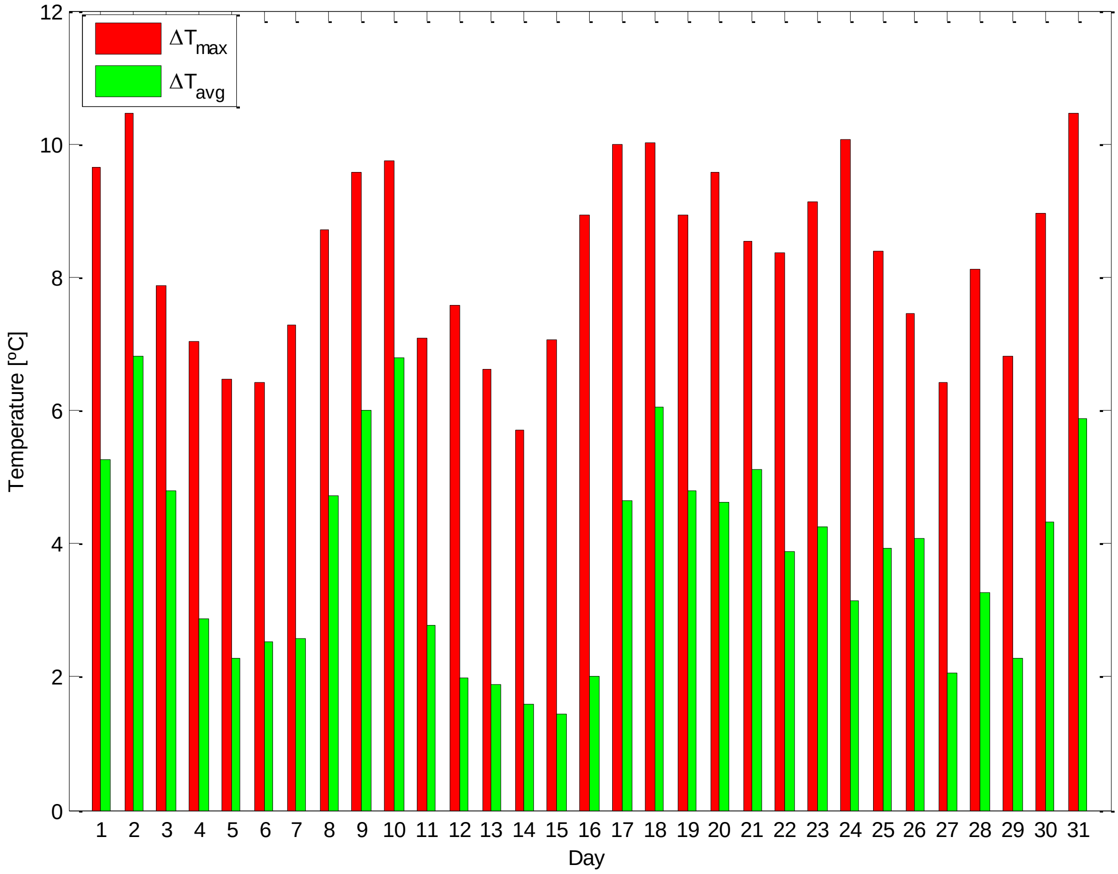

Figure 33 - Maximum and average variation of daily temperature (August 2014)

Maximum daily temperature difference between battery box inside and ambient temperature and the corresponding daily average (Equation 28) are represented in Figure 51. This data shows that maximum and average difference occurs on the 2nd August, 10.5ºC for maximum and 6.8ºC for average variation. The average of maximum difference is 8.3ºC. If this maximum difference occurred during daytime the main conclusion of these study would be that, on average, we should consider that the temperature inside the box is 8.30º C higher than environmental temperature. However, in this context this value is not interesting because this maximum range occurs for lower temperatures, as a result of the thermal inertia inside the box during night.

A further detailed analysis should be done in order to understand the influence of temperature on battery lifetime. It is also important to know the influence of each component (except PV module and LED module) on the box temperature. For example, 20% of battery power might be used to heat the box. It is also important to note that a fan could be used to decrease temperature inside the box. This fan could work all day or only when temperature inside the box reaches a predefined difference relative to ambient temperature.

3.4 Grid Connected Street Light with Storage Capacity

Only available on confidential document.

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4 Marketing Plan

A marketing plan report should include 6 chapters, namely: executive summary, company description, market overview, market analysis, marketing strategies and appendices [53]. However, in this document, only some of these topics will be analysed: a briefly description of the company, and a market overview/analysis.

The products were developed within an existing partnership between RVE.Sol and the Faculty of Sciences, University of Lisbon. The University was responsible for the know-how and the development of the prototype, while RVE.Sol would be responsible for marketing and product distribution. RVE.Sol was chosen as a partner for their vision on renewable energy market, namely because one of their missions consists in contribute to the human right to light [54].

Africa had in 2006 about 2,221,760 km of roadways, representing 3.5% of world roadways [55]. In the world, in 2011, 1.3 billion people did not have access to electricity. In Sub-Saharan Africa almost 600 million people live without access to electricity and 75.6 million people are connected to under-serviced grids [56]. Products developed in the present work will contribute to a better life for these people. Lumisol may contribute to the first one of these groups and the grid connected system to the second one.

If one wants to assess the African market for these products, considering all the African roadways is not a good approach. Hence, a case study will be used to develop a simple methodology to define a market potential in some African countries. Bambadinca, in Guinea-Bissau, will be used as an example, and then a extrapolation for other places will be done. Bambadinca was chosen for this simply because the research group that supports this work in the University has a good knowledge about this village due to the fact that they were directly involved in the local electrification project using an hybrid PV-Diesel (for back-up) configuration. During this work the distribution grid was projected, including street lighting, and thus a good set of reliable information is available.

It is important to note that street lighting is a public good, which means that it is a good that is non-excludable, being shared by all members of a community. Accordingly, the main consumer of the developed products will be in general the local government. Despite being the consumer, the government can impose a tax to fund the product availability. Costs presented until now are restricted to manufacturing costs. To establish a retail price it is essential to have reliable information about transport costs, taxes and profit margins. If profit margin definition seems easy, transport will depend on distance and diesel costs, and taxes will change from country to country (or even municipality). As an example, in Mozambique, a 20% tax on imports exists, although all the products that are required by the government do not have to pay these taxes[10]. Hence, in addition to the initial investment, a cost per person and household should be defined, as well as a possible influence in people income based on Bambadinca's case.

Lastly a SWOT[11] analysis of each developed product will be presented.

4.1 Bambadinca case study

Bambadinca is a village near Bafatá, Guinea-Bissau having 6,400 inhabitants in 2009, 99% of them living with less than 2$/day, in one thousand of households [57].

The road length in Bambadinca is not known and accordingly the electrical grid length will be used as road length. Roads in Bambadinca are divided into principal or primary roads and

[10] Information obtained via email
[11] Strengths, Weaknesses, Opportunities and Threats

secondary or residential roads: 3.50 km of primary roads (highlighted in orange) and 8.55 km of secondary roads, a little more than 12 km in total (Figure 34).

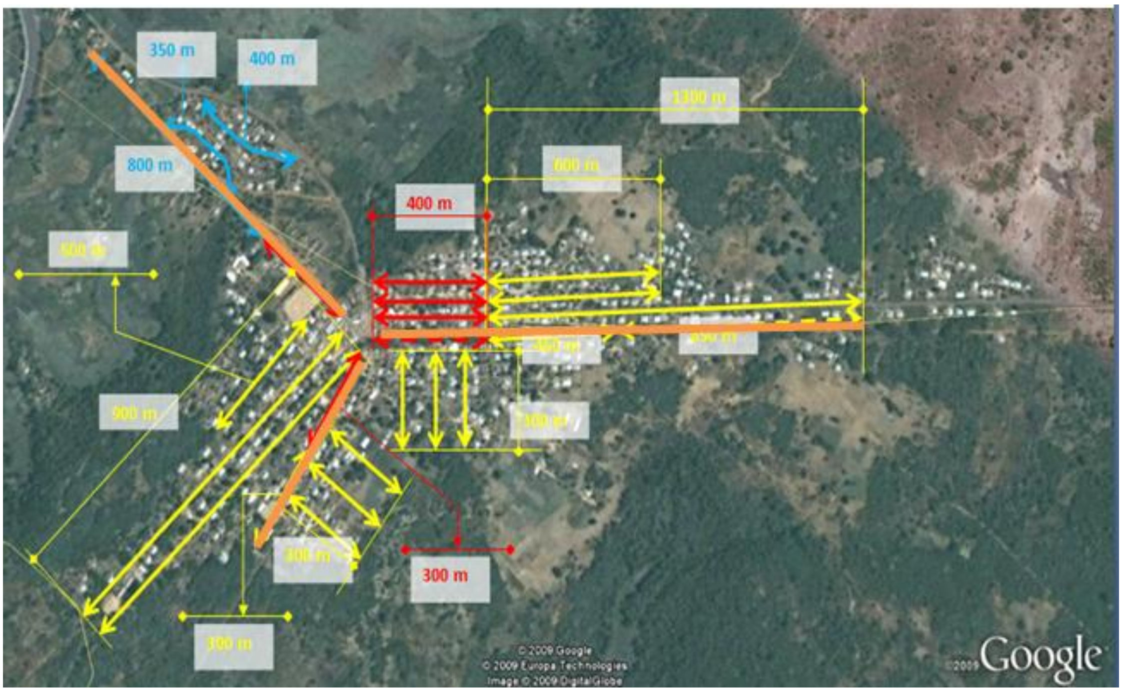

Figure 34 - Electrical grid in Bambadinca

For primary roads typical speed of main user is between 5 and 30 km/h and for secondary roads this value is below 5 km/h. This means that CE classes will be considered for primary roads and S for secondary roads. According to the lighting classes defined in **Error! Reference source not ound.** (for CE class) and **Error! Reference source not found.** (for S class) 4 options are available for street lighting in Bambadinca:

- CE5 for primary roads and S4 for secondary roads;
- CE5 for primary roads and S3 for secondary roads;
- CE4 for primary roads and S4 for secondary roads;
- CE4 for primary roads and S3 for secondary roads.

Table 22 includes the number of poles for each available options, while Table 23 includes this information per person and per household.

Table 22 - Number of poles for each available option

Illumination classes	Number of poles		
	All	Primary	Secondary
CE5+S4	1139	455	684
CE5+S3	1567	455	1112
CE4+S4	1209	525	684
CE4+S3	1637	525	1112

If we consider street lighting in all roads, the total number of systems will range between 1139 (CE5+S4) and 1637 (CE4+S3).

Table 23 - Number of poles per person and per household for each available option

Illumination classes	Number of poles					
	per person			per household		
	All	Primary	Secondary	All	Primary	Secondary
CE5+S4	0.18	0.07	0.11	1.14	0.46	0.68
CE5+S3	0.24	0.07	0.17	1.57	0.46	1.11
CE4+S4	0.19	0.08	0.11	1.21	0.53	0.68
CE4+S3	0.26	0.08	0.17	1.64	0.53	1.11

As can be seen above, the number of poles per person, if we considered street lighting systems in every road, ranges from 0.18 to 0.26, and the number of poles per household ranges between 1.14 and 1.64.

To have an idea of the necessary investment, a retail price for each available scenario is presented below (Table 24). These retail prices were obtained through the application of discount quantities relative to the prototype price and excluding VAT (23% in Portugal). In the end, an increase of 50% was applied (considered here as transport, taxes and profits). In the present example, Scenario B will be used on primary roads and Scenario C on secondary roads.

Table 24 - Retail price

Load Scenario	Cost [€]	
	Without remote monitoring	With remote monitoring
A	755.87	803.90
B	674.09	714.71
C	693.00	728.35
Grid (with pole)	496.15	NA
Grid (without pole)	421.92	NA

Table 25 summarizes the investment needed for each available option for street lighting in Bambadinca, and Table 26 has yearly investment per person and influence on people's income. This last information was done in order to understand the importance of paying for street lighting considering that in general people in Bambadinca's live with 2$ a day[12].

Table 25 - Initial investment for each available option for street light in Bambadinca

Illumination classes	Initial investment [k€]		
	All	Primary	Secondary
CE5+S4	781	307	474
CE5+S3	1077	307	770
CE4+S4	828	354	474
CE4+S3	1124	354	770

Table 26 - Yearly investment per person and by income (for a lifetime of 3 years) for each available option

Illumination classes	Yearly investment					
	per person [€/person.year]			by income [%]		
	All	Primary	Secondary	All	Primary	Secondary
CE5+S4	41	16	25	7.21	2.83	4.37
CE5+S3	56	16	40	9.94	2.83	7.11
CE4+S4	43	18	25	7.64	3.27	4.37
CE4+S3	59	18	40	10.38	3.27	7.11

[12] At 15th of September 1US$=0.773024536€

Initial investment is important in the short-run term but in this context one should also consider operation and maintenance costs. In Table 6 we present an estimation of the total Bambadinca street lighting cost in a 25 year horizon including, initial investment, eight battery replacements, and two LED module and driver replacements. The same is done in Table 28 in what concerns the yearly investment per person and by income.

Table 27 - Total investment for each available option for street light in Bambadinca (lifetime of 25 years)

Illumination classes	Total investment [k€]		
	All	Primary	Secondary
CE5+S4	1,565	620	945
CE5+S3	2,156	620	1,536
CE4+S4	1,661	716	945
CE4+S3	2,251	716	1,536

Table 28 - Yearly investment per person and by income (for a lifetime of 25 years) for each available option

Illumination classes	Yearly investment					
	per person [€/person.year]			by income [%]		
	All	Primary	Secondary	All	Primary	Secondary
CE5+S4	9.78	3.88	5.91	1.73	0.69	1.05
CE5+S3	13.48	3.88	9.60	2.39	0.69	1.70
CE4+S4	10.38	4.47	5.91	1.84	0.79	1.05
CE4+S3	14.07	4.47	9.60	2.49	0.79	1.70

If street lighting will be installed in all roads, its influence on people's income ranges from 1.73 to almost 2.5%. If it is installed only in primary roads, these values will decrease to 0.69 or 0.79%. It should be noted that these values were calculated based on a fixed price for battery and LED module and driver as well as on a fixed income.

4.2 Potential market

Worldwide potential market includes off-grid population and on-grid under-serviced. Table 29 presents the potential market for 1.3 billion people, Table 30 for 598.7 million and Table 31 for 75.6 million people. It is important to note that these values are clearly influenced by street distribution and population density of Bambadinca. This may be a reasonable approach if, in general, the population density and distribution in urban environment does not change to much across different countries.

Table 29 - Number of poles considering a potential market of 1.3 billion people

Illumination classes	Number of poles [million]		
	All	Primary	Secondary
CE5+S4	231.3	92.4	138.9
CE5+S3	318.2	92.4	225.8
CE4+S4	245.5	106.6	138.9
CE4+S3	332.4	106.6	225.8

Table 30 - Number of poles considering a potential market of 598.7 million people

Illumination classes	Number of poles [million]		
	All	Primary	Secondary
CE5+S4	106.6	42.6	64.0
CE5+S3	146.6	42.6	104
CE4+S4	113.1	49.1	64.0
CE4+S3	153.1	49.1	104

Table 31 - Number of poles considering a potential market of 75.6 million people

Illumination classes	Number of poles [million]		
	All	Primary	Secondary
CE5+S4	13.5	5.4	8.1
CE5+S3	18.5	5.4	13.1
CE4+S4	14.3	6.2	8.1
CE4+S3	19.3	6.2	13.1

If we considered worldwide potential market, the total number of poles would range between 231.3 and 332.4 million. If one focus on African market alone, off-grid potential ranges between 106.6 to 153.1 million poles and on-grid potential represents 13.5 to 19.3 million poles. However, considering all Sub-Saharan market or even a short market share of this does not seem to be a reasonable approach because it would require a huge distribution channel. Hence, a selection of some countries was done in order to define a potential market: Guinea-Bissau (the example used in the current study), Uganda and Mozambique (the most likely site of installation according to RVE.Sol) were used for this. Population, market size and business environment in each country is available in Table 32.

Table 32 - Populations, market size and business environment in the selected countries [56]

Country		Guinea-Bissau	Mozambique	Uganda
Population in 2012 [millions]	**Total**	1.7	25.2	36.3
	Off-Grid	1.3	20.7	30.4
	On-Grid under-serviced	0.1	0.8	0.9
Market size (in 43)		38	8	6
Business environment		NA	Average	Average

The number of poles in each country and the total number of poles is presented in Table 33.

Table 33 - Number of poles in Guinea-Bissau, Mozambique and Uganda

Illumination classes	Number of poles [thousand]							
	Guinea-Bissau		Mozambique		Uganda		Total	
	All	Primary	All	Primary	All	Primary	All	Primary
CE5+S4	249.2	99.5	3,826.3	1,528.5	5,570.4	2,225.2	9,645.9	3,853.2
CE5+S3	342.7	99.5	5,262.5	1,528.5	7,661.2	2,225.2	13,266.4	3,853.2
CE4+S4	264.5	114.8	4,061.5	1,763.7	5,912.8	2,567.6	10,238.8	4,446.1
CE4+S3	358.0	114.8	5,497.6	1,763.7	8,003.5	2,567.6	13,859.1	4,446.1

The numbers corresponding to a market share of 5% on these markets are presented in Table 31. As expected, Uganda represents the biggest market and Guinea-Bissau the smallest.

Table 34 - Number of poles in Guinea-Bissau, Mozambique and Uganda for a market share of 5%

Illumination classes	Number of poles [thousand]							
	Guinea-Bissau		Mozambique		Uganda		Total	
	All	Primary	All	Primary	All	Primary	All	Primary
CE5+S4	12.4	5.0	191.3	76.4	278.5	111.3	482.3	192.7
CE5+S3	17.1	5.0	263.1	76.4	383.1	111.3	663.3	192.7
CE4+S4	13.2	5.7	203.1	88.2	295.6	128.4	511.9	222.3
CE4+S3	17.9	5.7	274.9	88.2	400.2	128.4	693.0	222.3

Market limiting factors in each country are also important points to consider. Access to financing and corruption are the most problematic factors for business in Mozambique and Uganda. According to Solar Energy Foundation, freedom from corruption is 20% in Guinea-Bissau, 24% in Uganda and 26% in Mozambique. Organization of the market and competition are 50% for Mozambique and 65% for Uganda, investment freedom varies between 30% (Guinea-Bissau) and 60% (Uganda), availability of financial services are slightly larger than 50% in Uganda and Mozambique, although ease of access to loans are 26% for Mozambique and 37% for Uganda. In what concerns openness to foreign participation, Mozambique has a percentage of 57% and Uganda 71%. Efficiency of import-export procedures are higher in Mozambique (54% versus 40% in Uganda) [56].

After achieving a market share of 5% in Guinea-Bissau, Mozambique and Uganda, our target market should increase. Hence, a 2% of market share will also be presented for Kenya and Tanzania (countries that have land borders with Uganda and Mozambique respectively). Population, market size and business environment in each of these countries is presented in Table 35.

Table 35 - Populations, market size and business environment in Kenya and Tanzania [56]

Country		Kenya	Tanzania
Population in 2012 [millions]	**Total**	43.2	47.8
	Off-Grid	34	38.6
	On-Grid under-serviced	2	1.9
Market size (in 43)		5	4
Business environment		Average	Average

Total number of poles, considering a market share of 2% are available in Table 36.

Table 36 - Number of poles in Kenya and Tanzania considering a market share of 2%

Illumination classes	Number of poles [thousand]					
	Kenya		Tanzania		Total	
	All	Primary	All	Primary	All	Primary
CE5+S4	128.1	51.2	144.2	57.6	272.3	108.8
CE5+S3	176.2	51.2	198.3	57.6	374.5	108.8
CE4+S4	136.0	59.1	153.0	66.4	289.0	125.5
CE4+S3	184.1	59.1	207.1	66.4	391.2	125.5

These two countries will increase our potential market in at least 272.3 thousand poles. Access to financing and corruption are also the most problematic factors for business here (freedom from corruption is 21% in Kenya and 29% in Tanzania). Levels of organization of the market and competition are also identical. Efficiency of import-export procedures are 47% in Kenya and 63% in Tanzania [56].

4.3 SWOT analysis

A SWOT analysis will be done for stand-alone (Table 37) and grid connected products (Table 38). For the stand-alone case a SWOT analysis for each competitor one-by-one is presented in Appendix 7.3. SWOT of Lumisol presented here includes the key items of these last ones.

Table 37 - Lumisol

Strengths	Weaknesses
• Fulfil European lighting standards • 1st generation prototype has been tested in Lisbon for more than 1 year • 2nd generation prototype has been tested in Lisbon for more than 1 month • Dimming mode available • Remote monitoring available • Low power	• High initial investment • Few days of autonomy • Battery type leads to a quick replacement
Opportunities	**Threats**
• Compact size (all in one) • Increased system lifetime by changing battery type • High potential market (600 million people in Sub-Saharan Africa)	• Large scale existing competitors • Competitors already on the market • Competitors with own components

Table 38 - Grid connected system

Strengths	Weaknesses
• Fulfil European lighting standards • Availability of continuous and sufficient supply of electricity • Low power	• High initial investment • Battery type leads to a quick replacement
Opportunities	**Threats**
• Increased system lifetime by changing battery type • Potential market of nearly 75 million people (on-grid under-service in Sub-Saharan Africa) • Unknown competitors so far	• The product value may be difficult to understand by local governments

5 Conclusions

The aim of this work was the development of two products for low income countries, namely, a stand-alone solar street light (based on a previous one developed at FCUL) and a grid connected street light with storage capacity. The stand-alone product is suitable for off-grid population while the grid connected system intends to overcome the problem of grid unreliability.

Street lighting, as a public good service, will increase the quality of life of people by increasing safety, comfort, commercial prosperity, and socialization. The products were developed taking into account EN13201. The "worst month" method was used to size the stand-alone product, while for on-grid system a typical daily failure of 3 hours was considered. Performance analysis across Africa demonstrate that the system can be installed everywhere, although battery lifetime decreases as distance from equator increases. Developed products' initial investment is higher compared to conventional grid power system.

In both systems storage capacity requires special attention since it is essential to know battery behaviour while it is charging and discharging, as well as temperature effect. Monitoring battery charge state could be important, since with this information one can in each moment forecast the energy that is available and adjust the lamp diming to fulfil the lighting time still required. For this it would be better to measure the battery current rather than the voltage, because the result will be much more accurate and independent of the type of the used battery. The most available battery type in the market was used (VRLA), although in the future a different type should be used.

In the stand-alone model, generation and consumption always occur at non overlapping time intervals and in most part of the year this system remains underused. This means that, using the installed PV power, other uses for the generated electricity could in principle be done after the battery is fully charge. However, in a decentralized solution the energy surplus cannot be enough to suppress other energy needs. A local mini-grid for street lighting with centralized storage could be interesting in this context, namely because these other uses for the energy (like cell phone charging for instance) could lead to a lower payback time, and also because of a lower theft risk and probably less expensive maintenance. Therefore, centralized solutions can be an area for further investigation.

Regarding monitoring, if remote monitoring is useless, a charge controller with automatic detection of day and night can be used in the stand-alone system and Arduino is unnecessary. In addition, the Zener diode can be replaced by an optocoupler, which will isolate power circuit from signal circuit. If we pretend to include monitoring, a new concept needs to be defined. Adafruit Data Logger Shield should be replaced by Arduino GSM Shield, meaning that SD card is not necessary and a SIM card should be used. The Arduino GSM Shield allows an Arduino board to connect to the internet using the GPRS wireless coverage (requiring at least an available second-generation wireless telephone technology).

One other important consideration is that, in the near future, the outsourced items should be locally assembled. This would not only contribute to local economy growth but also to a lower cost and probably a faster delivery time. This should be considered in marketing strategy definition in the future.

Developed prototype has been working in accordance with our expectation. Grid connected system has not been tested, although it has a high potential to overcome the problem of unreliable grid despite entailing a highest investment than the one corresponding to the luminaire alone. Concerning the marketing plan, an extrapolation from Bambadinca was done. According to this study, the number of poles per person and per household (based on population density and street distribution of Bambadinca) ranges between 0.18 and 0.26, while the number of poles per household ranges between 1.14 and 1.64. If we considered a market share of 5% in Guinea-Bissau, Uganda and Mozambique, as well as a market share of 2% in Kenya and

Tanzania, the total number of poles will be between 754.6 and 1,084.2 thousand poles (482.3 for the first three countries and 272.3 for the last ones for the lowest option, and 693.0 plus 391.2 for the most expensive option).

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7 Appendix

7.1 Drawings (component by component)

Only available on confidential document.

7.2 Arduino codes

7.2.1 RTC

Only available on confidential document.

7.2.2 Total

Only available on confidential document.

7.3 Cost of the components

Only available on confidential document.

7.4 SWOT analysis

Table 39 - Lumisol vs COVIMED

Strengths	Weaknesses
• Fulfil European lighting standards • 1st generation prototype has been tested in Lisbon for more than 1 year • 2nd generation prototype has been tested in Lisbon for more than 1 month • Lower investment cost • Dimming mode available	• Lower days of autonomy
Opportunities	**Threats**
• Compact size (all in one) • Increased system lifetime by changing battery type	• COVIMED has 10 years of experience

Table 40 - Lumisol vs Fosera

Strengths	Weaknesses
• Fulfil European lighting standards • 1st generation prototype has been tested in Lisbon for more than 1 year • 2nd generation prototype has been tested in Lisbon for more than 1 month • Higher luminous flux	• Lower days of autonomy • Battery type leads to a quickly replacement • Higher installed PV power • Higher initial investment • Fosera has a compact size and can be incorporated in almost every poles
Opportunities	**Threats**
• Increased system lifetime by changing battery type	• Fosera has an Africa sales network with almost 20 local partners

Table 41 - Lumisol vs Philips

Strengths	Weaknesses
• Fulfil European lighting standards • 1st generation prototype has been tested in Lisbon for more than 1 year • 2nd generation prototype has been tested in Lisbon for more than 1 month	• Lumisol always used the same components
Opportunities	**Threats**
• Increased system lifetime by changing battery type	• Philips developed a product for each case • Philips has its own components

Table 42 - Lumisol vs Sunna

Strengths	Weaknesses
• 1st generation prototype has been tested in Lisbon for more than 1 year • 2nd generation prototype has been tested in Lisbon for more than 1 month • Lower initial cost	• Lower days of autonomy • Battery type leads to a quickly replacement • Higher installed PV power
Opportunities	**Threats**
• Increased system lifetime by changing battery type	• Sunna developed a product for each case

Table 43 - Lumisol vs Uniglobe

Strengths	Weaknesses
• Fulfil European lighting standards • 1st generation prototype has been tested in Lisbon for more than 1 year • 2nd generation prototype has been tested in Lisbon for more than 1 month • Lower power consumption • Dimming mode available • Lower initial investment	• Lower days of autonomy (lower PV power and battery capacity)
Opportunities	**Threats**
• Increased system lifetime by changing battery type • Uniglobe available information is not reliable (each document has different system information)	• Uniglobe is already on the market

Table 44 - Lumisol vs ZYLED

Strengths	Weaknesses
• Fulfil European lighting standards • 1st generation prototype has been tested in Lisbon for more than 1 year • 2nd generation prototype has been tested in Lisbon for more than 1 month • Dimming mode available	• Lower days of autonomy (lower PV power and battery capacity)
Opportunities	**Threats**
• Compact size (all in one) • Increased system lifetime by changing battery type	• ZYLED is already on the market, in Africa has a retailer in Lagos, Nigeria