THE UNIVERSITY OF NAIROBI

SCHOOL OF ENGINEERING

DEPARTMENT OF MECHANICAL AND MANUFACTURING ENGINEERING

Project Report

ROAD LIGHTING ENERGY REDUCTION THROUGH TRANSITION FROM HPS LAMPS TO LEDS AND DIMMING

A CASE STUDY OF UGANDA STREET, MERKATO, ADDIS ABABA.

By

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A report submitted in partial fulfilment for the Degree of Master of Science in Energy Management in the Department of Mechanical and Manufacturing Engineering in the University of Nairobi

July 2021

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DEDICATION

This research work is dedicated to my girls Nazarene and Melody and my boy Polycarp. That they may grow up with science and engineering as a friend. Jackline and Tonny, my energetic teenage sister and brother, remember nothing makes you more valid than yourself and what is inside you – go for the best.

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Special thanks to my wife, Pauline Wanjiku, for her ceaseless support and grace in putting up with the enormous hours of study that were necessary to deliver this work.

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ABSTRACT

Street lighting systems are integral to modern cities and greatly enhance their ability for night-time business continuity, provide pedestrian and driver safety through improved road visibility, deter criminal elements and is a source of pride for the communities in which they are installed. Despite their many benefits, city authorities incur huge expenses in establishing and maintaining street lighting systems. The energy costs are even more punitive where HPS lamps are installed. Many interventions have been sought in a bid to reduce the street lighting energy consumptions: switching off streetlights has proved to negate the very essence of their installation since many accidents have resulted. The project has evaluated the energy saving benefits of replacing HPS with LED luminaires, on Uganda Street, a 1.35km road in Merkato, Addis Ababa. *Dialux evo* has been used to evaluate the lighting performance under HPS and LED lighting cases with reference to CEN13201-1 and EN13201-2. Dimming of LED luminaires has been employed to further evaluate additional energy savings. Road night-time traffic data has been utilized to recommend a suitable dimming schedule. Through transition from HPS to LED lighting, 48.52% energy savings have been realized; by further dimming the LED luminaires, a total of 75.98% savings were obtained. A six-year payback period was computed with a positive net present value. The study provides confidence to city authorities that transitioning from HPS to LED lamps significantly lowers their energy consumption burden and is a key measure of reducing their overall maintenance and annual energy consumption costs.

Key Words: HPS, LED, Energy Savings, Dimming and Lighting Performance.

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ABBREVIATIONS

AACRA	Addis Ababa City Roads Authority
CEN	European Committee for Standardization.
CIE	International Commission on Illumination
CRI	Color Rendering Index
CCT	Color Temperature
Cd/m^2	Candela per Metre Square
DALI	Digitally Addressable Lighting Interface.
DMX	Digital Multiplexing
EEU	Ethiopian Electric Utility
EF	Environmentally Friendly
EO	Easier Operation
ESA	Ethiopia Standards Authority
GHG	Green House Gas
GWH	Giga Watt Hour
HID	High Intensity Discharge
HPS	High Pressure Sodium
IEC	International Electro-technical Commission.
IEEE	Institute of Electrical and Electronics Engineers.
IGBT	Insulated Gate Bipolar Transistor.
KEBS	Kenya Bureau of Standards
KWH	Kilo Watt Hour
LED	Light Emitting Diode
LDD	Luminaire Dirt Depreciation
LDR	Light Dependent Resistor
LHS	Left Hand Side
LLD	Luminaire Lumen Depreciation
LLF	Light Loss Factor
MF	Maintenance Factor
MW	Mega Watt.
MWH	Mega Watt Hour
PWM	Pulse
RHS	Right Hand Side

ROW	Right of Way
RSB	Rwanda Standards Board
SCR	Silicon Controlled Rectified
TWH	Terra Watt Hour
UF	Utilization Factor
UK	United Kingdom
US	United States
UV	Ultra Violet
VW	Weighting Value
VWS	Sum of Weighting Value

1.0 CHAPTER ONE: INTRODUCTION

1.1. Background

Street lighting is a key enabler of the political, economic and social life of countries and cities. Social, political and economic activities in cities, at night, largely rely on the visibility, safety and confidence afforded, to drivers and pedestrians, by adequate and quality street lighting. A survey of studies in 13 cities conducted in the United Kingdom and United States noted that introduction of street lighting resulted in crime reduction, in 8 out of the 13 cities, and a generally positive effect in reducing issues of burglary and lawlessness [1]. Installation of street lighting is therefore a source of confidence for communities and a great tool of surveillance offering required deterrence to non-civil elements and actions within a society.

A great emphasis has been laid on lighting up cities all over the world which has fuelled projections that lighting demand will grow by 80% between 2005 and 2030 [2]. This will undoubtedly lead to greater strain on the energy generation utilities and raise the amounts cities spend on offsetting public lighting bills.

Merkato is reputed to be the biggest market not only in Ethiopia but also in the entire Africa, attracting over 200,000 people every day and contributing 20-25% revenue to Addis Ababa City [3]. The market supports hundreds of thousands of people through established businesses and employment. Adequate lighting is central in guaranteeing the safety of the high number of visitors, businesses, tourists and employees within this market.

Addis Ababa City Roads Authority (AACRA) is responsible for the installation and maintenance of street lighting systems in Addis Ababa. Street lighting systems in Merkato are supplied from the Ethiopia Electric Utility (EEU) interconnected grid.

1.2. Problem Statement

150W HPS lamps are currently being utilized for road lighting on Uganda Street leading to a high installed power density and high energy consumptions. The installed road lighting system is a 'full on - full off' system offering the same (100%) level of lighting for the whole of the night which is not only wasteful but also unnecessary since the market road traffic reduces with night-time progression.

Due to overreliance on hydropower, and an electrical load growing by 30% every year, power cuts are frequent [4], in Addis Ababa, rendering installed street lighting systems unavailable. The currently installed street lighting system does not allow lighting level manipulation which would enable a certain, low, level of illumination to be maintained in seasons of low power generation; road lighting is switched off entirely in low power generation seasons.

1.3. Objectives

The main objective of this project was to evaluate the energy consumption reduction contributions of replacing the HPS lamps with LED luminaires.

The specific objectives of the proposed project were:

i) Evaluate existing HPS based road lighting and obtain the total electrical load, average energy consumption density and lighting compliance to EN13201 standards.
ii) Determine the total electrical load, average energy consumption density and lighting compliance to EN13201 standards under LED lighting.
iii) Compute the energy savings achieved through transition from HPS to LED lighting.
iv) Cost benefit analysis of the HPS to LED transition.

1.4. Research Questions

i) What was the power density of the HPS street lighting system?
ii) What LED luminaire sizes were optimal in replacing the HPS luminaires?
iii) What was the resulting road power density under LED lighting?
iv) Based on availed traffic data, which lighting dimming schedules were possible under existing standards?
v) What energy savings were achieved with the recommended dimming schedules?

1.5. Justification

Due to high costs of energy relating to installed streetlights, municipal authorities have been looking for ways to minimize the overall energy consumptions. In the United Kingdom, some authorities have been switching off the lights during some hours of the night as a measure to reduce costs [5]. Such measures, however, may be potentially dangerous and may reduce road visibility and lead to accidents. In 1973, roadway lighting was turned off in Austin, Texas, as an energy conservation measure - this resulted into significant energy savings (450,000 kWh of energy per year) but led to a surge in the rate and severity of accidents on the dark highway [6]. While there were cuts in the costs of energy consumed by the lighting, costs due to accidents over-ran the benefits of switching off the lights. This experiment allowed the conclusion that completely switching off road lighting would be a hazardous way of addressing high highway lighting energy demands.

Merkato, being a market centre with round the clock business and social activities, demand street lighting for all major (principal arterial) streets and interconnecting (secondary arterial) streets - HPS lamps are currently installed in all principal arterial and secondary arterial streets leading to high annual energy consumptions and consequently high energy costs to the Addis Ababa Municipal Authorities. Uganda Street, a principal arterial street, on the boundary of the market is chosen in this project to demonstrate the energy consumption reduction potentials of replacing HPS with LEDs.

Replacement of HPS with lower wattage LEDs should greatly reduce the installed energy consumption density and reduce the annual street lighting energy consumptions - lower energy consumptions should eliminate the need for costly power generation and consequently reduce greenhouse gas emissions. Merkato, being a market area, has significantly predictable traffic volumes and hence lighting levels can be dimmed as the traffic volumes reduces leading to further energy consumption reductions. A dimmed street lighting system, for Merkato, ensures that energy consumption is matched to the visibility needs of the road.

1.6. Scope

Existing and recommended road lighting systems have been simulated (on *Dialux*). Full night traffic data was sought and received from Dorsch GRE German Rail Engineering GmbH, a consultant who undertook traffic studies of the project area in 2019, to inform the LED lighting dimming concept. The project covered lighting on Uganda Street which is a full-length street to the south of Merkato.

1.7. Beneficiaries

The main project beneficiaries are the AACRA, the street lighting infrastructure owner who responsible for installation and maintenance, the EEU, who supply power to the street lighting system, and the people of Merkato who foot the street lighting bills through taxes and various fees.

1.8. Report Organization

This report has five main chapters: the introduction, literature review, methodology, results, analysis and discussion and conclusion and recommendation. The introduction provides the study's background information, problem statement, objectives, research questions, justification, scope and beneficiaries. The second chapter offers literature review on related studies. The third chapter (methodology) describes the project approach including the simulation and calculations' procedures. Chapter four describes the obtained results and analyses their meaning with respect to the project objectives – the energy savings, lighting performance and cost benefit analysis. Chapter five offers a conclusion with an overview of the findings and recommendations.

2.0 CHAPTER TWO: LITERATURE REVIEW

2.1. Introduction

This chapter discusses how street lighting inventions and applications have varied and grown over the ages, the effects of urbanization on street lighting and how modern LEDs differ from HPS lamps in road lighting uses. The chapter also explores the energy reduction possibilities in the use of LEDs (from previous studies), highlights the most recent street lighting design standards, identifies the research gaps from previous studies, explores relevant illumination theory and documents economic assessments that are desirable for road lighting projects.

2.2. Evolution of Street Lighting

With human activities revolving around the ability to see, lighting is one of the aspects of civilization that has been intimately interweaved with the everyday progress of man since the ancient and medieval ages.

2.2.1. Pre-Electricity Street Lighting

Under the Roman Civilization, as early as 500 BC, slaves were used to light vegetable oil lamps, replenish the oil in the lamps, clean, maintain the lamps and extinguish them. This was usually done in front of residences belonging to the rich. Large fireplaces, flaming torches and lanterns were also lit outdoors to provide security and create a different neighbourhood atmosphere and definition. Oil lamps were also carried as people moved and were relied to light up paths and deter thieves.

In 1417, Sir Henry Barton, the Mayor of London ordered that lanterns must be hung outside residences during the winter evenings. This was one of the precursors to modern organized road lighting. In 1524, Paris gave a similar order [7] that all houses facing the streets must have lights on their windows - the lantern had to be hung by 6pm in the most optimal place such that the street would receive adequate lighting. Wealthy Londoners, in the same period, had 'link-boys' who they paid to carry torches on their way, at night, as a measure of security. This was however reliant on the good will of the 'link-boys' who would sometimes lead their masters to dark areas where they would be mugged.

Over the 17th Century, lanterns were made of candles placed in glasses and were hung on cables which would be hoisted across the streets such that the light fell on the middle of the streets. This practice was predominantly demonstrated in Europe - Amsterdam, Paris and London - and human beings were tasked with estimating the sunset and sunrise hours during which they would light or extinguish the lanterns. Towards the end of the 17th Century, lanterns would be mounted on iron brackets. Concerns over energy consumptions were raised during this period and in London, for instance, oil guts were replaced with canola oil to fuel the lanterns [7] - canola oil was reputed as less smelly, cheaper and produced more white light.

In the 1800s, lighting was powered by gas whereby a pipe would relay the gas to a pole mounted lantern. London managed its first gas-lit street in 1807, Baltimore in 1816 and Paris in 1820 - these were the first cities in the United Kingdom (UK), United States (US) and France respectively to offer street lighting.

2.2.2. Arc Lighting

Electric street lighting debuted with the invention of the arc lamps in the late 19th Century (1880-1900) [8] and was greatly enabled by inventions in modern electricity. The arc lamps incorporated the passage of a high electric current between two carbon electrodes. Due to the consequent significantly high light output, the lamps were mounted very high, usually between 20 and 45m, and served as flood lights. While the super brightness of the arc lamps was a major breakthrough since they could illuminate large areas, they faced major shortcomings: the carbon electrodes required frequent replacement and this turned into a full-time engagement for city personnel, the lamps generated huge amounts of heat as they burnt and this resulted into fires in various areas whist burning many technicians, lamp burning emitted the pollutant carbon monoxide, the lamp flickered and would be noisy producing a buzz sound and ultra-violet rays were produced as the lamp burned.

2.2.3. Incandescent Bulbs

Incandescent bulbs were commercialised in early 20th century and their use accelerated between 1900 and 1930 (Though Thomas Edison had invented it in late 19th Century). Light was produced, in incandescent bulbs, through the passage of an electric current on a carbon filament enclosed in a vacuumed glass - vacuum helped prevent oxidation. Discovery of tungsten filament improved the incandescent bulb since they produced brighter light and lasted longer than the carbon filaments. While the incandescent bulb had the desirable qualities of offering intense light with good colour rendering index (CRI) [8], it was limited in that its life span was short.

2.2.4. Low Pressure Discharge Lamps

The passage of an electric current through a long glass tube, within which air has been removed, resulted into the development of discharge lamps such as low sodium vapour lamps. The glass tube is usually filled with inert gas at low pressure and a small portion of other materials such as mercury or sodium. The passage of an electric current makes the free electrons, from the ionised gas, to move across the tube and collide with the metal and gas atoms - the atoms are consequently excited to a higher energy level. When the atoms fall into a lower energy level they produce a photon which result into visible, infra-red and UV light - a fluorescent coating inside the lamp helps in the conversion of the UV radiation to visible light.

Though low-pressure sodium lamps, a type of discharge lamps, produce light at high efficiency, their light is yellow in colour and has a poor colour rendering index and hence only finding limited street lighting / outdoor applications.

The major setback of low-pressure discharge lamps was in in the diffuse, non-directional nature of the light produced which meant they were more suited for high height mountings and occasioned significant light losses.

2.2.5. Mercury Vapour Lamps

Mercury vapour lamps operate under the same principle as the low-pressure discharge lamps, described above, except that vaporized mercury is utilised to produce light. Mercury vapour lamps were brighter than the fluorescent lamps - their major drawback was the hazardous mercury waste.

2.2.6. Metal Halide Lamps

These high discharge lamps were invented to replace the mercury laden vapour lamps and operated by the action of passing an electric current through a mixture of mercury and metal halide salts - the mercury and metal halides being contained in an arc tube made of quartz or ceramic, as shown in Figure 2-1. The metal halides are usually fitted with a ballast that supplies the required high starting voltage.

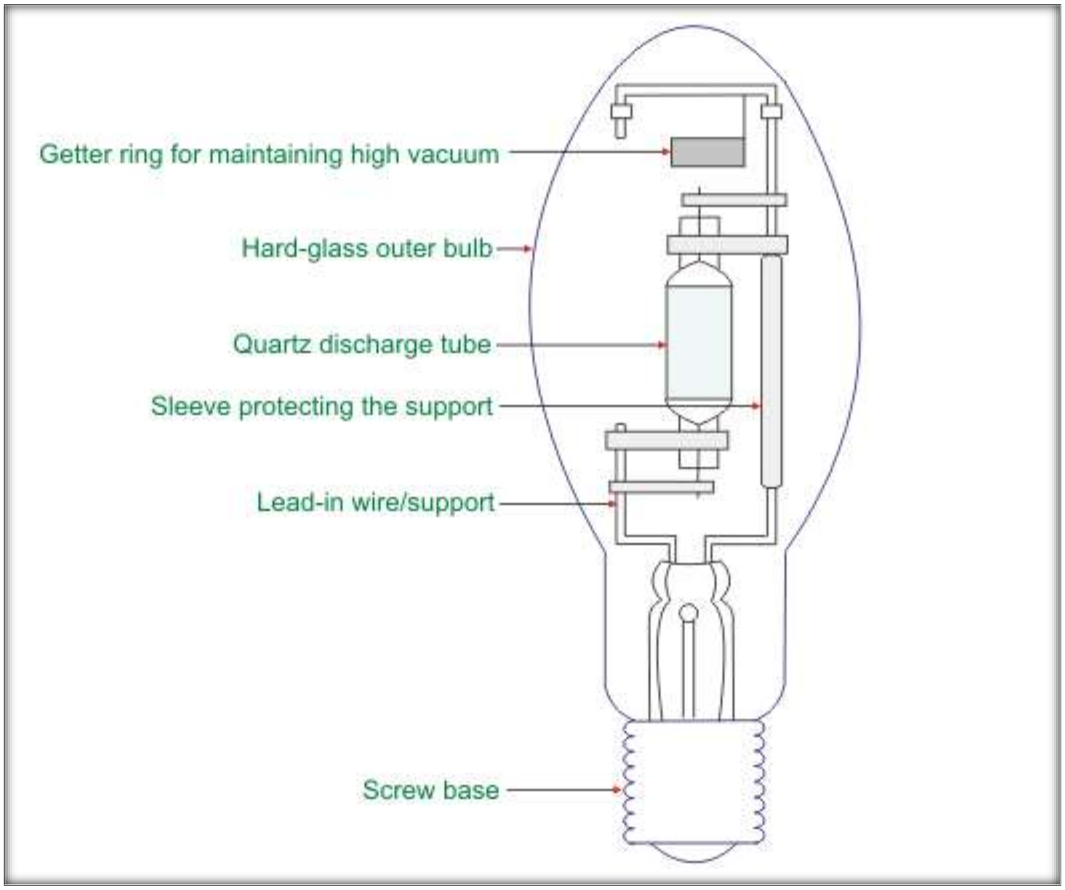


Figure 2-1: Metal Halide Lamp.

Source: Website on https://www.electrical4u.com/metal-halide-lamps/ - accessed in October 2020.

2.2.7. High Pressure Sodium (HPS) Lamps

HPS lamps were invented in the 1970s and have been most widely used in street lighting applications [8]. HPS lamps quickly replaced mercury vapour and metal halide lamps due to their superior efficacy (lumen per watt). The tube surface is made of polycrystalline aluminium to prevent reaction with sodium, and is filled with xenon gas, in the inside, at low pressure. A high voltage, for ignition, is passed through the stem which generates an arc which lights up the xenon gas to blue. The xenon arc consequently vaporises the mercury resulting into a white, blue light. As the tube temperature rises, sodium is vaporised and adds a yellow spectrum to the lighting. Mercury and xenon help add a blue spectrum to the yellow sodium light. The getter ensures a vacuum inside the tube by sucking any unwanted gases. Figure 2-2 shows the main features of a HPS lamp.

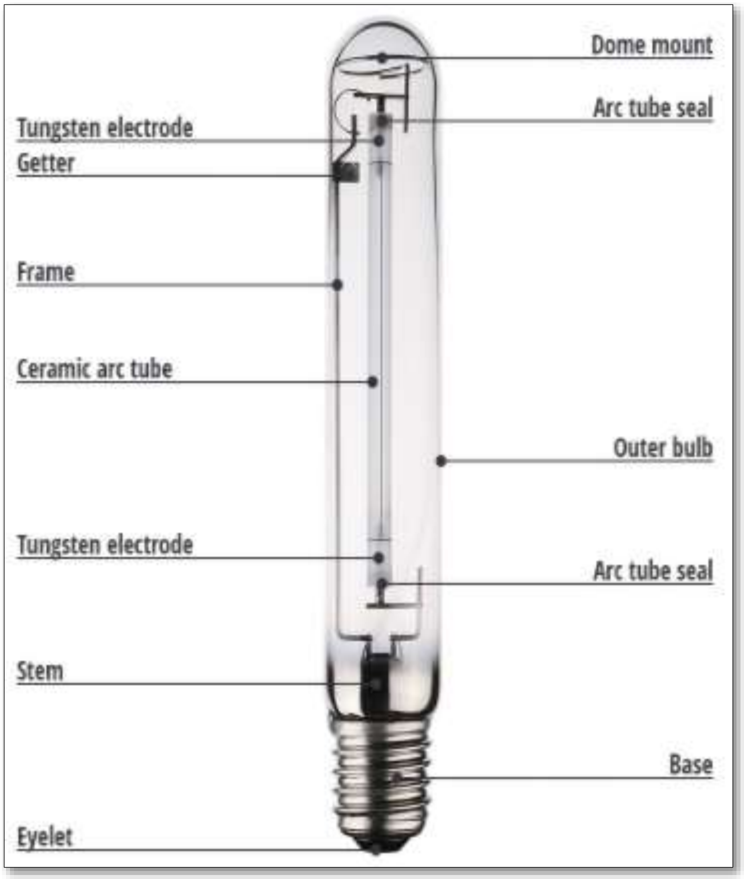


Figure 2-2: High Pressure Sodium Lamp.

Source: Website on https://www.hitentechno.in/sodium-vapour-lamp-working-principles/ - accessed in October 2020.

2.2.8. Light Emitting Diodes (LEDs)

Nick Holonyak, an employee of General Electric, invented the first LED in 1962. LEDs are semiconductor devices which have two leads (p-type and n-type) and emit visible light when a current is passed through them (this action causes holes and electrons to recombine and hence complete the circuit). LEDs were initially used as indicators due to their high costs. With the modern focus on sustainability and lowering of the energy consumptions in lighting, the work of Nick Holonyak and other pioneering scientists has been improved leading to the use of LEDs in street lighting in the 21st Century. LED luminaires boast high lumen per watt, lower sizes compared to other luminaires, faster start-up time and being environmentally friendly since they are not laced with mercury and other pollutants.

2.3. Urbanization and Street Lighting

It was estimated, in 2008, that 50% of the world's population lived in urban centres and the figure was anticipated to rise to 70% by 2050 [9]. The high urban population brings with it great pressure on utilities such as water and energy. Most modern cities, therefore, have witnessed exponential growth in the need for street lighting as a measure to enhance security and guarantee business and social activities during the night-time.

The installation of more street lighting within the ever-expanding cities has led to increases in the amounts cities spend to pay for recurrent energy consumptions and street lighting maintenance. In addition, the effectiveness of street lighting systems depends on the availability of energy and especially a reliable grid. With the street lighting electrical load being supported from the interconnected grid ever growing, power utilities bear the brunt of the consequent pressure to generate more. Power utilities themselves, in Africa especially, face multiple challenges in consistently delivering required energy supplies - chief among them their high dependence on the seasonal hydropower generators. Ethiopia and Kenya are cases in point.

Ethiopia's interconnected grid is supplied from 18 power plants, 14 of these being hydro-power plants [10]. Out of Ethiopia's 4244 MW overall power demand, hydro-electric plants contribute 3808.7 MW (89.74%) while the others (1 geothermal plant, 1 diesel plant and 2 wind power plants) contribute 435.3 MW (10.26%) [10]. Due to overreliance on hydropower, and a load growing by 30% every year, power cuts are frequent [4] rendering installed street lighting systems unavailable. The Kenya Electricity Generation Company (KenGen) summarises Kenya's electrical power generation mix as follows: Geothermal 705.9 MW (39.2 %), Hydro-power 818.2 MW (45.3%), Wind 25.5 MW (1.4%) and Thermal 253.5 MW (14.1%) [11].

Faced with an increasing energy bill due to street lighting, many cities are looking for ways to reduce the consumptions. Between February and November 2010, Colorado Springs turned off 8,800 street lights (out of a total 24,500) due to financing challenges [8]. The City, during this period, introduced an adopt a streetlight program where members of the public could pay 75 dollars to adopt and keep a streetlight powered for an year. While turning off streetlights may temporarily reduce the energy expenditure, it effectively negates the value of investing in the streetlights in the first place. Measures that reduce the instantaneous Road Street lighting power consumptions are more effective in ensuring long term energy sustainability: replacement of old street lighting luminaire with more efficient ones has proven to lead to significant reductions in overall consumptions.

2.4. The Case for LED over HPS Luminaires

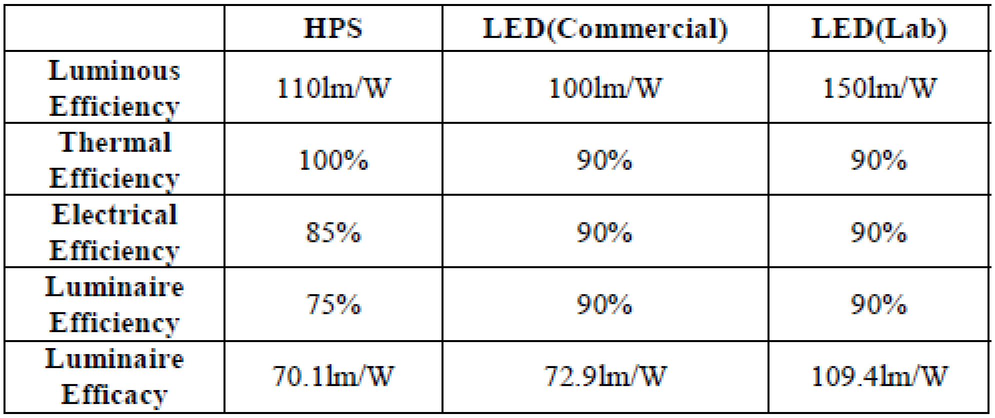
LEDs present a myriad of superior qualities yielding better overall performance over HPS luminaires in street lighting applications as described below;

2.4.1. Higher Useful Light per watt

HPS and LED lamps offer the same range of efficiency (between 100 - 150 lumen per watt). However, HPS lighting is produced in all directions resulting into less light portions falling on the desired surfaces; LED luminaire on the other side emit light in a particular direction resulting into more light quantities being focussed on the required surfaces.

Even though the efficiency of LED and HPS lamps was comparably on the same level, LED lighting with higher efficacy was already in the final stages of deployment due to the remarkably greater attention to LED lighting [12]. Whereas, the current LED lights retain a small edge, in overall efficacy, over HPS lamps, the anticipated developments would significantly push the overall efficacy of LED lighting further ahead as detailed on Table 2-1. For instance, the luminaire utilized for simulations (as attached in the Appendices) has an efficacy of 138 lumens per watt.

Table 2-1: Efficacy of HPS vs LED luminaire [12].



	HPS	**LED(Commercial)**	**LED(Lab)**
Luminous Efficiency	110lm/W	100lm/W	150lm/W
Thermal Efficiency	100%	90%	90%
Electrical Efficiency	85%	90%	90%
Luminaire Efficiency	75%	90%	90%
Luminaire Efficacy	70.1lm/W	72.9lm/W	109.4lm/W

With LED lighting achieving a more targeted spread, over the intended lighting surface, less watts are used to achieve the same illumination level compared to HPS luminaires.

2.4.2. Higher Operational Life

LEDs exceed the operational life of HPS lamps by at least a factor of 4. LEDs, on average have minimum 100,000 running hours [13] while HPS luminaire have an average of 20,000 running hours - HPS lamps consequently have a higher replacement demand which leads to more costs. Based on the longer operational life, LEDs luminaire obtain a higher life guarantee (not less than 10 years compared to HPS luminaire whose guarantee cannot be more than 4 years).

Since more heat is generated with HPS luminaire compared to LED luminaire, especially during starting, a faster natural deterioration is anticipated for HPS lamps. Modern constant lumen output (CLO) LED luminaire guarantee the same lumen output at the end of life of the luminaire - on the other side, HPS lamps have no mechanism to assure of the same level of light quantity at the end of life. The CLO function is integrated as an intelligent circuit, in modern LED addressable ballasts, and adjusts the lumen output of the luminaire, with age, by increasing its wattage relative to expected drop in lumens. The deterioration of the lumen output in HPS lamps means that the lighting level calculated during their initial installation cannot be sustained within its entire life.

2.4.3. Higher Colour Rendering Index

Colour rendering index denote the ability of a light source to reveal the true colours and hence provide an unbiased revelation of an object - the CRI is scaled from 0 to 100 with higher numbers representing a better ability of the light source to reveal an object. HPS luminaires have a poor CRI, not more than 25, while LEDs have a superior CRI of at least 80.

Whereas CRI is important in providing a clearer impression of objects, to drivers at night, its requirement has gained prominence with modern smart cities where more devices have been deployed on the roads to collect law enforcement data (track and trace criminal elements and monitor compliance to traffic regulations) - high CRI lighting is more suited with the growing needs for surveillance. To achieve facial recognition, twice the level of illumination is required for HPS luminaires compared to LED luminaires [12] - leading to higher wattage requirements for HPS luminaires where facial recognition is required.

Some countries allow reduction of lighting levels with high CRI sources [12]. Whereas colour corrected HPS lamps are being developed, with an additional surface to improve the CRI to almost

80, their efficiency and life remains low and hence falling behind the superior and longer life LEDs.

2.4.4. Environmentally Friendly (EF)

Due to their relatively lower wattages, LED lamps result into lower Green House Gas (GHG) emissions. Deployment of more LEDs on the roads and reduction of HPS installations will greatly reduce the amount of GHG that cities release. Modern cities, who are already grappling with high GHG levels due to increased use of fossil fuels and other pollutants, are pressed to look for viable ways to cut down on their carbon footprint and LEDs provide a viable path.

Ye-Obong Udoakah et al, in a carbon footprint assessment of street lighting systems in Nigeria, shows that replacement of 250W HPS with 120W LED luminaires reduces the carbon footprint by more than 50% - this is based on a similar 12 hour daily operation period under diesel power supply [14].

2.4.5. Better Light Colour Temperature (CCT)

LED lighting's colour temperature is between 3500K-4200K [13] compared to HPS's 1900K-2100K [15]. HPS lighting is yellow and warm while LED light is whiter and closer to daylight whose colour temperature is at least 5500K. Smita Shirsale, et al, [16] indicate that LED sources with a wide range of colour temperature 2200K-6000K are available. A higher light temperature is cooler and more intense as opposed to the dull, warm lower temperature lighting.

2.4.6. Easier Operation (EO)

HPS lamps have a warmup time while LEDs switch on and off almost instantaneously. The warm period in HPS lamps takes up to four minutes during which the lamp has not yet achieved full brightness and it displays varying colours.

2.5. Street Lighting Control Techniques

2.5.1. The Photocell

Photocells utilize a light dependent resistor (LDR) to switch on streetlights in the evening and switch them off in the morning based on a set lux level - the resistance of the photocell varies depending on the amount of light falling on it.

Photocells hold the advantage that they are small, cheap and easy to deploy. Power from the distribution sources, usually the grid, is channelled to feeder pillars for onward supply to a group of luminaires - the luminaires are usually wired in parallel from the feeder pillar. Photocells are integrated with the feeder pillars and allow / cut off power supply to the luminaires.

The greatest challenge of deploying conventional photocells as the only means of street lighting control is that they are inflexible - they only switch on and off and cannot be adjusted to vary the lighting levels owing to changes in traffic volumes or other factors. AACRA street lighting design manual 2004 prescribes a lux setting of 20 (±10%) [17] for on/off street lighting switching - a switching ratio of 1. The switching ratio is the ratio between the ON photocell setting and OFF photocell setting.

2.5.2. Dimming

Dimmers are semiconductor devices connected to lighting circuits with the intention of lowering the lighting brightness by altering the waveform of the electrical supply to the lamp.

Rheostat dimmers were the pioneers and utilized a variable resistor to regulate the amount of current flowing through a lamp. These dimmers experienced high heat dissipation and the need for constant cooling was a major setback. Coil-rotation transformer dimmers were next and used two coils, a fixed and a varying position coils, and a varying output was realized by varying the relative positions of the two coils. Auto-transformer followed - they have a tapping knob which steps down the voltage thereby reducing the supply to the lamp and dimming it. Auto-transformers' major disadvantage is that their dimming range is limited, usually 75% to 100%. The challenges with these overly manual dimmers gave rise to the discovery of solid-state dimmers. Dimming can be achieved through the following methods.

i) Forward Phase Control: Current is curtailed during a portion of each half cycle of the sine wave as shown in Figure 2-3. A lower current is consequently achieved by limiting the time through which power is power is ON. Forward phase control is produced through either the triac, dual silicon control rectifier (SCR) and gate-controlled semiconductors (IGBT).

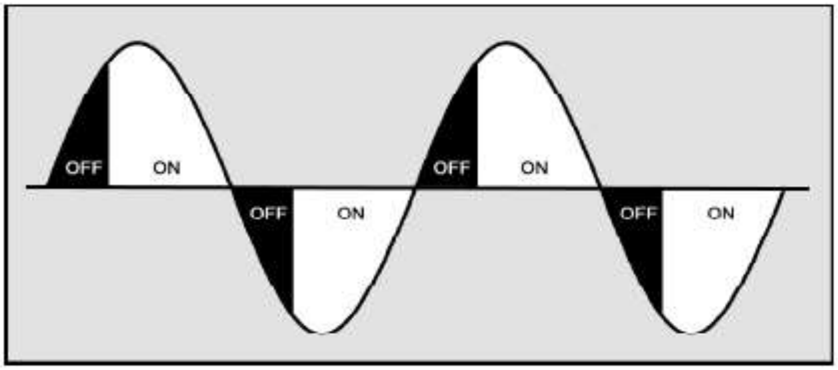


Figure 2-3: Forward Phase Control [18].

ii) Reverse Phase Control: For each half of the sinewave, power is initially allowed to flow and curtailed at the end. Reverse phase control is illustrated in Figure 2-4.

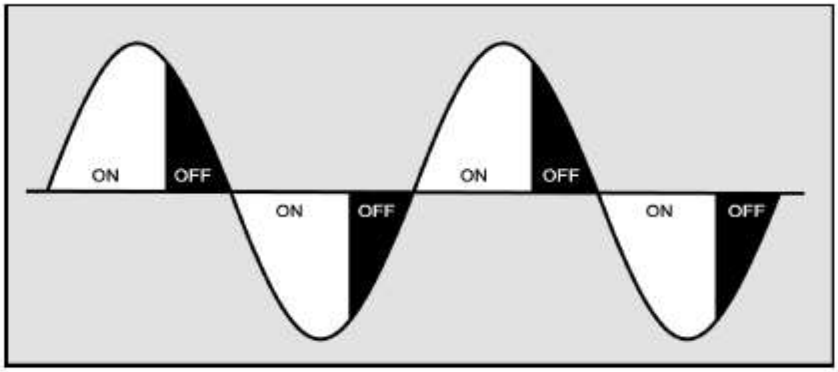


Figure 2-4: Reverse Phase Control [18].

iii) Centre Notch Dimming: This combines the forward and reverse phase control methods in its operational approach as shown in Figure 2-5. Power is allowed in the initial and final portions of each half cycle and curtailed in between.

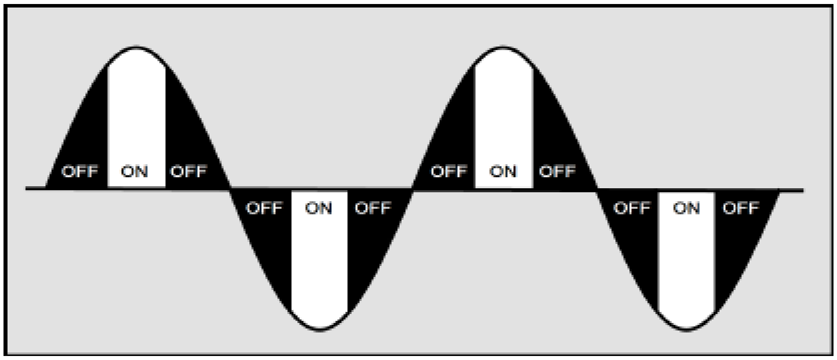


Figure 2-5: Centre Notch Dimming [18].

Modern LED luminaire utilize ballasts which transform ac power supplies to dc. Since the luminaire have a dc input, wired dc signalling is incorporated as part of the ballasts, to relay dimming instructions. Low voltage dimmers have therefore been developed for these ballasts - these dimmers include: 0-10V dimmers, DSI, DMX512 and PWM dimmers. These are discussed below:

i) 0-10V dimmers - the dimming pulse is supplied from the secondary side to the lamp driver, at 0 to 10V; the lamp outputs a current directly proportional to the voltage received from the driver. A Schematic of the 0-10V dimmers is shown under Figure 2-6.

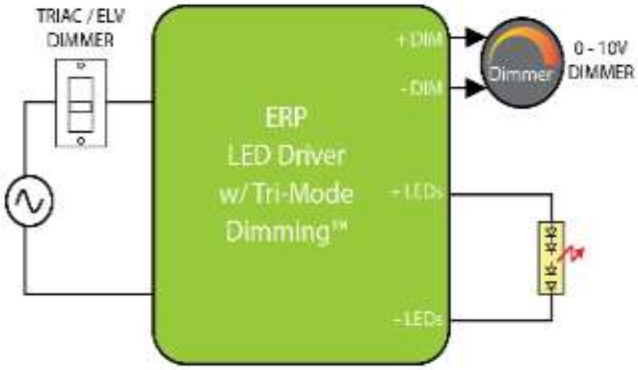


Figure 2-6: 0-10V Dimming [19].

ii) Digitally Addressable Lighting Interface (DALI) Protocol - The protocol is defined under IEC 62386 and utilizes a master and slave arrangement where a number of luminaires with a DALI ballast are connected to a master controller through two wires. One DALI circuit supports a maximum of 64 luminaires over a maximum length of 300m.

iii) Digital Multiplexing (DMX512) Dimming - this is popular in theatre applications and is similar to DALI in that it is a two-wire master/slave configured system. It is however faster than DALI and utilizes RS485 cabling.

iv) PWM dimming - Through pulse wave modulation, the voltage of the incoming electrical supply signal is switched on and off at high frequency. A varying brightness is achieved through varying the duty cycle (the time during which the sine wave is on as a ratio of the total duration).

Dimming has become very popular with the increasing application of LEDs in lighting. Digital dimming allows bi-directional transfer of instruction from the master to the slaves. The master usually is internet enabled and has the capacity to provide luminaire status information (such as status and energy consumption of the luminaire) which could be relayed to a central location for monitoring.

While dimming is mainly carried out to achieve reduced energy consumptions, it is also beneficial in distinguishing the distinct areas through which a road may be passing through. For instance, residential areas could be dimmed to lower levels than commercial areas, during certain hours of the night, to underline that fewer activities are anticipated for residential areas compared to commercial areas.

2.6. LEDs and Dimming -Energy Reduction Potentials

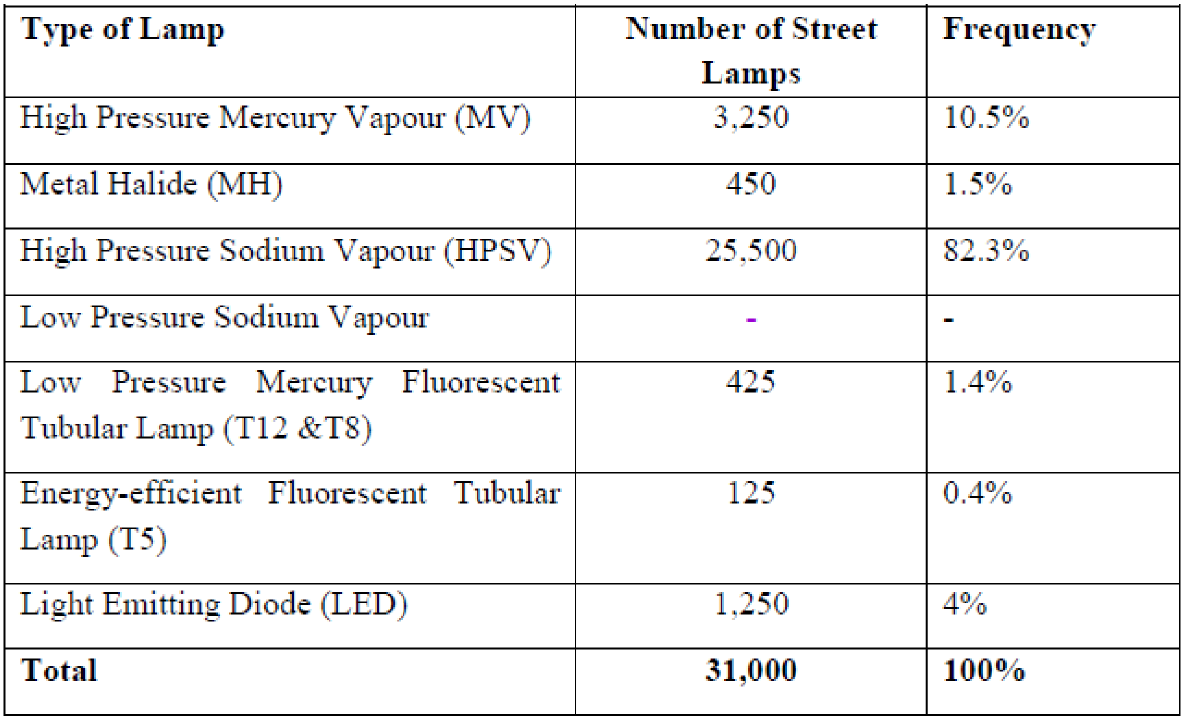
The US Department of Energy estimated, in 2012, that by 2030, 300 TWh of energy savings would be achieved due to an accelerated transition into LED lighting technologies [20]. The enormous number of inefficient street lighting installations was a major contributor to the huge energy consumption and generation burdens and hence the need to move to LED lighting. For instance, more than 26 million aging streetlights, utilizing inefficient technologies existed [21], clearly leaving municipal authorities with huge road lighting energy expenses.

The European e-street project identified 38 TWh [22] of energy savings by replacing old street lighting installations with new luminaire with adaptive capabilities. Under this project, 20,000 luminaires were installed between January 2006 and January 2008 within 12 European Countries. The e-street project report acknowledges the possibility of achieving higher road luminance values with reduced luminaire wattages and hence achieve lower energy consumptions. The report recommends application of CEN TR 13201-1 criterion of road lighting evaluation: selection of required road lighting class and computation of road performance parameters namely the average road luminance, uniformity, threshold increment and surround ratio. The e-street project report, however, does not compare the achieved lighting levels under CEN TR 13201 before and after replacement of the old luminaire.

The city of Pittsburgh in 2011 intended to replace 40,000 HPS and HID streetlights with LED street lights - based on proof of concept studies, undertaken by a consultant before commencing the project, the City estimated that 70% savings in energy and maintenance costs would be achieved; annual reductions would be to the tune of 1.7 million dollars in energy and maintenance cost and 6,818 metric tonnes of carbon dioxide [8].

Available information indicates that old inefficient street lighting installations are still prevalent in Africa representing massive potential energy conservation opportunities. In Nairobi City, Kenya, 82.3% of installed street street lights were high pressure sodium vapour lamps, with LED luminaires representing a paltry 4% - in 2014 [23]. The overall luminaire representation was as detailed under Table 2-2.

Table 2-2: Lamp Types in Nairobi City [23].



Type of Lamp	**Number of Street Lamps**	**Frequency**
High Pressure Mercury Vapour (MV)	3,250	10.5%
Metal Halide (MH)	450	1.5%
High Pressure Sodium Vapour (HPSV)	25,500	82.3%
Low Pressure Sodium Vapour	-	-
Low Pressure Mercury Fluorescent Tubular Lamp (T12 &T8)	425	1.4%
Energy-efficient Fluorescent Tubular Lamp (T5)	125	0.4%
Light Emitting Diode (LED)	1,250	4%
Total	**31,000**	**100%**

The HPS luminaire in Nairobi City is a mix of 150W, 250W and 400W lamps. Florence went ahead to compute that replacement of the 250W HPS street lights with 120W LEDs, would result into 14.52 GWh annual energy savings [23]. Florence [23] did not substantiate the choice of 120W LEDs - through photometric calculations - it is possible that a lower LED luminaire could provide the same illumination level and hence achieve greater energy savings. The energy savings computations were based on 12-hour night-time lighting and further studies may be necessary to ascertain whether all the City areas require lighting for the entire night duration - it is probable that a significant number of areas have a predictably low number of traffic volumes, with night progression, and hence affording the chance to dim the lighting for some hours - this would result into further energy savings.

In Durban, South Africa, the eThekwini Municipality partnered with Philips Lighting, the Department of Environmental Affairs and Eskom in replacing old and inefficient street lighting luminaires with modern high efficiency LEDs. A total of 149 LED Street lights were installed in place of 250W metal halide luminaires in six streets around Durban. A 27% energy savings was reported from this intervention - 47.4 MWh per year- and further savings were expected on the maintenance costs [24]. Philips indicates that better lighting was achieved - no detailed values were offered on the actual photometric values before and after the introduction of LEDs. The LEDs used had a lifetime expectancy of 60,000 hours and a CRI of 68 - this is considered low compared to modern LEDs which have superior performance with running hours and CRI of 100,000 hours and 80 respectively.

Mohammed, Nour, et al, observed in 2018 that non-dimmable, HPS lamps were prominently installed in Bahrain, potentially resulting into unnecessary night-time power consumptions [25]. Traffic surveys conducted, as part of their study confirmed that traffic volumes were significantly reduced between midnight and 6.00 am compared to the other hours of the night. By replacing the HPS luminaire with LEDs, a 35% reduction in power consumption was calculated [25] - this was based on a 1km of a highway study area and a 12-hour night-time luminaire operation. By further dimming the LEDs to 30% of rated output and only allowing full brightness at the passage of a vehicle, 18.69% additional energy reductions were computed under Table 2-3.

Table 2-3: Average energy reductions with LED replacement [25].

Number of luminaire	Energy Consumption (kWh)	Dimmable LED energy consumption (kWh)	% reduction
1	28.22	22.94	18.71
2	56.45	45.90	18.69
4	112.90	91.81	18.68
Average			18.69

Street lighting under the dimmable LEDs was computed using an average speed of 70 km/h for the vehicles passing through the study section - and hence the time the LEDs would be turned on. This method of calculation was uniformly applied for the entire night (12 hours) which is erroneous in that the traffic volume patterns are different for various night times. This dimming arrangement is also difficult to implement in cities with relatively slow or low internet connectivity since sensor and luminaire communication is online.

Mohammad M Mohamoud indicates that LEDs consume 40-80% less compared with conventional HPS lamps [13]. For street lighting applications within enclosed premises belonging to an energy producer, he proceeds to calculate the benefits of HPS replacement with LEDs as being constituted in three: extra energy sales from conserved street lighting energy, pollution savings and operational savings due to lower LED luminaire watt ratings. Eventually, a savings of 433.36 dollars/KW was realized. While the benefits of using LEDs in favour of HPS luminaire were clearly demonstrated, this study method would only be limited in application to energy producing countries/premises where further benefits due to extra sales attributable to HPS replacement are computed.

Fusheng Li, et al advise that 30% savings can be saved through dimming of street lighting and intelligent control [12]. They further indicate that the visibility of drivers is impaired when the dimming executed is below 50% and hence the need for an analysis of how the lighting provided under dimmed circumstances affects the overall drivers' experience on the roads.

2.7. Design Standards

Street lighting guidelines may vary in particulars between regions and countries depending on the specific country and regional needs. The International Commission on Illumination (CIE - french abbreviation for Commission internationale de l'éclairage) is the international authority body on issues of light, lighting and radiations. Besides developing basic standards and guidelines on light and lighting, CIE provides an international platform for engagements on issues of light and lighting. From these basic guidelines, regional and country standards are developed - Most East African countries, are associate members of CIE through their National standards body [26] - for instance Kenya, Ethiopia and Rwanda through the Kenya Bureau of Standards (KEBS). Ethiopia Standards Agency (ESA) and Rwanda Standards Board (RSB). These countries also supplement their country guidelines through the detailed standards made by other members of CIE - for instance in Addis Ababa, Ethiopia, the Addis Ababa City Roads Authority (AACRA) Street Lighting Design Manual, Guideline 7 of 2004 is the elementary design reference - these guidelines are borrowed from CIE publications and portions of BS and New Zealand / Australian Standards. The design discussion, that follow, relied on BS street lighting standards which were developed from CEN & IEC provisions and consequently broadly acceptable in the greater East African region.

CEN provides street lighting guidelines as tabulated under Table 2-4.

Table 2-4: CEN Road Lighting Standards [27].

CEN/TR 13201 Part 1	Guidelines on selection of lighting classes.
EN 13201 Part 2	Performance Requirements.
EN 13201 Part 3	Calculation of Performance.
EN 13201 Part 4	Methods of Measuring Lighting Performance.
EN 13201 Part 5	Energy Performance Indicators.

Under CEN13201-1, there are three road lighting categories as stated below:

i) M class - main driveway lighting class.
ii) P class - pedestrians, cyclists, and other road speed areas.
iii) C class - conflict areas or areas where vehicular and pedestrian traffic are intersecting or constantly coming into contact.

2.7.1. Main Driveway Lighting - M Class

The main driveway is usually characterised by the highest speeds and is susceptible to the greatest level of accidents compared to the other road areas, such as the walkway. CEN13201-1 breaks down M classes into six sub-categories, M1 to M6 where M1 is the most stringent and M6 is the least stringent in terms of lighting requirements [27]. The lighting class to be applied for a given road or road section is evaluated by allocating weighting values (VW) to specific parameters. The M class is calculated as M class = 6 - VWS (Where VWS is the total weighting class).

The specific fields that are to be considered in establishing the VWS are [27]:

i) The design speed/limit of the road.
ii) Traffic volume of the road.

iii) Traffic composition - whether it is dedicated for motorized traffic only or it is mixed with non-motorized traffic.
iv) Whether the carriageways are separated or not.
v) Junction density which is defined based on the number of intersections, interchanges or bridges per kilometer.
vi) Presence or absence of parked vehicles.
vii) Ambient luminosity: Factors in the presence or absence of illumination from the surroundings that may be contributed by neighborhood lighting such as advertisement billboards.
viii) The designers' impression of the navigational ease or difficulty on the road section - this is described as easy, difficult, or very difficult.

CEN13201-1 anticipates that the designer offers an accurate consideration of the above nine parameters - this is a key step in ensuring that the lighting designed for a road is proportional to its requirements. According to EN13201-2, the following parameters are to be computed for class M lighting [28]:

i) Average road surface luminance in Candela per square metre, Cd/m^2. This refers to the required lighting intensity per unit area.
ii) Overall uniformity of the road surface luminance. This is the ratio of the lowest luminance value to the average value.
iii) Longitudinal uniformity of the road surface luminance. This is the ratio of the lowest luminance value to the maximum value as calculated on the centre line of the drive lanes.
iv) Threshold increment / disability glare - this factor accounts for disability glare (discomforting sensation resulting due to the intensity of the light on the eye). The standard acknowledges that glare may vary based on the age of the road user.
v) Edge Illumination ratio - this is the ratio of the average horizontal illumination of a portion outside the roadway to a portion inside the roadway.

2.7.2. Walkway / Cycle Lane Lighting - P Class

P class is applied for all non-motorized road areas including walkways, cycle lanes and parking areas. CEN13201-1 breaks down P classes into six sub-categories, P1 to P6 where P1 has the highest and P6 the least lighting requirements. The lighting class to be applied for a given road or road section is evaluated by allocating weighting values (VW) to specific parameters. The P class is calculated as P class = 6 - VWS (where VWS is the total weighting class).

The specific fields [27] that are to be considered in establishing the VWS are:

i) Definition of the speed - whether it is walking or low speed (less than 40 km/h).
ii) User intensity - normal, busy or quiet.
iii) Traffic composition - whether it is pedestrians only, cyclists only or a mix.
iv) Presence or absence of parking facilities.
v) Ambient luminosity - factors in the presence or absence of illumination from the surroundings that may be contributed by neighborhood lighting such as advertisement billboards.
vi) Whether facial recognition is necessary or not - this is however not weighed but extra requirements are computed.

According to EN13201-2 [28], minimum and average horizontal illuminances are to be computed for class P lighting. If facial recognition is necessary, as may be dictated by the country standards, hemispherical and average hemispherical illuminance are to be calculated.

2.7.3. Conflict Areas Lighting - C Class

Intersections, underpasses, interchanges, and other areas where motorized and non-motorized traffic may be coming into contact fall under this lighting classification. Many country standards allow that the lighting for these areas be provided as the highest of the intersecting roads [17].

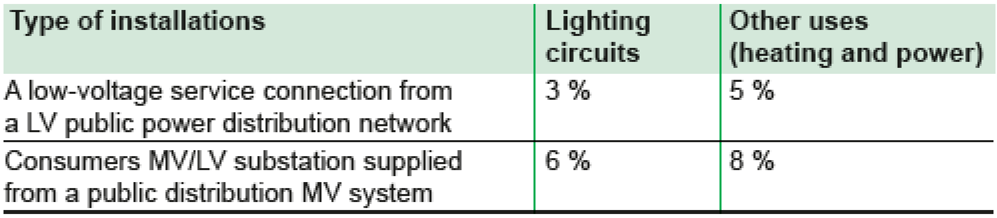
2.7.4. Position of Street Lights

The most optimal positions for streetlights is usually the median (in between the carriageways) or the walkway. The median may not be ideal if it is too wide - very long lighting arms may be structurally expensive and unstable. Poles on the walkway must be positioned such that they are not obstructive to pedestrians. Based on the availability of space and budget, City authorities may dedicate landscaping space which may also be utilized for street lighting positioning.

2.7.5. Power Supply

Grid connected street lighting power is usually supplied from the secondary side of low voltage distribution transformers. Distribution transformers may be served from overhead or underground medium voltage power lines usually located within the roads' right of way. Cabling between the transformer and the furthest luminaire is sized to ensure that the voltage drop does not exceed 3% as provided under IEC60364-5-52 Table G.52.1 as shown under Table 2-5 below.

Table 2-5: IEC Table G.52.1, voltage drop between points of connection and use [29].



Type of installations	**Lighting circuits**	**Other uses (heating and power)**
A low-voltage service connection from a LV public power distribution network	3 %	5 %
Consumers MV/LV substation supplied from a public distribution MV system	6 %	8 %

2.8. Lighting Design Theory

2.8.1. Illuminance and Luminance

Illuminance is the quantity of light, measured in lumens, incident on a road surface per unit area (m^2) - it is expressed in lux (the equivalent to lumens/m^2) as shown in equation 2-1. Under EN13201, illumination is usually computed for intersections (conflict areas) and pedestrian areas. The lumen output of a luminaire is the product of its efficiency and the power (watt) rating as expressed in equation 2-2.

$$\text{Illuminance} = \text{Lamp lumen output (Lumens) / Illumination Area (}m^2\text{).} \qquad \textit{2-1}$$

$$\text{Lumens} = \text{Luminaire efficiency (Lumens / Watt) x Power (Watts).} \qquad \textit{2-2}$$

Luminance is a measure of the effect of the light falling on a given surface - it is also seen as an indication of the perception of the human eye to the light reflected from a surface due to incident light. It is calculated in the same way as Illuminance, but in candela per unit area, Cd/m2.

Luminance and illumination relate as per equation 2-3 for asphalt roads [30].

$$Luminance\ (\frac{Cd}{m2}) = \frac{Illumination\ (lux)}{15} \qquad \textit{2-2}$$

For concrete roadways, luminance and illumination are related as expressed in equation 2-4.

$$Luminance\ (\frac{Cd}{m2}) = \frac{Illumination\ (lux)}{10} \qquad \textit{2-3}$$

2.8.2. Maintenance Factor (MF)

It is assumed that the installed road lighting luminaire provides maximum brightness when newly installed and depreciates gradually with time due to the effects of pollution (especially dirt and other physical materials that may reduce the light lumens reaching the intended surface), the frequency of cleaning, temperature and natural luminaire depreciation. A regular maintenance regime is critical in assuring a faithful and high lumen output and ultimately in guaranteeing the life of the luminaire. The maintenance factor is also referred to as the light loss factor (LLF).

The maintenance factor is accounted by derating the lumen output, such that illumination is given by equation 2-5.

Illuminance = Lamp lumen output (Lumens) x Maintenance Factor / Illumination Area (m^2). *2-4*

Since LLF is influenced by dirt and the luminaire's intrinsic qualities, it may be expressed as the product of the luminaire dirt depreciation (LDD) and the luminaire lumen depreciation (LLD) as shown in equation 2-6.

LLF = LDD x LLD *2-6*

MF underpins technological limitations relating to luminaire manufacture and leads to an oversizing of the lighting installation [31]. While each luminaire is purchased with a given manufacturer recommended maintenance factor, the lighting designer judges whether to adopt or reduce the recommended maintenance factor based on his assessment of the installation site and the capacity/history of the maintenance personnel. A very optimistic maintenance factor means that the level of lighting attained at the end of life of the luminaire is far lower than just after installation. A reasonable maintenance factor also implies that a higher dimming factor can be applied at the beginning of the installation - this can be lowered as the luminaire lumen output reduces.

2.8.3. Utilization Factor (UF)

This denotes the useful luminous flux - the ratio of the number of lumens reaching the intended surface to the number of lumens emitted from the source. UF is a factor and therefore is usually less than 1. UF depends on the lamp light distribution, mounting height and the type of surface where light is incident.

2.8.4. Laws of Illumination

2.8.4.1. The Inverse Square law

The inverse square law states that the 'illumination of surface is inversely proportional to the square of the distance between the surface and a point source' [32]. Given three positions, point 1, 2 and 3, whose distances are d, 2d and 3d from the light source, respectively, as shown in Figure 2-7, the illumination at points 1, 2 and 3 (E1, E2 and E3) are related as per equation 2-7.

$$E1{:}\,E2{:}\,E3 = \frac{1}{d^2} : \frac{1}{(2d)^2} : \frac{1}{(3d)^2} \qquad 2\text{-}5$$

The ratio $\frac{I}{d^2}$ represents the lighting intensity between two points which are d units apart. And hence E is a product of the ratio $\frac{I}{d^2}$ and the luminous intensity of the point source I in candela – this is expressed as per equation 2-8.

$$E1 = \frac{I}{d^2} \qquad 2\text{-}6$$

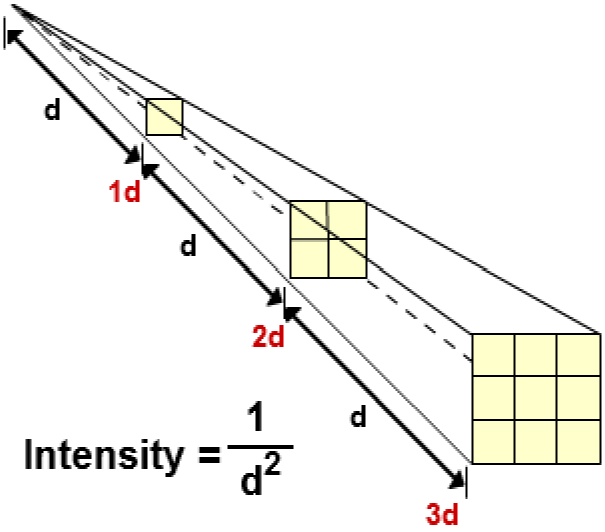


Figure 2-7: Inverse Square Law.

Source: https://www.nde-ed.org/EducationResources/CommunityCollege/Radiography/Physics/inversesquare.html (Accessed November 2020)

The inverse square law implies that the brightness of the light falling on a road surface reduces as the distance from the point source increases; as the pole height also increases, the illumination experienced in a certain surface reduces.

2.8.4.2. Lambert's Cosine Law

Lambert's cosine law states that 'the Illumination, E, at any point on a surface is directly proportional to the cosine of the angle between the normal at that point and the line of the flux [32].

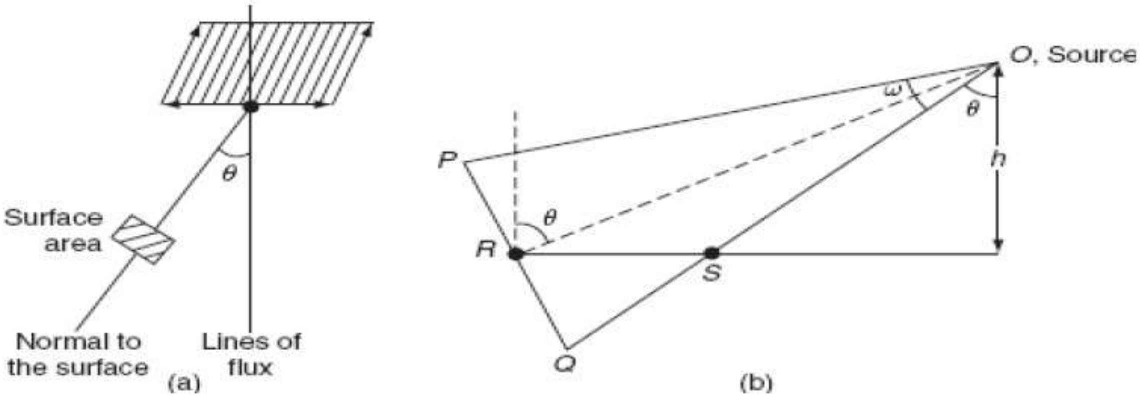


Figure 2-8: Lambert's Cosine Law *[32]*

Assuming that the surface is inclined at an angle θ to the flux normal as shown in Figure 2-8, the illumination incident to the surface RS, Ers, is expressed from Lambert's law as per equation 2-9.

$$\text{Ers} = Ers = \frac{I}{d^2} \text{Cos}\ \theta \qquad \textit{2-7}$$

Lambert's cosine law implies a direct relationship between the cosine of the inclination angle and the surface being illuminated - which means a reduction in the illumination with an increment in the inclination angle. HPS luminaire usually have an omnidirectional light distribution pattern leading to a huge angular inclination and hence reduced illumination as per Lambert's cosine law. On the other hand, LED luminaire have a lower angular inclination resulting into more targeted lighting - a higher illumination is consequently realized.

2.9. Economic Analysis

Economists have developed financial performance indicators that help to gauge the suitability of a project before it is undertaken. These indicators are important for various stakeholders to gauge various financial parameters that point to a project's competitiveness and viability. These indicators include the Net Present Value, Payback Period, and Internal Rate of Return (IRR).

2.9.1. Net Present Value (NPV)

The NPV is the sum of the discounted cash flows from beginning to the close of a project. The NPV is expressed by equation 2-10.

$$NPV = \sum_{i=0}^{n} \frac{CFi}{(1 + Rd)i} \qquad \textit{2-8}$$

Where n is the project period in years, *i* is the base year, CF*i* is the cash flow in the given year and R*d* is the discount rate.

With a positive NPV value, the project owners realize a net present benefit and hence the project is considered profitable.

2.9.2. Payback Period

This is the period it takes for the project to realize the initial investment amount based upon the net cash flows. It is calculated as the time it takes for the net receipts to equal the value of the initial investment.

2.9.3. Internal Rate of Return (IRR)

This is the rate of return at which the NPV equals to zero. The IRR is related to the NPV as shown under equation 2-11.

$$0 = \sum_{i=0}^{n} \frac{CFi}{(1 + Rd)i} \qquad \textit{2-9}$$

2.9.4. Sensitivity Analysis

The sensitivity analysis allows the evaluation of the economic viability of a project under various 'what if' situations. This analysis acknowledges the volatility of the various project cost components. Since the streetlights under this study are grid powered, the feasibility of the HPS to LED transition is susceptible to changes in the costs of energy.

2.10. Research Gaps

Previous road lighting studies, as discussed under section 2.6, did not evaluate the effect of transition to LEDs on the overall lighting performance for each of the respective roads. Lighting performance helps to benchmark the lighting levels to the parameters defined under EN 13201-2 [28]. A summary of the research gaps identifies was made as shown under Table 2-6.

Table 2-6: Summary of research gaps.

			Energy Savings Through Transition To		
Study	Scope	Year	LEDs	dimmed LEDs	Research Gap
European e-street project [22]	12 European countries	2006-2008	38 TWh		Lighting performance before and after LED transition not elaborated.
City of Pittsburg [8]	40,000 HPS/ HID lamps	2011	70%		Dimming not attempted. Lighting performance not illustrated.
Nairobi City [23]	31,000 lamps	2014	14.52 GWh		250W HPS to 120WLED transition not based on photometric valuations. Road lighting standards not applied in the transition.
Durban, eThekwini Municipality [24]	Six streets, 149 lamps	2020 (accessed online)	47.4 MWh / 27 %		No lighting photometric valuations.
Bahrain [25]	1 km	2018	35%	18.69%	Lighting quality and quantity not computed.

2.11. Chapter Two Conclusion

Road lighting is an absolute necessity for all modern cities that desire to ensure unhindered night-time social and business life. Advances in LED technology present an opportunity for city authorities to reduce the energy consumed by street lighting. Any transition from HPS to LED must be preceded by photometric designs to ensure that the level of final lighting is better.

3.0 CHAPTER THREE: METHODOLOGY

3.1. Introduction

This chapter elaborates how the objectives of this project have been met by describing the data that was collected and how it was analysed. The sources of data collected was included and the various platforms enabling data manipulation.

3.2. Project Area

The project covers Uganda Street which forms the southern ring of Merkato, Addis Ababa. Merkato is located to the North of Addis Ababa as shown in the Figure 3-1 (left). Four main Principal arterial streets surround Merkato - these streets are Uganda Street, Tesema Aba Kemaw Street, Fitawrari Habte Giorgis Street and Central Africa Republic Street and are 1.35km, 0.8km, 1.1km and 1.6km respectively as shown in Figure 3-1, below (right).

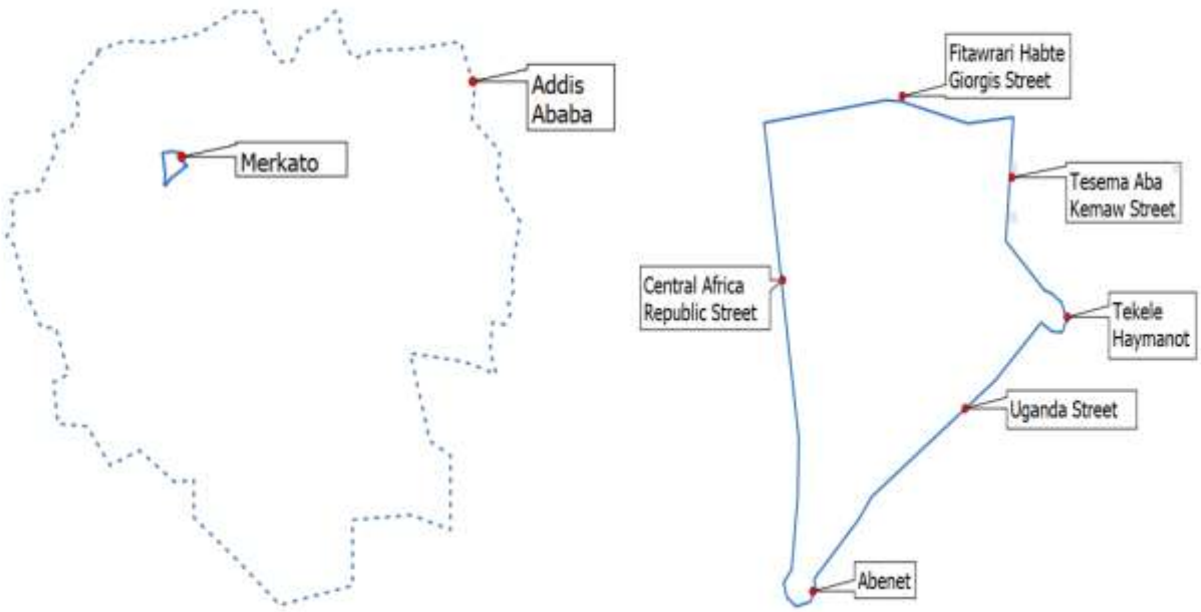


Figure 3-1: Merkato (left) and its boundary streets (right).

The focus area, Uganda Street, is in between Abenet and Tekle Haymanot intersections, which are major traffic linkages to the rest of Addis Ababa City. All the Merkato roads are dual carriageways and hence traffic from other parts of Addis Ababa join into/from Merkato through any of these roads - each of the roads is independently a full street, with distinct characteristics, and Uganda Street is chosen to demonstrate the LED lighting energy saving potential which would be accordingly applicable to all the other streets.

3.3. Conceptual Framework

The conceptual framework is the blueprint that offered the philosophical and methodical model that was the basis of successfully implementing this research. It visually provided the study architecture and weaved together the necessary inter-relationships between the research problem, defined solution, and the variables.

The conceptual framework depicted the researcher's summary of how to approach and explore the research problem – it described the relationships between the main concepts of the project undertaken.

The main items of the conceptual framework were:

- Problem outline – this was identified as high installed power density due to inflexible HPS luminaire. The effects of the high installed power density were also highlighted as high load (kW), high consumption (kWh), higher GHG emissions and greater pressure on the power generation plants.
- Solution definition. The recommended solution (HPS to LED transition) was noted as including an assessment of the existing HPS installation and computation of an appropriate LED luminaire. The recommended LED lighting system would further require brightness control through dimming.
- Variables; independent and interdependent. The solution generation was guided by the AACRA and EN13201 standard which stipulate the independent variables, as speed and traffic composition, and dependent variables as traffic volume, ambient luminosity, weather, and navigational ability.

The relationship between the identified problem, solution and the variables was illustrated in Figure 3-2 – this visual expression provided an understanding of the project study and the intended solution building approach.

By formulating the conceptual framework, a systematic guideline of achieving the research objectives was established. Consequently, it was possible to give attention to the range of issues defined as a priority in the conceptual framework.

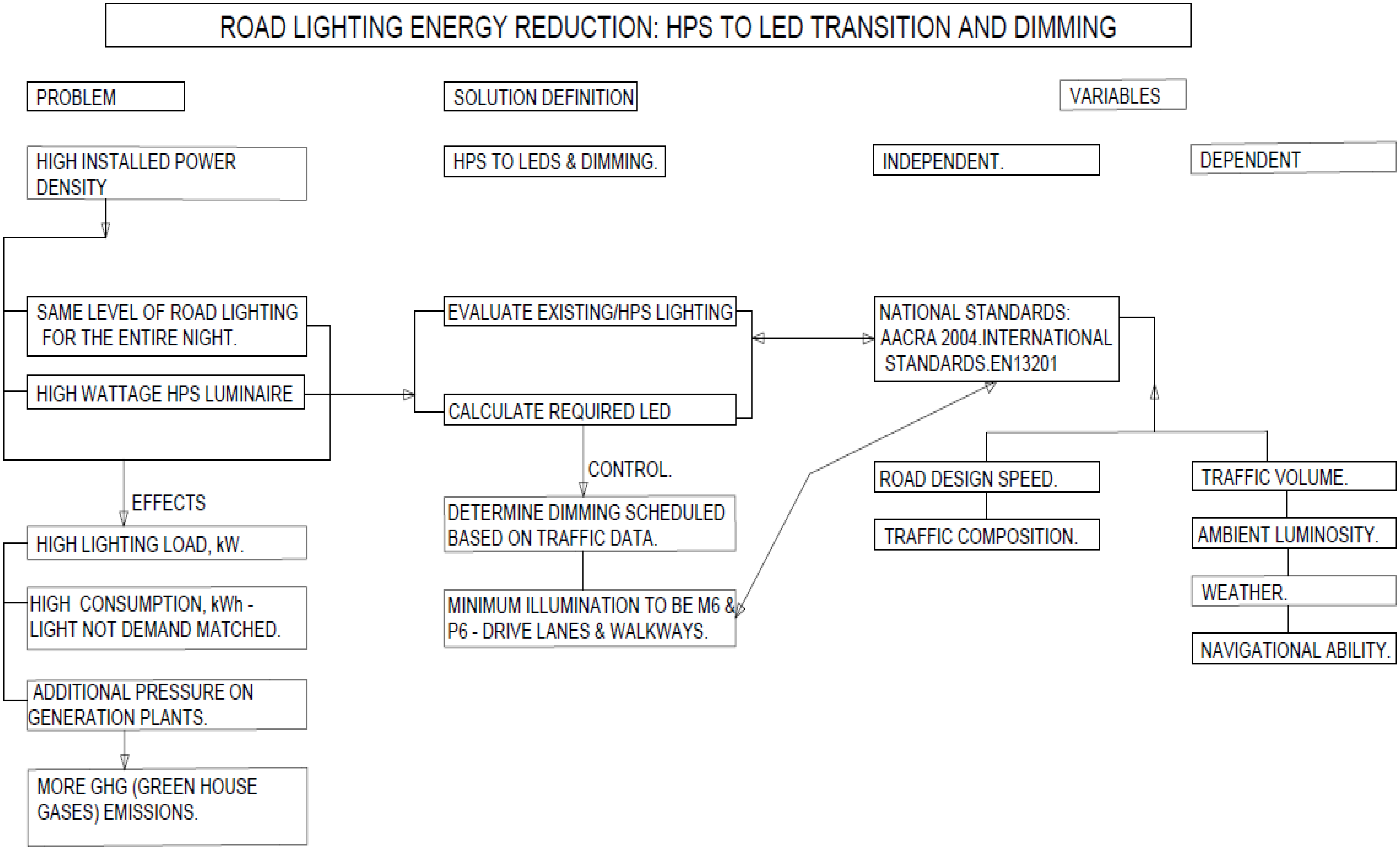


Figure 3-2: Project Conceptual Framework.

3.4. Lighting and Energy Performances

The existing and recommended lighting situations were evaluated through *Dialux* software simulations. *Dialux* is a freely available software developed by DIAL GmbH, a German organization formed in 1989 [33], initially as a lighting academy. *Dialux* has been updated to ensure that lighting performance is evaluated according to the latest road lighting standard, namely EN13201:2015. *Dialux* was downloaded from DIAL's website, *https://www.dialux.com/en-GB/download* [33]. *Dialux* requires lighting designers to install plugins from a range of many international luminaire manufacturers. Each plugin contains the photometric details of the luminaire developed by the particular manufacturer including the wattage, light distribution, efficacy and overall lumen output. Currently, *Dialux* allows plugins from more than 190 manufacturers. It was noted that *Dialux* does not dictate the choice of the luminaire - this is the prerogative of the lighting designed based on the lighting application and the performance required.

3.4.1. Existing Situation - HPS Lighting - Objective 1.

Road profile data was obtained from Dorsch GRE German Rail Engineering GmbH, a Consulting firm which carried out engineering work within the project area. This data revealed the main road features necessary for lighting simulation namely the right hand side (RHS) of the carriageway, the left hand side (LHS) of the carriageway, median (where it exists), walkway and general right of way (ROW). All the road areas were georeferenced and to scale. The road data also indicated the exact positions of the existing street lighting system in AUTOCAD.

The currently installed HPS lighting was modelled on *Dialux* software - modelling involved defining the widths of all the road areas requiring lighting and the road surface material, declaration of the required lighting class/level for each road area, selection of luminaire and optimization. The software applies a certain reflectance factor based on the road surface material indicated. While optimization for a new road design is iterative, fixed values of pole orientation and spacing were applied as they exist under the current installation.

Since the road profile is non-uniform, the road was divided into seven sections with each section representing a unique road cross-section. Lighting modelling was carried out separately for each road section resulting into a unique lighting performance for each road section. While the road was sectionalized, there were slight variations within the road cross section under each of the respective 7 road sections. The widest road area were selected, for each section, resulting to the most stringent lighting performance calculation.

Dialux software calculated the energy consumption density and road lighting performance indicators (the parameters described under sections 2.6.1 and 2.6.2 of this report). The average road consumption density was computed as

Average road energy consumption density = sum of energy consumption density for each road section / number of road sections.

The total installed electrical load was computed as shown under equation 3-1.

Total load, kW = power rating of each sodium lamp (150 W) x total number of lamps / 1000 *3-1*

The total energy consumption per year was also be calculated as indicated under equation 3-2.

Annual energy consumption, kWh = Total load (kW) x 12 hours x 365 days *3-2*

Consequently, the installed power density was computed as per equation 3-3.

Installed power density, Watts/m = Total load (kW) x 1000 / length *3-3*

3.4.2. Simulation of Lighting with LED - Objective 2.

Road sections similar to 3.3.1 above were used in the computation under LED lighting. Once the road model was made on *Dialux*, a suitable LED luminaire was selected for each road section. Since the same road was under consideration in both 3.3.1 and 3.3.2, the same lighting levels were utilized. Optimization in this case was iterative with the objective being to achieve the required lighting level with the least combination of pole height and luminaire wattage - this was done by changing the pole to pole spacing, pole height, luminaire type and wattage and pole arm configurations. The software ultimately computed the lighting performance indicators and energy consumption density for each road section based on the optimization option selected. The average road energy consumption density, total installed electrical load, total energy consumption per year were thereafter calculated as described under section 3.3.1.

3.4.3. Light Dimming Scenario - Objective 3.

Traffic data was received from Dorsch GRE German Rail Engineering GmbH and was the basis of the proposed schedule of light dimming - lighting was set for full brightness at the noted maximum traffic level and subsequently reduced with lower traffic levels. Not more than six dimming schedules were considered for the entire night and hence traffic data was analysed for every two hours.

The energy consumption for each dimming schedule was computed as

$$\text{Schedule energy, kWh} = \text{Luminaire rating, W} \times \text{\% brightness} \times \text{number of hours} / 1000 \qquad \textit{3-4}$$

The total energy consumed, for the entire night) was aggregated based on the number of dimming schedules recommended. The annual energy consumption was consequently realized based on the total days in the year.

3.4.4. Analysis: Energy Savings with LED and Dimming

Energy consumptions under HPS, LED and dimmed LED were compared - the savings realized under LED and dimmed LED were tabulated accordingly - including the percentage energy savings/reduction with LED and with dimmed LED. In addition, *Dialux* computes power and energy consumption density indicators which were also compared in each case. The power density indicates the installed power per unit lux-area of road surface, in W/lxm^2 while energy consumption density denotes the annual energy consumption per square metre, measured in kWh/m^2 yr. Lighting performance under HPS and LED lighting were also be compared.

3.5. Economic Analysis

This was carried out by computing the NPV, IRR and payback period as detailed in the literature review under section 2.9. A sensitivity analysis was then carried out under various energy cost scenarios (three scenarios were consequently compared: no change in energy costs, energy cost increasing and energy cost reducing over the life of the LED luminaire).

3.6. Case Validation

This project demonstrated the benefit of replacing HPS with LED lamps in reduced energy consumption density and reduced overall annual energy consumption. Whereas the total annual energy consumption reduction is an impressive indicator of improvement, it may not be directly compared for different cases since the road profile and lengths varies. This project therefore computed the percentage annual energy reductions, which was the basis of comparing the achieved savings with other cases as summarized in Table 3-1.

Table 3-1: Project Validation - energy reduction benchmarks.

	% Energy Reduction	
	Step 1: HPS to LED	Step 2: Dimmed LED
Mohammed, Nour, et al, [25]	35 %	18.69 %
Philips, Durban [24]	27 %	
Fusheng Li, et al [12]	30 %	
Florence [23]	24 %	
Annika K. Jägerbrand [34]	49 %	

From Table 3-1, above, at least 20% energy reductions were achieved in previous studies (with HPS to LED transition) and further 15% were achieved with dimmed LED. The case study was expected to exceed these minimums with lighting remaining within the required photometric performances.

3.7. Summary of Methodology

To meet the project objectives, the required data and the consequent analysis was summarised under Table 3-2.

Table 3-2: Methodology Summary.

	Format	Data / Tool Source
Existing Lighting	AUTOCAD	Dorsch GRE German Rail Engineering GmbH
Traffic Data	Excel	Dorsch GRE German Rail Engineering GmbH
Lighting Simulation	Dialux	https://www.dialux.com/en-GB/
Data Analysis	Excel / Word	Microsoft
Proposed Lighting	Dialux	https://www.dialux.com/en-GB/
	AUTOCAD	https://www.autodesk.com/products/autocad/free-trial

3.8. Assumptions

The project was carried out under the following assumptions.

i) Modelling assumed that facial recognition was not necessary and hence extra parameters were not computed for the walkway.
ii) *Dialux* software only allows LLF to be factored in during computation - it was taken that the LLF value considered the required UF since both have the effect of reducing the eventual useful lumens.
iii) Since traffic data is usually carried out at the main intersections, it was assumed that the intersectional traffic changes represent a proportional change in the traffic for all the intersecting roads.
iv) Traffic fata for a single position, over at least two days, was assumed to be representative.
v) That all nights are the same - each having 12 hours - hence the lighting requirement was 12 hours per night throughout the year.
vi) That traffic data received represented a general yearlong trend.

3.9. Chapter Three Conclusion

The methodology provided an outline of the stages necessary to achieve the project objectives. These stages offered a step-to-step approach enabling the research case to be built and demonstrated.

The project’s methodical approach benefitted from the conceptual framework as a primary tool which visually laid the independencies between the various case components. This helped clarify the specific areas of focus within the various subjects.

The methodology emphasized the need for a detailed and systematic analysis within the project’s main stages: the simulation of the present case and the recommended case. For each of these cases, the specific parameters that must be evaluated were outlined and defined. The need to validate the recommended case against previous studies was also established.

4.0 CHAPTER FOUR: RESULTS, ANALYSIS AND DISCUSSION

4.1. Road Sections

Raw street lighting topographical data received was cleaned to isolate only required features and ensure clarity of the main road areas, within the road cross-section. The road cross-section refers to all the features found from walkway (RHS) to walkway (LHS) and represents the primary surface area under which the existing lighting is intended.

Since the road was drawn to scale, it was divided into seven sections, to ensure visibility – two sections are shown under Figure 4-1 and Figure 4-2 while the other sections are captured in the Appendices. The road referencing was done from the left with the chainages indicating actual distances measured from Abenet. The road features marked under Figure 4-1 and Figure 4-2 have the same meaning for all the other sections.

The road sections were identified as shown under Table 4-1.

Table 4-1: Road sectionalizing.

	Chainage		
	From	To	Length (metres)
1)	0+000	0+200	200
2)	0+200	0+400	200
3)	0+400	0+600	200
4)	0+600	0+800	200
5)	0+800	1+000	200
6)	0+000	1+200	200
7)	1+200	1+350	150
Total			1,350

All the existing luminaires were anchored on a galvanized steel pole, 8 metres above ground, on a 10 degrees boom angle and 1m boom (the steel road lighting poles were on average erected 1m from the edge of the road).

The lighting poles were erected on the pedestrian walkway (on each side) offering an advantage because of the relative proximity to the main surface where lighting is intended, namely the drive lanes.

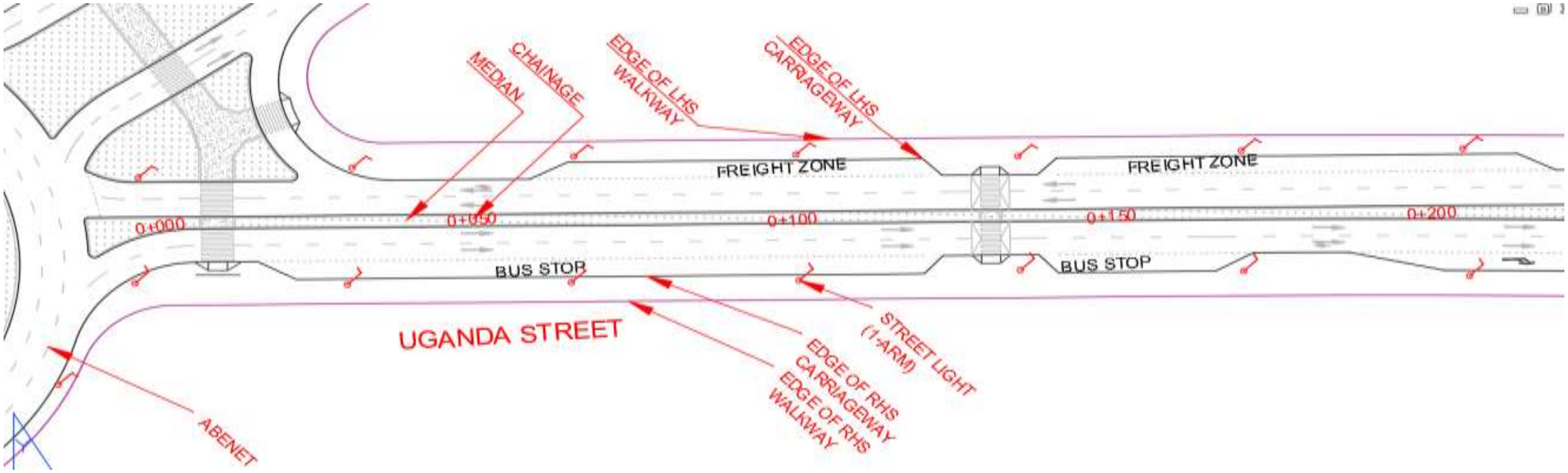


Figure 4-1: Uganda Street, existing lighting; Chainages 0+000 to 0+200.

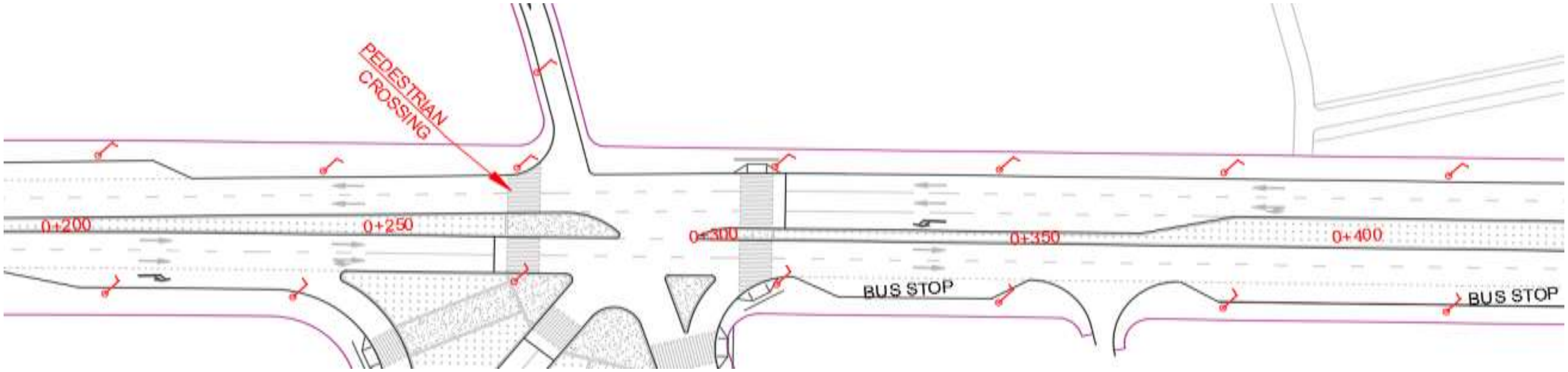


Figure 4-2: Uganda Street, existing lighting; Chainages 0+200 to 0+400

4.2. Existing Street Lighting Analysis – HPS Luminaire

4.2.1. Electrical Load

Based on the street lighting quantities indicated under Figure 4-1 to Figure 4-7, the total electrical load was summarised on Table 4-2.

Table 4-2: HPS Street Lighting Electrical Load Summary.

	Chainage		Number of luminaires (N)	Total Load = N x 169* / 1000, kW
	From	To		
1)	0+000	0+200	14	2.366
2)	0+200	0+400	14	2.366
3)	0+400	0+600	12	2.028
4)	0+600	0+800	12	2.028
5)	0+800	1+000	12	2.028
6)	0+000	1+200	12	2.028
7)	1+200	1+350	10	1.690
Total			86	14.534

4.2.2. Installed Power Density and Energy Consumption

The annual energy consumption and installed power density of Uganda Street was calculated using Equations 3-2 and 3-3 respectively, as tabulated on Table 4-3.

Table 4-3: Power density and energy consumption.

Section	Length, m	Total Load, kW	Energy, kWh	Power Density, Watts/m
1)	200	2.366	10,363	11.83
2)	200	2.366	10,363	11.83
3)	200	2.028	8,883	10.14
4)	200	2.028	8,883	10.14
5)	200	2.028	8,883	10.14
6)	200	2.028	8,883	10.14
7)	150	1.690	7,402	11.27
			63,660	75.49

Average installed power density = 75.49 / 7 = 10.78 Watts / m

4.2.3. Lighting Performance - Installed Street Lighting System

The required lighting class for the main carriageway was computed as M4 based on the description under section 2.6.1 and as summarised under Table 4-4.

Table 4-4: Main carriageway lighting class determination.

Parameter	Option (selected)	Description	Weighting Value
Design Speed	Moderate	40<v≤70 km/h	-1
Traffic volume	High	>65 % maximum capacity (multilane routes)	1
Traffic composition	Mixed		1
Separation of carriageway	Yes		0
Junction density	Moderate	≤3 intersection/km	0
Parked vehicles	Present		1
Ambient luminosity	Moderate	Normal situation	0
Navigational task	Easy		0
Sum of weighting value, VWS			2
Lighting class = 6 - VWS			4

Note that a mixed traffic composition was selected since there are currently no dedicated non-motorised traffic lane (cycle lane, hand carts etc). There are 4 major intersections for Uganda Street leading to a junction density of 4/1.35 = 2.97 intersections per km, and hence the selection of a moderate junction density. Lighting classification for the walkway was similarly achieved as P3, based on the considerations under section 2.6.2 as summarised under Table 4-5.

Table 4-5: Walkway lighting class determination.

Parameter	Option (selected)	Description	Weighting Value
Travel Speed	Low	v≤40 km/h	1
Use intensity	Busy		1
Traffic composition	Pedestrians and cyclists		1
Parked vehicles	Not present		0
Ambient luminosity	Moderate	Normal situation	0
Sum of weighting value, VWS			3
Lighting class = 6 - VWS			3

4.2.3.1. Section 1 (Chainage 0+000 – 0+200)

For simulation purposes, the bus-stop and/or the freight zone was considered a normal driving lane – this ensured the same level of lighting was determined for them as to the usual drive lanes. The dominant characteristics of this road section, used for the simulation, were:

i) LHS: Carriageway has 3 lanes, total width 9.2m and 3.8m pedestrian walkway.
ii) RHS: Carriageway has 3 lanes, total width 9.2m and 4.5m pedestrian walkway.
iii) The LHS and RHS are separated by a 2.3m median.
iv) The pole to pole spacing is between 33.5m and 35.0 m. The higher value is used leading to the least possible lighting level.
v) Main carriageway surface material is asphalt which corresponds to CIE C2 leading to a reflectance characteristic of 0.07.
vi) A maintenance factor of 0.816 was applied; equivalent to a calibration value obtained in a maintenance factor experiment using an equivalent HPS luminaire [35].

A 2D simulation of lighting under the above set of characteristics was made following the road cross section shown in Figure 4-3 while a 3D lighting output was illustrated in Figure 4-4.

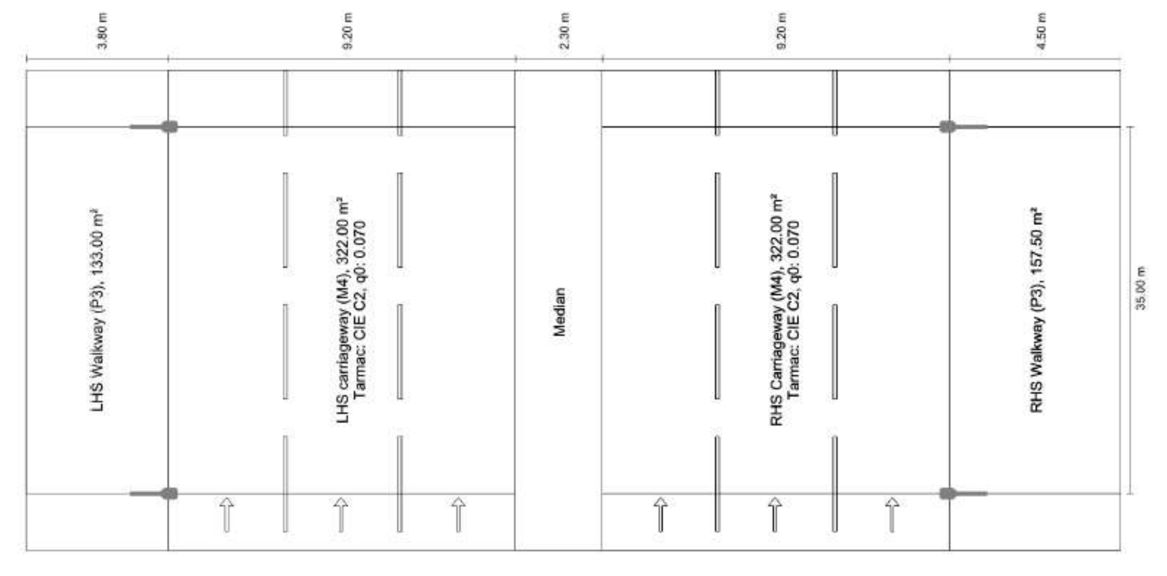


Figure 4-3: Cross-Section of Uganda Street, 0+000 to 0+200

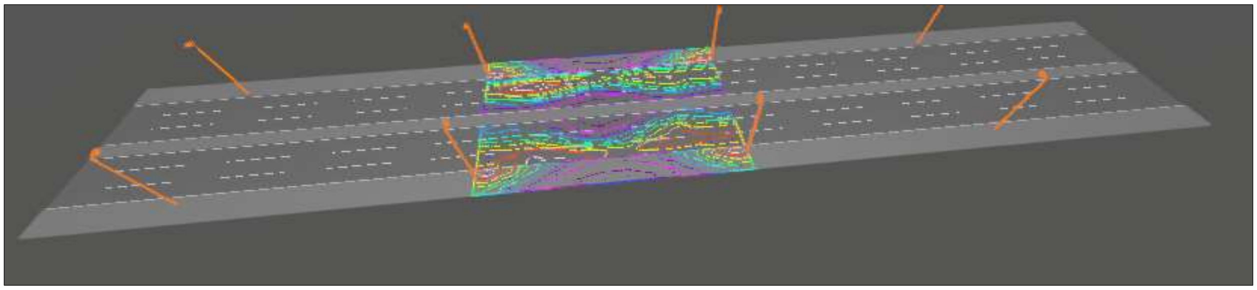
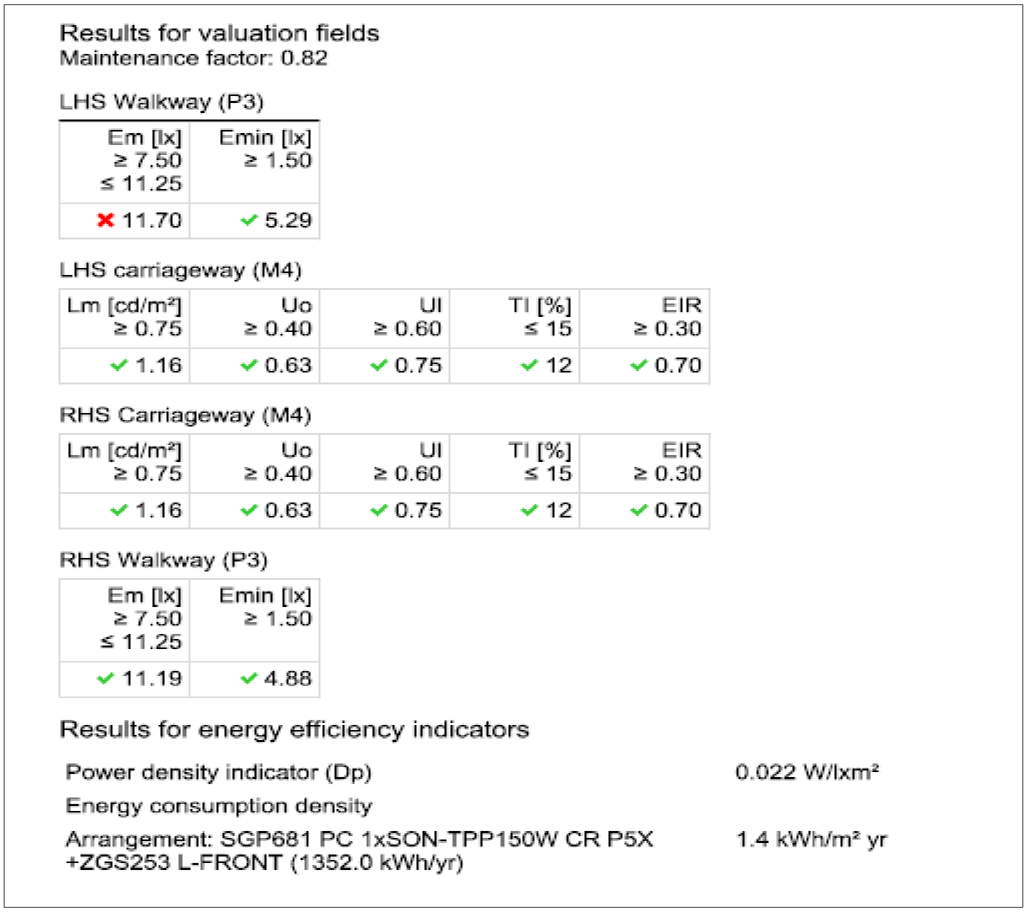


Figure 4-4: 3D impression of HPS lighting for 0+000 to 0+200

The 3D simulation results indicated the light distribution curves along the road, as shown on Figure 4-4; the inmost parts of the road attained an illuminance of 0.82 Cd/m^2 while the highest illuminance, 1.4 Cd/m^2 was attained near the inner edge of the walkway – closer to the foot of the street lighting poles. The existing street lighting's overall computational output was transferred from Dialux as shown on Figure 4-5.



Results for valuation fields
Maintenance factor: 0.82

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 11.70	✓ 5.29

LHS carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.16	✓ 0.63	✓ 0.75	✓ 12	✓ 0.70

RHS Carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.16	✓ 0.63	✓ 0.75	✓ 12	✓ 0.70

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✓ 11.19	✓ 4.88

Results for energy efficiency indicators

Power density indicator (Dp)	0.022 W/lxm²
Energy consumption density	
Arrangement: SGP681 PC 1xSON-TPP150W CR P5X +ZGS253 L-FRONT (1352.0 kWh/yr)	1.4 kWh/m² yr

Figure 4-5: Lighting performance results for 0+000 to 0+200

The Appendices contains the full simulation presentation for this section.

4.2.3.2. Sections 2 and 3 (Chainage 0+200 – 0+400 and 0+400-0+600)

The road cross sections between 0+200 and 0+600 are predominantly similar; these sections also have the main attributes similar to those of section 1, and only differ mildly as follows.

i) The walkways are narrower at 3m and 4m for LHS and RHS respectively.
ii) The median is also narrower – 2m wide.
iii) There is no freight station but a third lane on the LHS.

The walkway and main carriageway achieve lighting classification P3 and M4 respectively – as computed under Section 4.2.3. The simulation model for these sections was illustrated as shown under Figure 4-6.

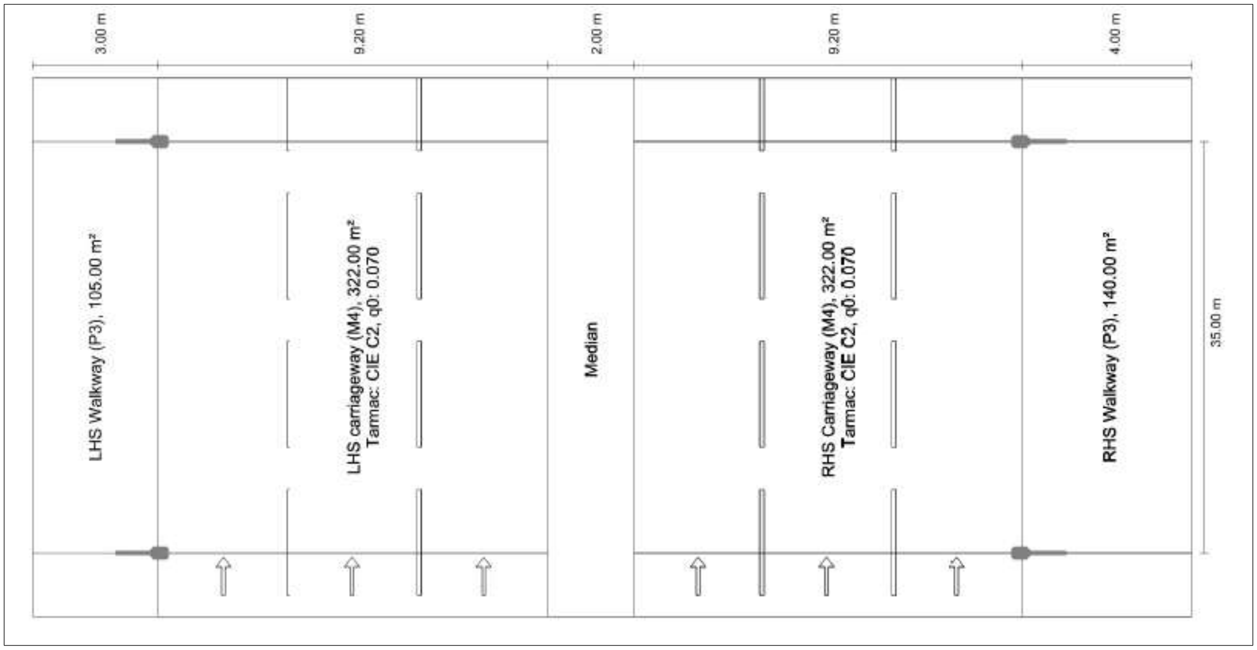
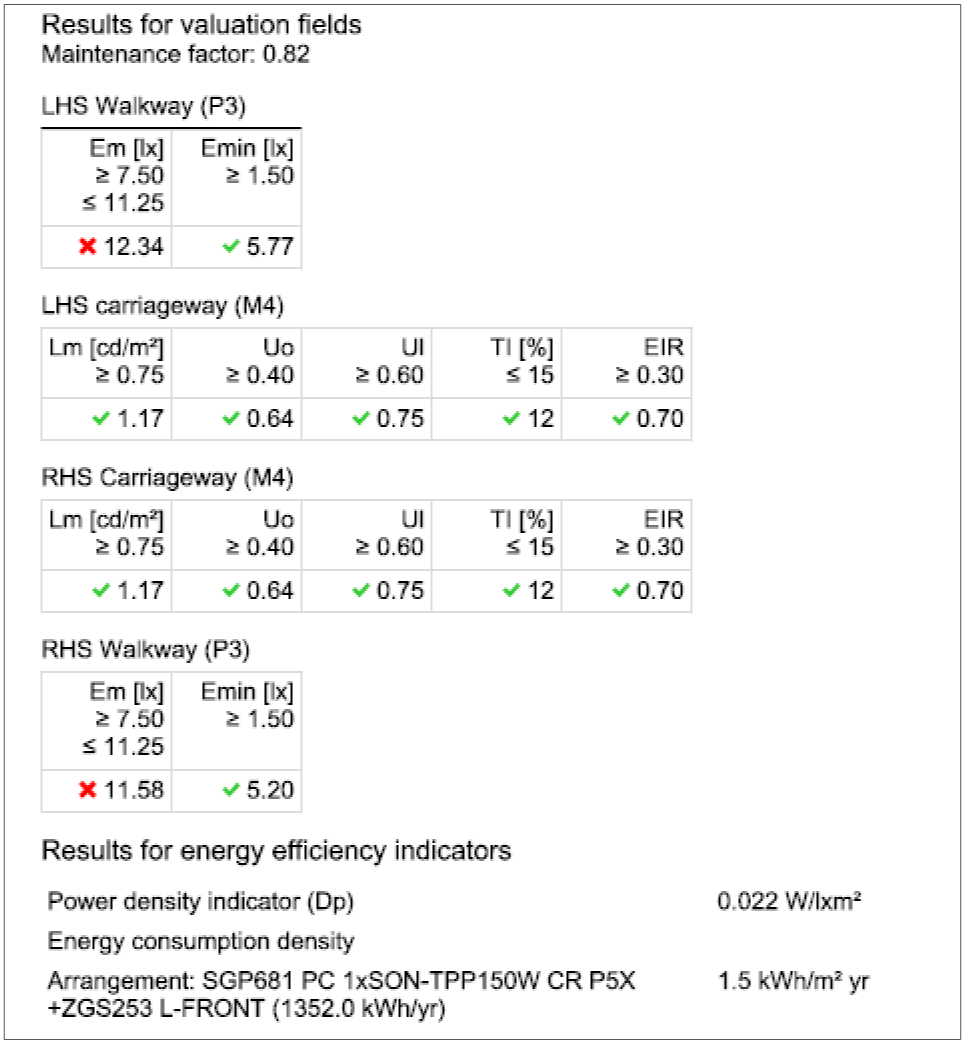


Figure 4-6:Cross-Section of Uganda Street, 0+200 to 0+600

The resulting photometric results, based on Figure 4-6, was presented as shown in Figure 4-7. The rest of the performance results are contained in the Appendices. A tick against a parameter value means the lighting met the threshold requirements. For instance, the average drive lane luminance required for class M4 lighting is 0.75 Cd/m^2 while the evaluated lighting achieved 1.17 Cd/m^2 – this meant that the lighting level was satisfactory.



Results for valuation fields

Maintenance factor: 0.82

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 12.34	✓ 5.77

LHS carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.17	✓ 0.64	✓ 0.75	✓ 12	✓ 0.70

RHS Carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.17	✓ 0.64	✓ 0.75	✓ 12	✓ 0.70

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 11.58	✓ 5.20

Results for energy efficiency indicators

Power density indicator (Dp)	0.022 W/lxm²
Energy consumption density	
Arrangement: SGP681 PC 1xSON-TPP150W CR P5X +ZGS253 L-FRONT (1352.0 kWh/yr)	1.5 kWh/m² yr

Figure 4-7: Lighting performance results for 0+200 to 0+600

4.2.3.3. Section 4 (Chainage 0+600 – 0+800)

The drive lanes and walkways are similar, in classification, to 0+200 – 0+600 as M4 and P3 respectively. The RHS carriageway is however wider (3 lanes at 9.8m) while the LHS is 9.3m. The median is 1.5m wide. The other attributes resemble those of section 2 and 3.

The road cross-section was modelled on Dialux as shown in Figure 4-8. The main simulation results, indicating the lighting performance based on the Figure 4-8 model, were transferred from Dialux as shown in Figure 4-9.

From the results shown under Figure 4-9, the lighting met the set standard requirements, and in most cases exceeded them, for instance the average horizontal illuminance.

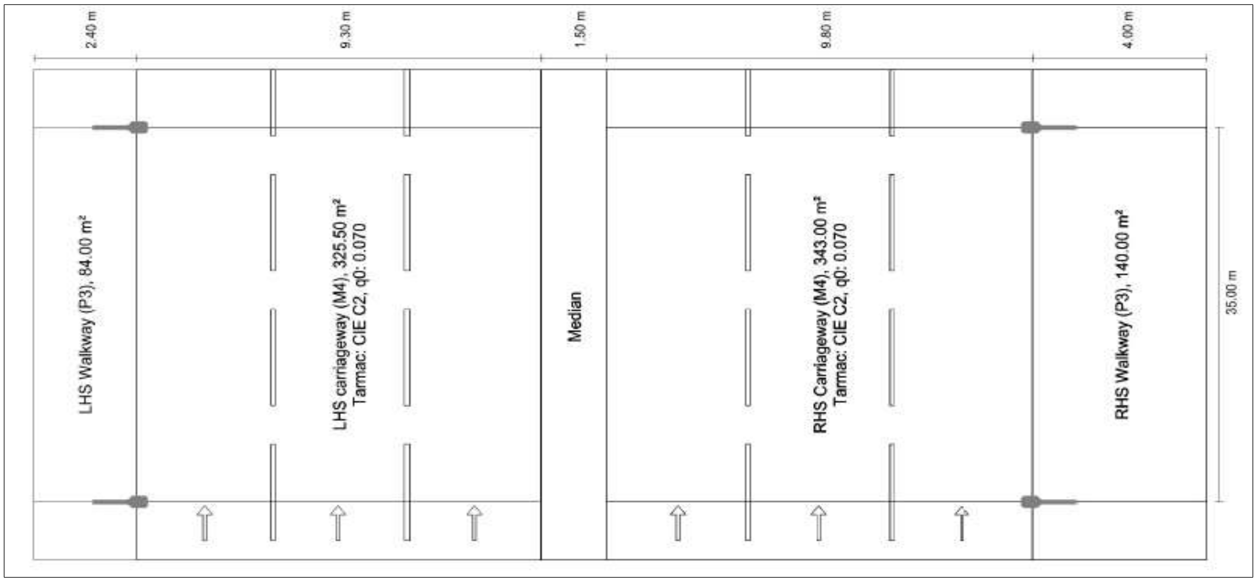
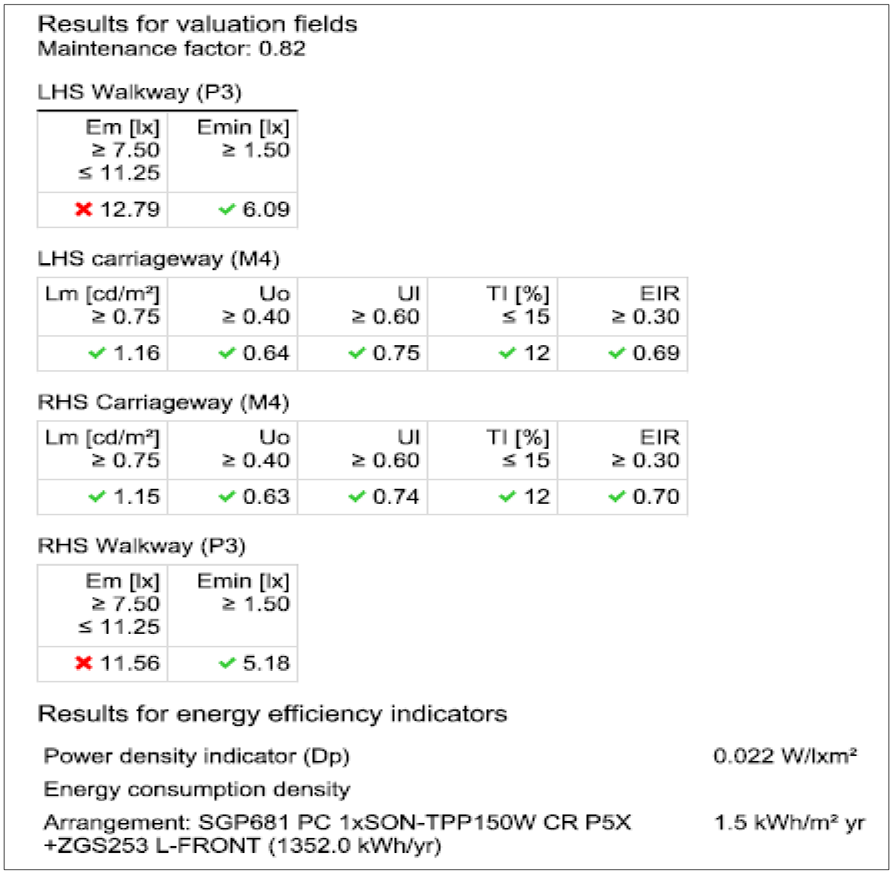


Figure 4-8: Cross-Section of Uganda Street, 0+600 to 0+800


Results for valuation fields
Maintenance factor: 0.82

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 12.79	✓ 6.09

LHS carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.16	✓ 0.64	✓ 0.75	✓ 12	✓ 0.69

RHS Carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.15	✓ 0.63	✓ 0.74	✓ 12	✓ 0.70

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 11.56	✓ 5.18

Results for energy efficiency indicators

Power density indicator (Dp)	0.022 W/lxm²
Energy consumption density	
Arrangement: SGP681 PC 1xSON-TPP150W CR P5X +ZGS253 L-FRONT (1352.0 kWh/yr)	1.5 kWh/m² yr

Figure 4-9: Lighting performance results for 0+600 to 0+800

The Appendices contains the full simulation presentation for this section.

4.2.3.4. Section 5 (Chainage 0+800 – 1+000)

The first 50m of this section resembles Section 4 highway plan (0+800 to 0+850) and hence the same lighting performance applies. The remaining portion is predominantly two drive lanes on each carriageway (6.5m and 6.3m on the RHS and LHS respectively), with a wide median (7.2m wide). The walkways to the RHS and LHS are 4m and 3m respectively. The existing street lighting model for this road section was made as shown in Figure 4-10.

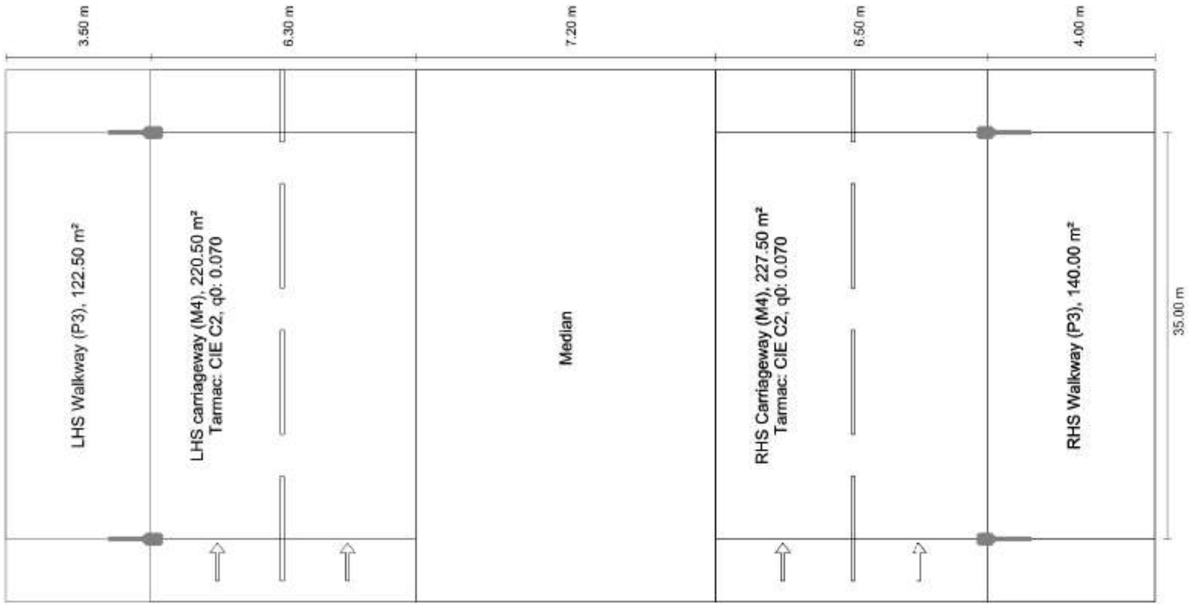
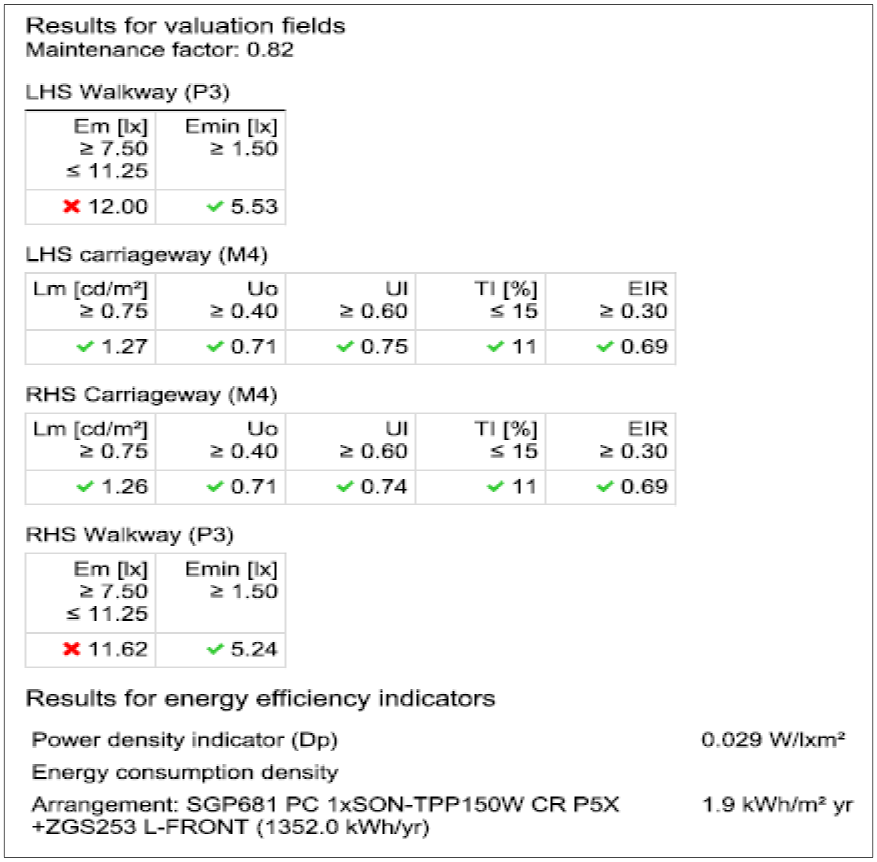


Figure 4-10: Cross-Section of Uganda Street, 0+800 to 1+000

The photometric results for section 5 were shown in Figure 4-11. The results indicated the parameters which were satisfied (in tick) and those which were not (cancelled in red).

4.2.3.5. Section 6 (Chainage 1+000 – 1+200)

Two drive lanes characterize the RHS and four drive lanes exist to the LHS; 6.5m and 12.5m respectively. Either walkways are 3.5m wide while the median is narrower at 1m. The road cross-section (for this section of Uganda Street) complete with the lighting poles was made in Dialux as illustrated in Figure 4-12. The lighting performance results for this road section was presented as shown in Figure 4-13 (the full road lighting simulation results, including road lighting planning data, are contained in the Appendices). The results indicated compliance with the set level of lighting on the drive lanes and excess horizontal illumination at the walkways.



Results for valuation fields
Maintenance factor: 0.82

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 12.00	✓ 5.53

LHS carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.27	✓ 0.71	✓ 0.75	✓ 11	✓ 0.69

RHS Carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.26	✓ 0.71	✓ 0.74	✓ 11	✓ 0.69

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 11.62	✓ 5.24

Results for energy efficiency indicators

Power density indicator (Dp)	0.029 W/lxm²
Energy consumption density	
Arrangement: SGP681 PC 1xSON-TPP150W CR P5X +ZGS253 L-FRONT (1352.0 kWh/yr)	1.9 kWh/m² yr

Figure 4-11: Lighting performance results for 0+800 to 1+000

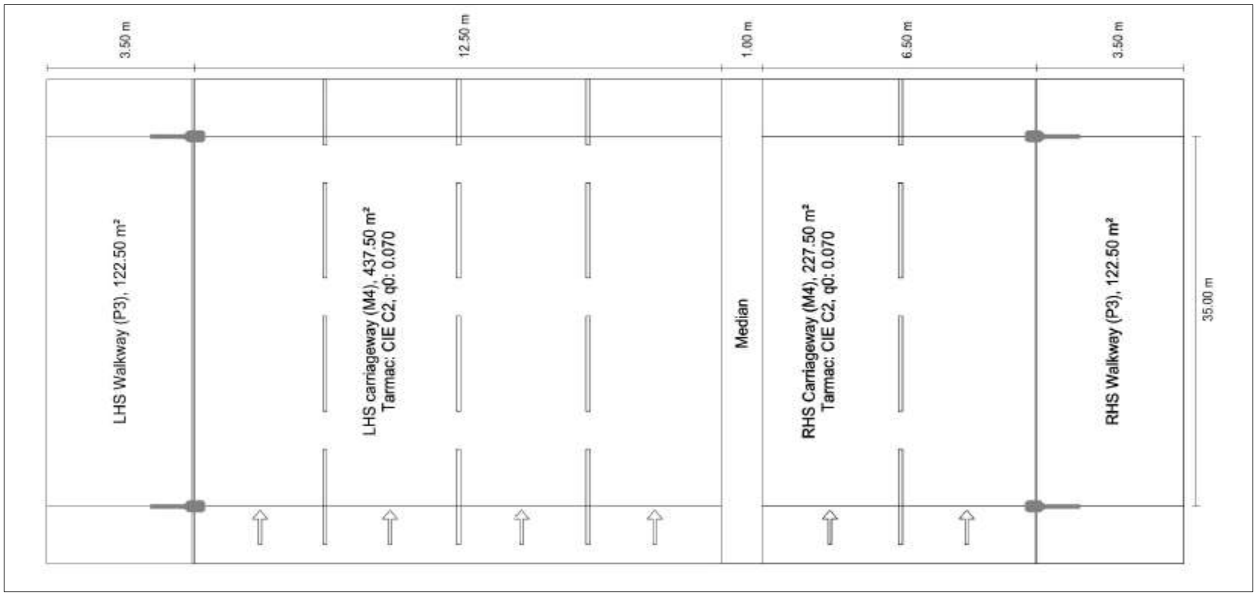
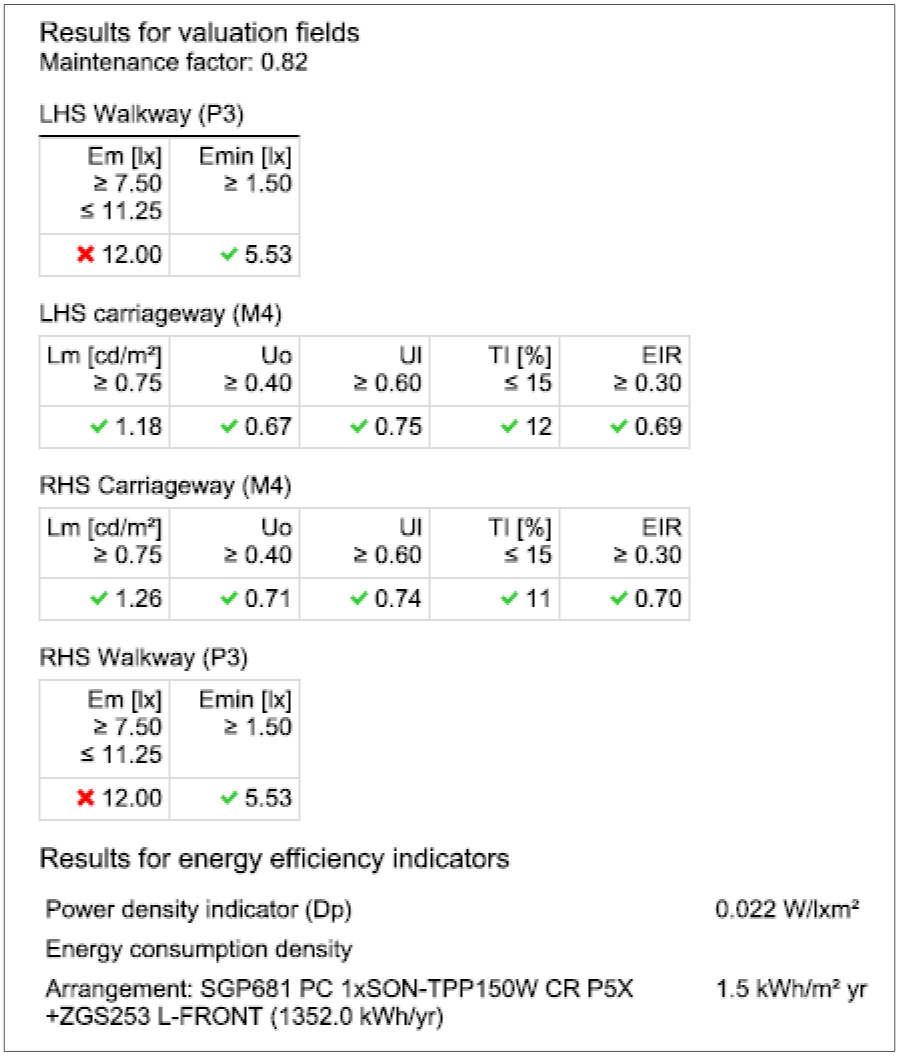


Figure 4-12: Cross-Section of Uganda Street, 1+000 to 1+200



Results for valuation fields
Maintenance factor: 0.82

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 12.00	✓ 5.53

LHS carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.18	✓ 0.67	✓ 0.75	✓ 12	✓ 0.69

RHS Carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.26	✓ 0.71	✓ 0.74	✓ 11	✓ 0.70

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 12.00	✓ 5.53

Results for energy efficiency indicators

Power density indicator (Dp)	0.022 W/lxm²
Energy consumption density	
Arrangement: SGP681 PC 1xSON-TPP150W CR P5X +ZGS253 L-FRONT (1352.0 kWh/yr)	1.5 kWh/m² yr

Figure 4-13: Lighting performance results for 1+000 to 1+200

4.2.3.6. Section 7 (Chainage 1+200 – 1+350)

The RHS and LHS carriageways are 3 lanes each at 9.6m and 9.8m respectively; the walkways are also 4m and 3m in that order while the median is 1.2m wide. The model of the road section, in Dialux, complete with lighting pole positions was presented in Figure 4-14. A portion of the photometric results were also illustrated in Figure 4-15.

The photometric results indicated that the lighting levels were within class M4 requirements for the drive lanes and class P3 requirements for the walkways – the walkway lighting was, however, slightly more then required.

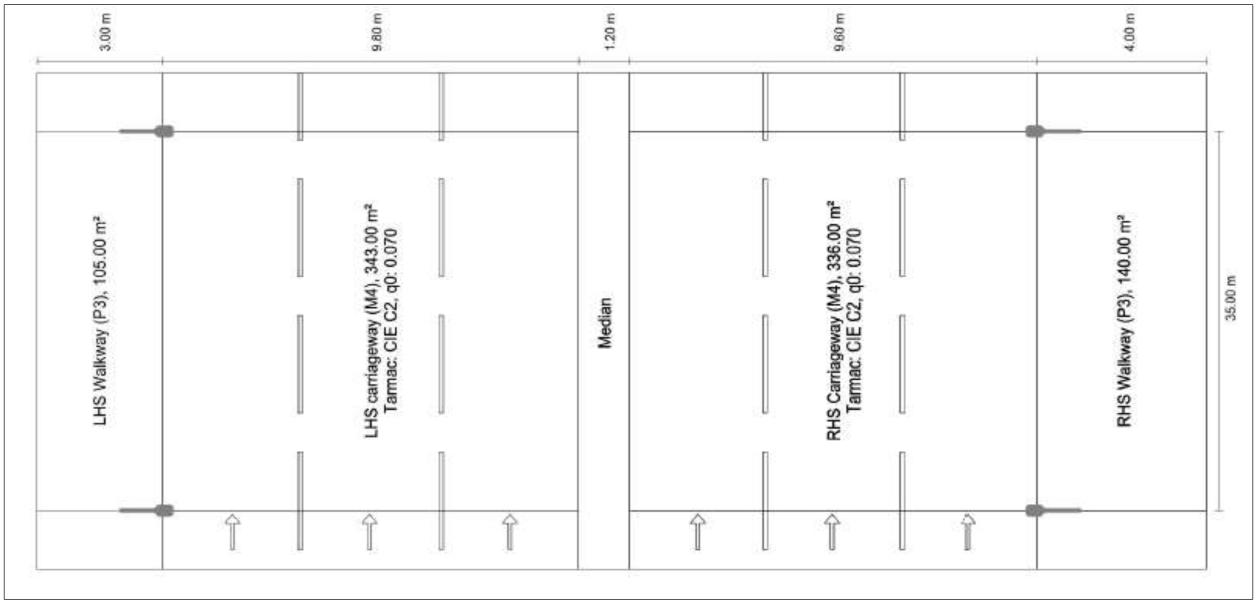
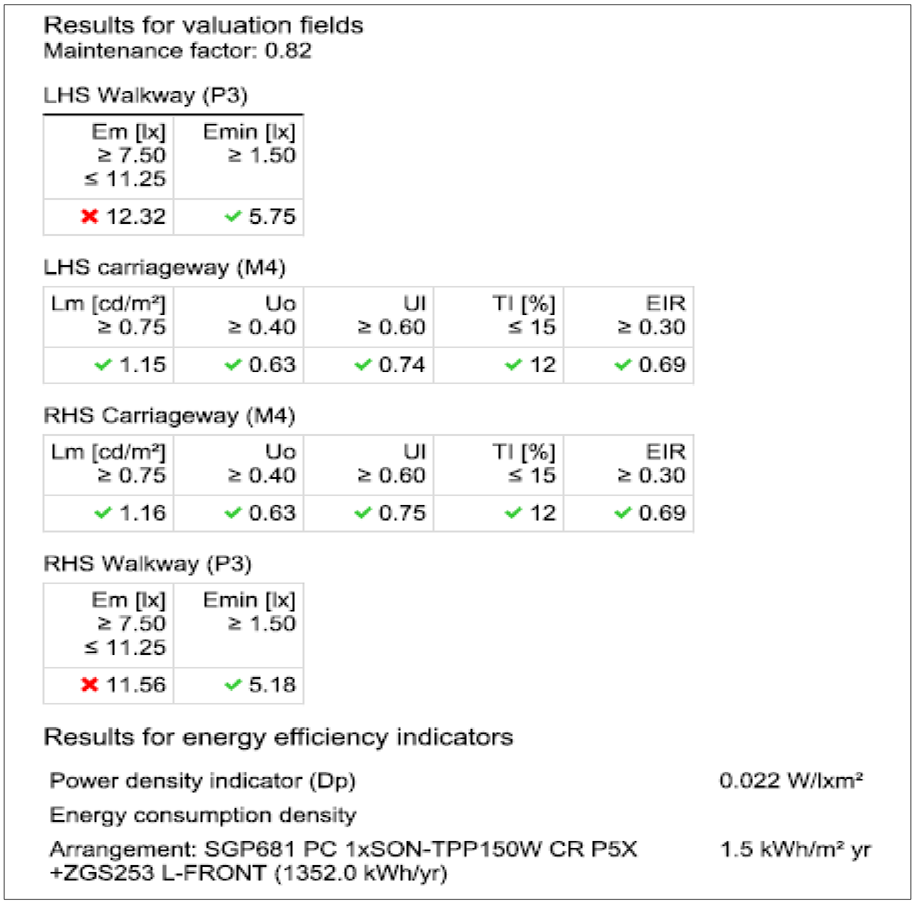


Figure 4-14: Cross-Section of Uganda Street, 1+200 to 1+350



Results for valuation fields

Maintenance factor: 0.82

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 12.32	✓ 5.75

LHS carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.15	✓ 0.63	✓ 0.74	✓ 12	✓ 0.69

RHS Carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.16	✓ 0.63	✓ 0.75	✓ 12	✓ 0.69

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 11.56	✓ 5.18

Results for energy efficiency indicators

Power density indicator (Dp)	0.022 W/lxm²
Energy consumption density	
Arrangement: SGP681 PC 1xSON-TPP150W CR P5X +ZGS253 L-FRONT (1352.0 kWh/yr)	1.5 kWh/m² yr

Figure 4-15: Lighting performance results for 1+200 to 1+350

4.3. Recommended System Analysis – LED Luminaires

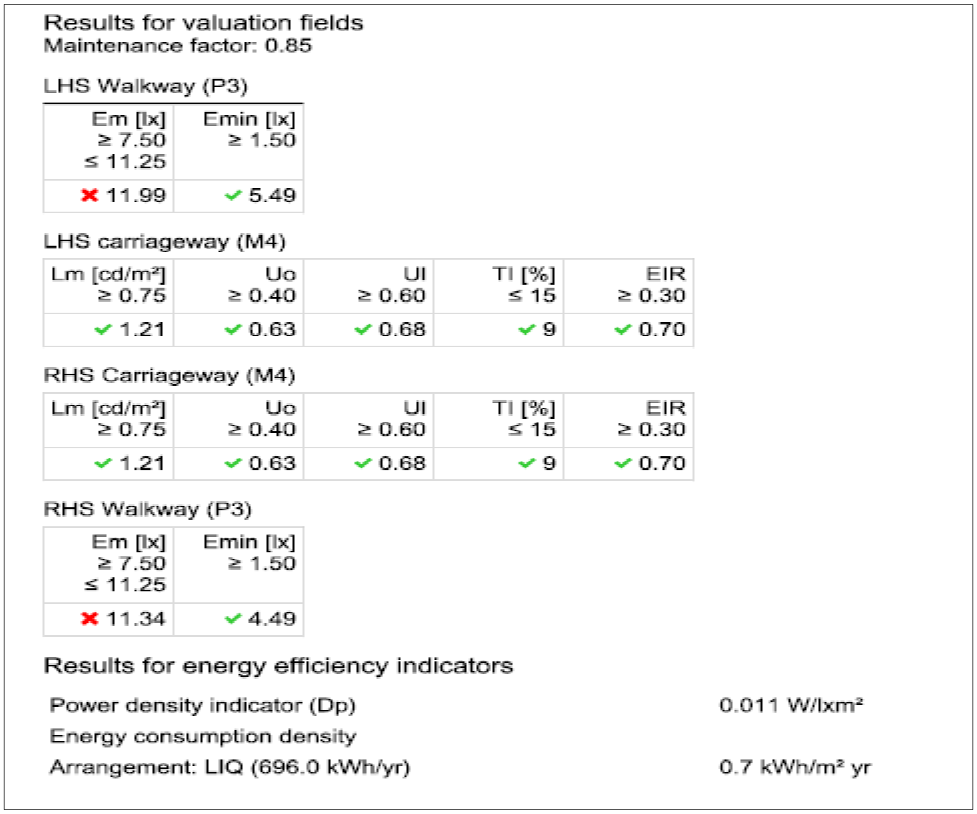
Recommend lighting system, for each of the road sections, is simulated based on drive lanes' and walkways classifications M4 and P3 respectively, in keeping with the EN 13201 standard, and as detailed under section 4.2.3 of this report.

4.3.1. Lighting Performance with LED lighting

Selection of the suitable wattage and luminaire combination of an LED luminaire was performed iteratively. An 87 W, 12000 lumen luminaires was generally observed to match the performance of the currently installed street lighting system. This is analysed below for each of the road sections.

4.3.1.1. Section 1 (Chainage 0+000 – 0+200) with LED

Section 1 road cross-section was modelled as shown in Figure 4-3 – the road section lighting valuation made with an 87W, 12,000 lumen dimmable LED yielded the performance results in Figure 4-16.



Results for valuation fields

Maintenance factor: 0.85

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 11.99	✓ 5.49

LHS carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.21	✓ 0.63	✓ 0.68	✓ 9	✓ 0.70

RHS Carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.21	✓ 0.63	✓ 0.68	✓ 9	✓ 0.70

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 11.34	✓ 4.49

Results for energy efficiency indicators

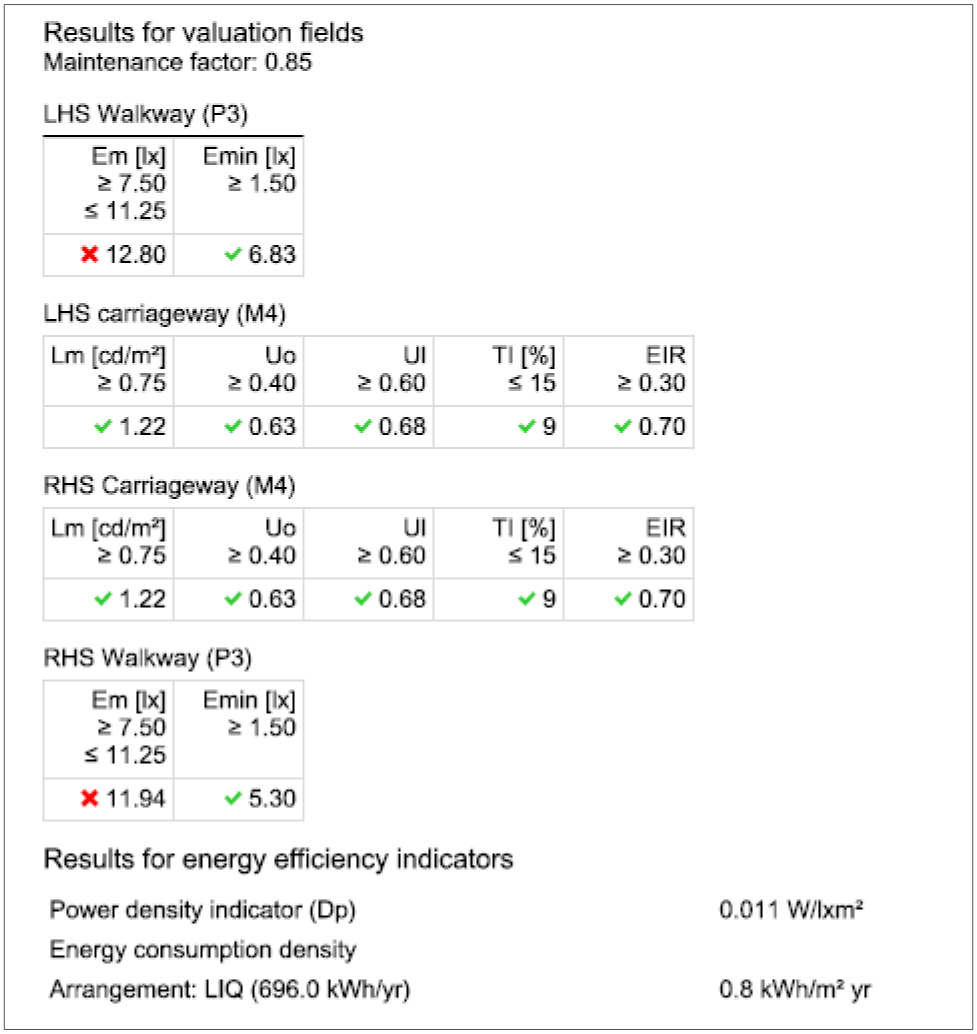
Power density indicator (Dp)	0.011 W/lxm²
Energy consumption density	
Arrangement: LIQ (696.0 kWh/yr)	0.7 kWh/m² yr

Figure 4-16: LED lighting performance results for 0+000 to 0+200

Full lighting simulation results, for section 1 under 87W LED lighting, are shown under the Appendices.

4.3.1.2. Section 2 & 3 (Chainage 0+200 – 0+600) with LED

Section 2 and 3 road cross-sections were modelled as shown in Figure 4-6 – the road section lighting valuation made with an 87 W, 12,000 lumen dimmable LED yielded the performance results shown in Figure 4-17.



Results for valuation fields
Maintenance factor: 0.85

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 12.80	✓ 6.83

LHS carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.22	✓ 0.63	✓ 0.68	✓ 9	✓ 0.70

RHS Carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.22	✓ 0.63	✓ 0.68	✓ 9	✓ 0.70

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 11.94	✓ 5.30

Results for energy efficiency indicators

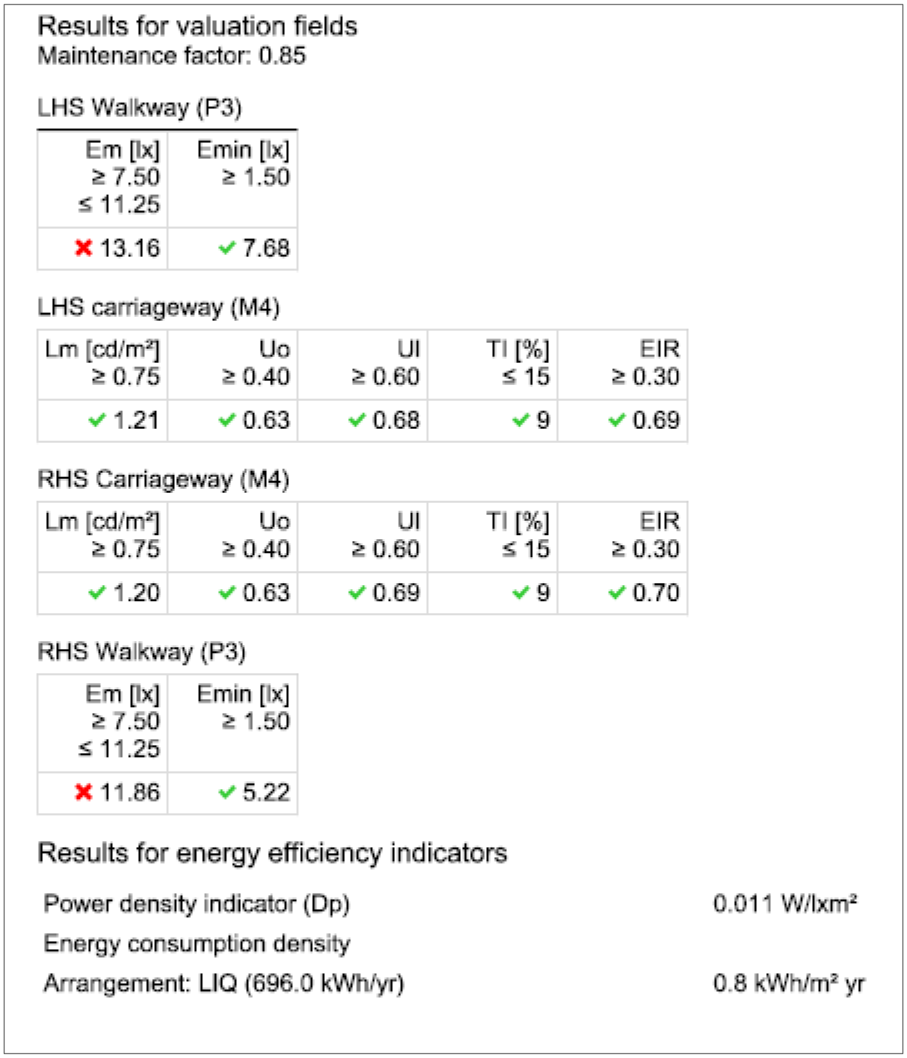
Power density indicator (Dp)	0.011 W/lxm²
Energy consumption density	
Arrangement: LIQ (696.0 kWh/yr)	0.8 kWh/m² yr

Figure 4-17: LED lighting performance results for 0+200 to 0+600

Full simulation results, of Section 2 & 3 under 87W LED luminaire, are contained in the Appendices.

4.3.1.3. Section 4 (Chainage 0+600 – 0+800) with LED

Uganda street, section 4 cross-section was modelled as shown in Figure 4-8 and the road Section lighting valuation made with an 87W, 12,000 lumen dimmable LED. The performance results were presented in Figure 4-18.



Results for valuation fields
Maintenance factor: 0.85

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 13.16	✓ 7.68

LHS carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.21	✓ 0.63	✓ 0.68	✓ 9	✓ 0.69

RHS Carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.20	✓ 0.63	✓ 0.69	✓ 9	✓ 0.70

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 11.86	✓ 5.22

Results for energy efficiency indicators

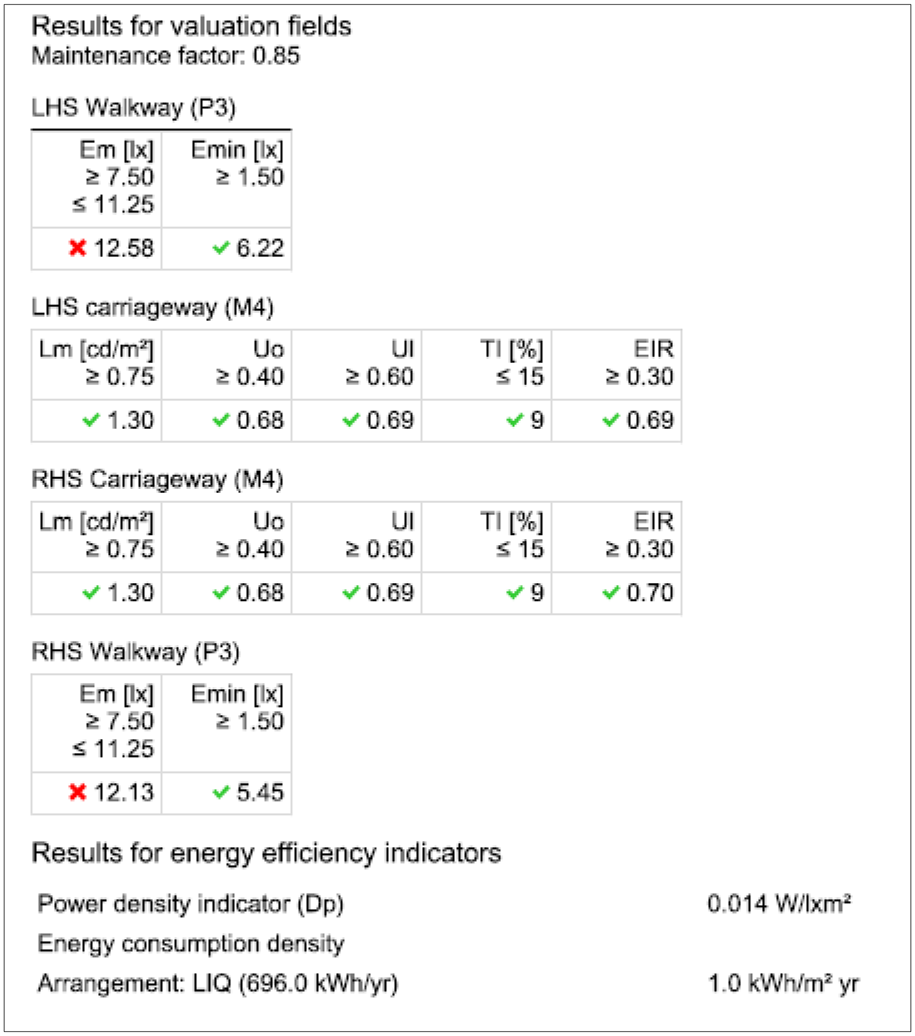
Power density indicator (Dp)	0.011 W/lxm²
Energy consumption density Arrangement: LIQ (696.0 kWh/yr)	0.8 kWh/m² yr

Figure 4-18: LED lighting performance results for 0+600 to 0+800

Full simulation results, of Section 4 based on 87W LED luminaire, are contained in the Appendices. The results in Figure 4-18 confirmed that the LED luminaire would achieve satisfactory lighting – it would therefore lead to a lower load compared to the existing 150W HPS luminaire (A saving of 63 W in electrical load for each lighting position).

4.3.1.4. Section 5 (Chainage 0+800 – 1+000) with LED

Uganda street, section 5 cross-section was modelled as shown in Figure 4-10 – the road section lighting valuation was computed with an 87W, 12,000 lumen dimmable LED. The road section performance results were obtained as shown under Figure 4-19.



Results for valuation fields
Maintenance factor: 0.85

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 12.58	✓ 6.22

LHS carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.30	✓ 0.68	✓ 0.69	✓ 9	✓ 0.69

RHS Carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.30	✓ 0.68	✓ 0.69	✓ 9	✓ 0.70

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 12.13	✓ 5.45

Results for energy efficiency indicators

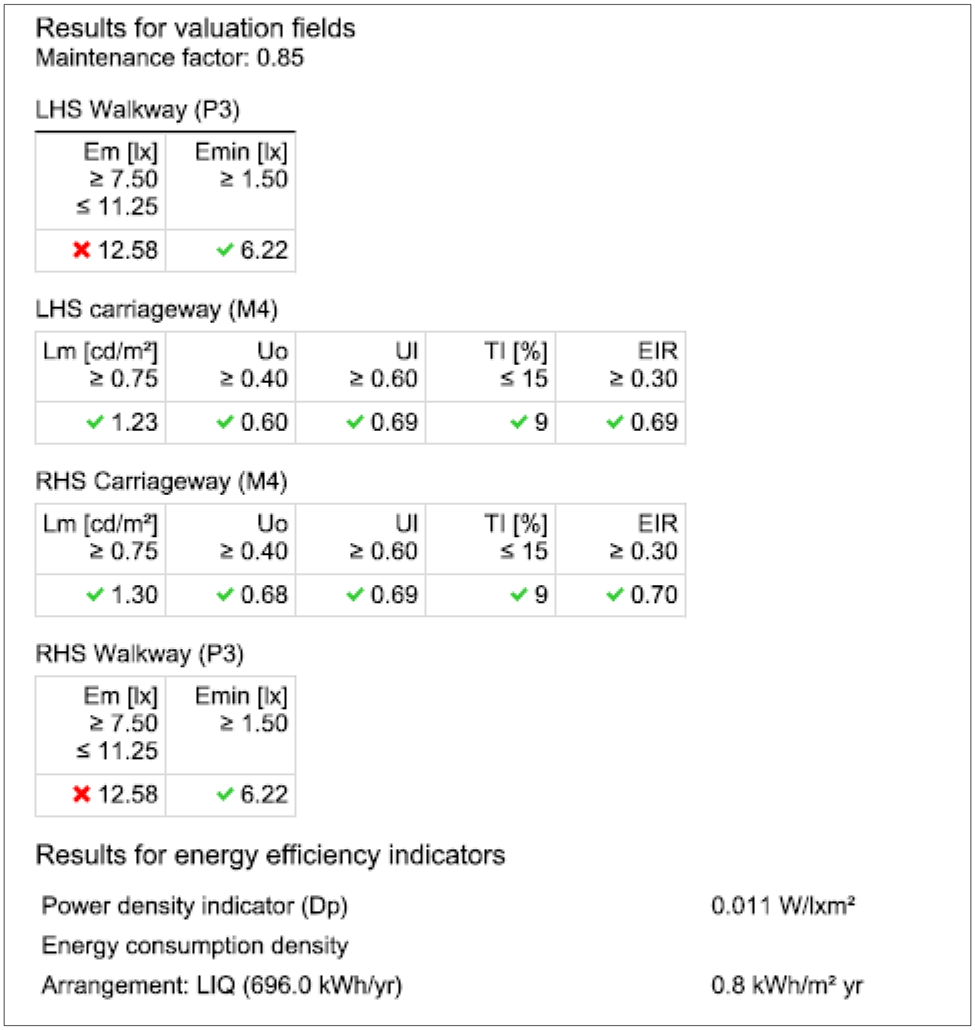
Power density indicator (Dp)	0.014 W/lxm²
Energy consumption density	
Arrangement: LIQ (696.0 kWh/yr)	1.0 kWh/m² yr

Figure 4-19: LED lighting performance results for 0+800 to 1+000

The results demonstrated that transitioning from HPS to LED lighting would not compromise the level of lighting – it would rather lead to lower electrical load requirement. The horizontal illuminance would, however, exceed the limits within class P3; this can only be cured by adjusting the pole configurations.

4.3.1.5. Section 6 (Chainage 1+000 – 1+200) with LED

Uganda street, section 6 cross-section was modelled as shown in Figure 4-12 – the road section lighting valuation made with an 87W, 12,000 lumen dimmable LED. The LED lighting performance results were obtained as shown in Figure 4-20.



Results for valuation fields
Maintenance factor: 0.85

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 12.58	✓ 6.22

LHS carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.23	✓ 0.60	✓ 0.69	✓ 9	✓ 0.69

RHS Carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.30	✓ 0.68	✓ 0.69	✓ 9	✓ 0.70

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 12.58	✓ 6.22

Results for energy efficiency indicators

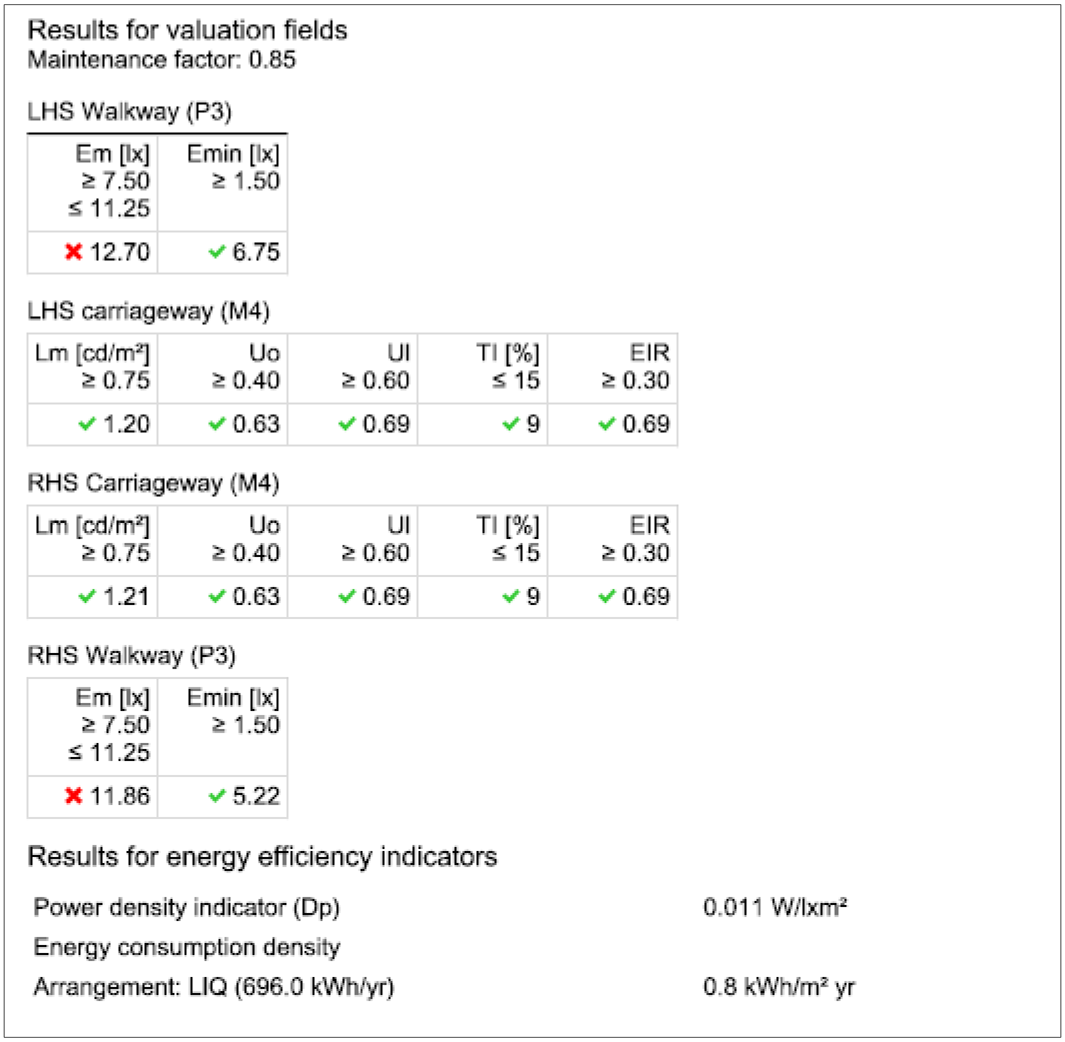
Power density indicator (Dp)	0.011 W/lxm²
Energy consumption density	
Arrangement: LIQ (696.0 kWh/yr)	0.8 kWh/m² yr

Figure 4-20: LED lighting performance results for 1+000 to 1+200

The results indicated an impressive achievement for the drive lane lighting levels – the walkway lighting levels were however slightly more than what is required by the standards (in terms of the average horizontal illuminance). Based on these photometric results, the 87W LED luminaire would be a suitable replacement for the high wattage HPS lamp.

4.3.1.6. Section 7 (Chainage 1+200 – 1+350) with LED

Uganda street, section 7 cross-section was modelled as shown in Figure 4-14 – the road section lighting valuation was made with an 87W, 12,000 lumen dimmable LED. Based on the Figure 4-14 model, and an 87W LED luminaire, the performance results were presented as shown in Figure 4-21.



Results for valuation fields
Maintenance factor: 0.85

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 12.70	✓ 6.75

LHS carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.20	✓ 0.63	✓ 0.69	✓ 9	✓ 0.69

RHS Carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.21	✓ 0.63	✓ 0.69	✓ 9	✓ 0.69

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 11.86	✓ 5.22

Results for energy efficiency indicators

Power density indicator (Dp)	0.011 W/lxm²
Energy consumption density	
Arrangement: LIQ (696.0 kWh/yr)	0.8 kWh/m² yr

Figure 4-21: Lighting performance results for 1+200 to 1+350

The results offered confidence that the HPS to LED transition would not only be beneficial in reducing the luminaire wattage, but also guarantee the required level of lighting for both the drive lanes and the walkways - it would, on the contrary, lead to lower electrical load requirement.

4.3.2. Electrical Load under LED

The electrical lighting load after replacing the existing HPS lamps with modern LED lamps was computed as summarized in Table 4-6.

Table 4-6: LED Street Lighting Electrical Load Summary.

	Chainage		Number of luminaires (N)	Total Load = N x 87 / 1000, kW
	From	To		
1)	0+000	0+200	14	1.218
2)	0+200	0+400	14	1.218
3)	0+400	0+600	12	1.044
4)	0+600	0+800	12	1.044
5)	0+800	1+000	12	1.044
6)	0+000	1+200	12	1.044
7)	1+200	1+350	10	0.870
Total			86	7.482

4.3.3. Installed Power Density and Energy Consumption

The annual energy consumption and installed power density of Uganda Street, based on LED lighting, was calculated, using Equations 3-2 and 3-3 respectively, as shown under Table 4-7.

Table 4-7: Power density and energy consumption – LED lighting.

Section	Length, m	Total Load, kW	Energy, kWh	Power Density, Watts/m
1)	200	1.218	5,335	6.09
2)	200	1.218	5,335	6.09
3)	200	1.044	4,573	5.22
4)	200	1.044	4,573	5.22
5)	200	1.044	4,573	5.22
6)	200	1.044	4,573	5.22
7)	150	0.870	3,810	5.80
			32,772	38.86

Average installed power density = 38.86 / 7 = 5.55 Watts / m.

From Table 4-3, the installed power density of the HPS lighting system was computed as 10.78 Watts/m. By replacing HPS with LEDs, the installed power density would be reduced by 48.52 %.

4.3.4. Scenario 2

During simulation, a 73W luminaire was also found to satisfy the requirements of class M4 lighting. A portion of the simulation results under 73W LED are attached in the Appendices.

4.4. LED Dimming Scenario

4.4.1. Traffic Data

Traffic data was acquired from Dorsch GRE German Rail Engineering GmbH, a consulting firm that conducted traffic studies in Merkato, in 2019. The data was collected at the intersection between chainages 0+250 and 0+300 – this included eastbound and westbound traffic. The data was collected over two days in different months - a weekday and a weekday.

A typical weekday traffic data was obtained and indicated the westbound and eastbound traffic volumes as presented under Figures 4-22 and 4-23 respectively.

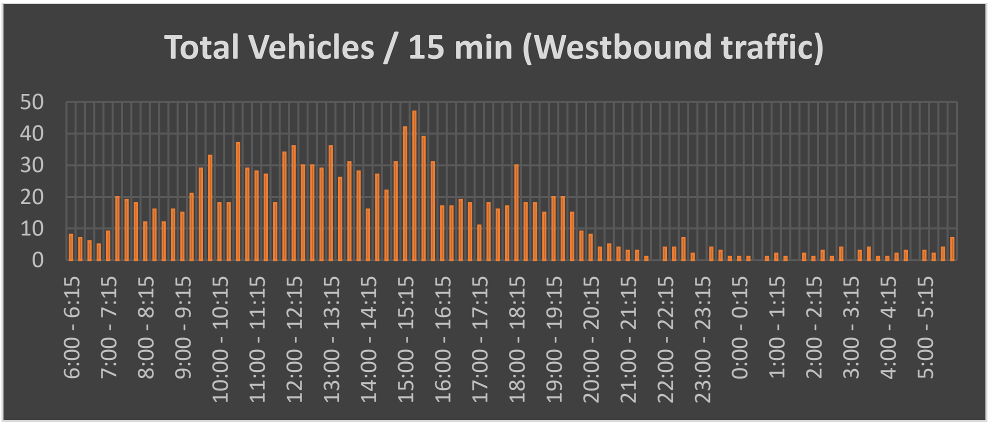


Figure 4-22: Westbound traffic on a weekday.

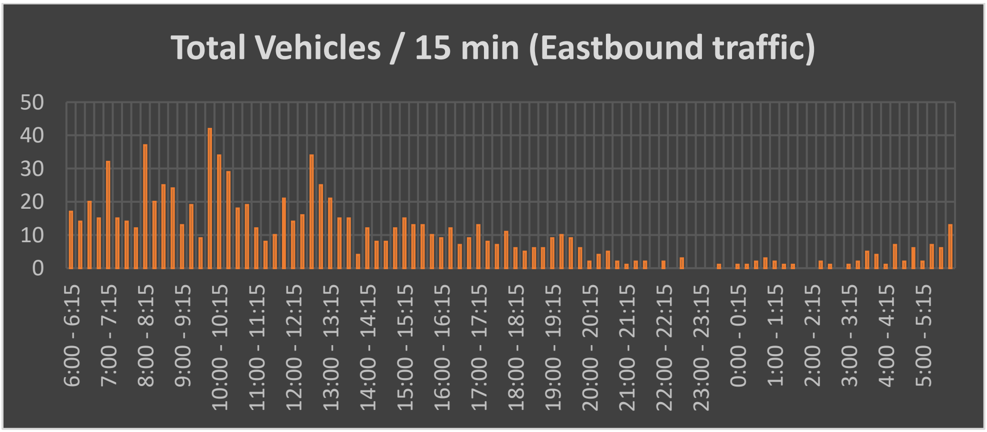


Figure 4-23: Eastbound traffic on a weekday.

A usual weekend data was also provided and revealed the westbound and eastbound traffic volumes as shown under Figures 4-24 and 4-25 respectively.

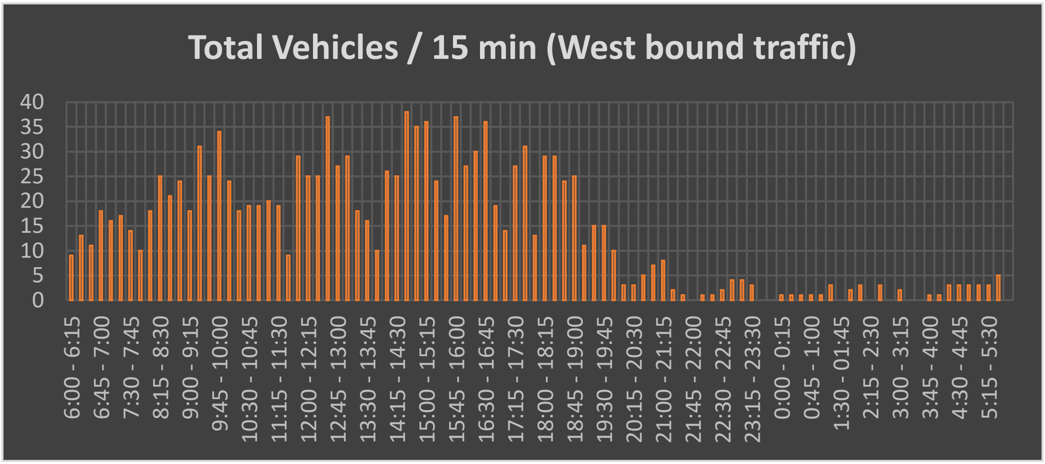


Figure 4-24: Westbound traffic on a weekend.

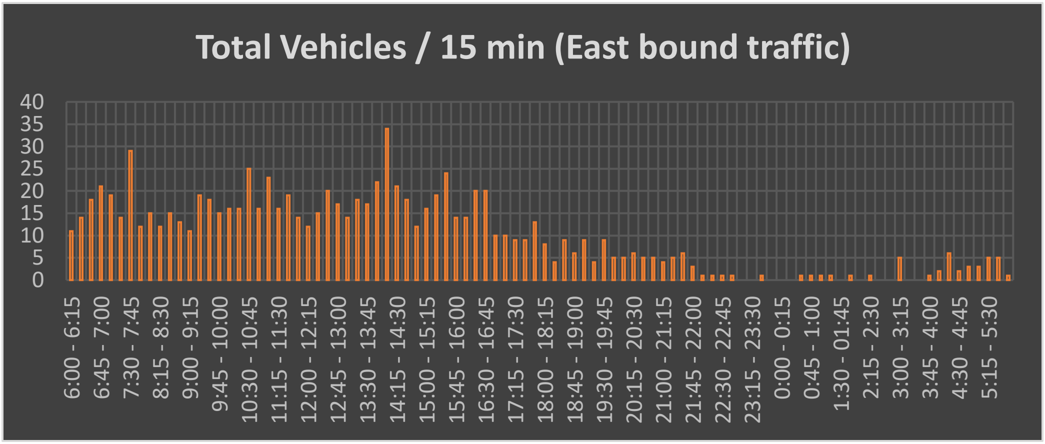


Figure 4-25: Eastbound traffic on a weekend.

The full numerical data is attached in the appendices.

4.4.2. Dimming Schedule and Lighting Levels

It was observed that the night-time traffic volumes reduced gradually as the night progressed. Generally, between 6pm and 8pm, the highest traffic volume was experienced – this was followed by a reduction of more than half in the next two hours. Towards midnight, traffic reduced further by half and stayed the same until 2am. After 2 am, traffic starts to increase slowly. This traffic trend was tabulated in Table 4-8. .

Table 4-8: Night-time Traffic progression.

	Weekday				**Weekend**				
	Westbound		Eastbound		Westbound		Eastbound		
Time (hrs)	Max 15 min traffic	% of highest	Max 15 min traffic	% of highest	Max 15 min traffic	% of highest	Max 15 min traffic	% of highest	Average traffic
1800-2000	30	100	10	77	29	100	9	100	94
2000-2200	5	17	5	38	8	28	6	67	38
2200-0000	7	23	3	23	4	14	1	11	17
0000-0200	2	7	3	23	3	10	1	11	13
0200-0400	4	13	5	38	3	10	5	56	29
0400-0600	7	23	13	100	5	17	5	56	49

The average night-time traffic, on weekdays and weekends, declined as plotted under the chart shown in Figure 4-26.

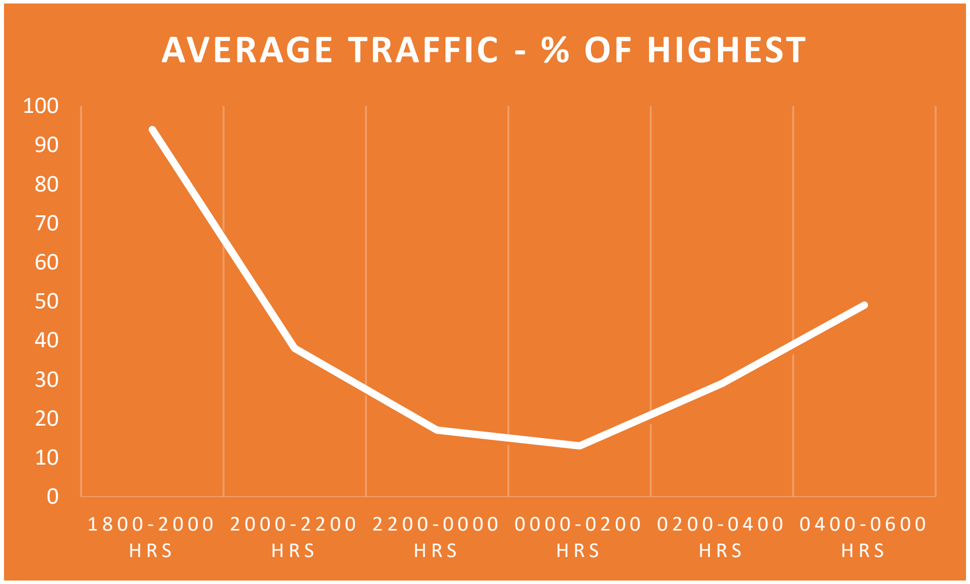


Figure 4-26: Average night-time traffic trend.

Based on the traffic decline observed, the recommended final lighting levels as a percentage of the installed lighting level, were summarized in Table 4-9.

Table 4-9: Recommended, dimmed, lighting levels.

Time (hrs)	Average traffic	Recommended lighting level
1800-2000	94	100 %
2000-2200	38	40 %
2200-0000	17	30 %
0000-0200	13	30 %
0200-0400	29	30 %
0400-0600	49	50 %

Based on the recommended dimmed levels in Table 4-9, the average luminance levels experiences for each of the road sections were summarised in Table 4-10 – the luminance levels corresponded to the required drive lane lighting for the class indicated to EN13201-2.

Table 4-10: 87W LED dimmed lighting levels – Drive lanes.

Section	Installed light, Cd/m^2	Drive lanes' Dimmed LED light, Cd/m^2			
		1800 -2000	2000 - 2200	2200-0400	0400-0600
0+000 - 0+200	1.16 / 1.16 (M4)	1.16 / 1.16 (M4)	0.46 / 0.46 (M6)	0.35 / 0.35 (M6)	0.58 / 0.58 (M5)
0+200 – 0+600	1.17 / 1.17 (M4)	1.17 / 1.17 (M4)	0.47 / 0.47 (M6)	0.35 / 0.35 (M6)	0.59 / 0.59 (M5)
0+600 – 0+800	1.16 / 1.16 (M4)	1.16 / 1.16 (M4)	0.46 / 0.46 (M6)	0.35 / 0.35 (M6)	0.58 / 0.58 (M5)
0+800 – 1+000	1.25 / 1.25 (M4)	1.25 / 1.25 (M4)	0.50 / 0.50 (M6)	0.38 / 0.38 (M6)	0.63 / 0.63 (M5)
1+000 – 1+200	1.18 / 1.25 (M4)	1.18 / 1.25 (M4)	0.47 / 0.50 (M6)	0.35 / 0.38 (M6)	0.59 / 0.63 (M5)
1+200 – 1+350	1.16 / 1.16 (M4)	1.16 / 1.16 (M4)	0.46 / 0.46 (M6)	0.35 / 0.35 (M6)	0.58 / 0.58 (M5)

Care was taken to ensure dimming did not reduce the luminance levels to values lower than the minimum given for class M6 (this is 0.3 Cd/m^2). The implication is that 30% would be lowest dimmed lighting level. Traffic volumes at midnight were computed as 13% of the highest traffic level – however, if 13% dimming was applied, it would lead to a luminance level of 0.15 Cd/m^2 which would be outside the least allowance under EN13201 classifications.

4.4.3. ‘Dimmed’ Electrical Load

The electrical load, for each of the seven road sections, due to the recommended dimming schedule was summarised under Table 4-11.

Table 4-11: 87W Dimmed LED Street Lighting Electrical Load Summary.

Section	Number of luminaires	Load, kW			
		1800 - 2000	2000 - 2200	2200-0400	0400-0600
0+000 - 0+200	14	1.218	0.487	0.365	0.609
0+200 – 0+400	14	1.218	0.487	0.365	0.609
0+200 – 0+600	12	1.044	0.418	0.313	0.522
0+600 – 0+800	12	1.044	0.418	0.313	0.522
0+800 – 1+000	12	1.044	0.418	0.313	0.522
1+000 – 1+200	12	1.044	0.418	0.313	0.522
1+200 – 1+350	10	0.870	0.348	0.261	0.435
		7.482	2.994	2.243	3.741

4.4.4. ‘Dimmed’ Energy Consumption

The annual energy consumption of Uganda Street, based on dimmed LED lighting, was calculated using equation 3-4 as shown under Table 4-12.

Table 4-12: Power density and energy consumption – Dimmed LED lighting.

Section	Dimmed load, kW				Energy, kWh
	1800 -2000	2000 - 2200	2200-0400	0400-0600	
1.	1.218	0.487	0.365	0.609	2,488.57
2.	1.218	0.487	0.365	0.609	2,488.57
3.	1.044	0.418	0.313	0.522	2,133.79
4.	1.044	0.418	0.313	0.522	2,133.79
5.	1.044	0.418	0.313	0.522	2,133.79
6.	1.044	0.418	0.313	0.522	2,133.79
7.	0.870	0.348	0.261	0.435	1,778.28
Total					15,290.60

Similarly, the energy consumption under a dimmed 73W LED was computed as 12,885.52 kWh per year.

4.5. Energy Savings & Lighting Performance Summaries

4.5.1. Energy Savings Under LED & Dimming

The summary of the annual energy consumptions under HPS, LEDs and dimmed LEDs, as calculated from Tables 4-3, 4-7 and 4-12 was summarised in Table 4-13.

Table 4-13: Energy savings summary (HPS to 87W LED).

Section	Length, m	Energy, kWh	Energy, kWh	Energy, kWh	HPS to LED savings	Dimmed LEDs savings
		HPS	LED	Dimmed LED		
1)	200	10,363	5,335	2,488.57	48.52%	75.98%
2)	200	10,363	5,335	2,488.57	48.52%	75.98%
3)	200	8,883	4,573	2,133.79	48.52%	75.98%
4)	200	8,883	4,573	2,133.79	48.52%	75.98%
5)	200	8,883	4,573	2,133.79	48.52%	75.98%
6)	200	8,883	4,573	2,133.79	48.52%	75.98%
7)	150	7,402	3,810	1,778.28	48.53%	75.98%
		63,660	32,772	15,290.60		
		30,888			48.52 %	53.34
		48,369.40			75.98 %	

By transitioning to the 73W LED luminaire, which also meets class M4 lighting, the following savings summary were similarly established (Table 4-14).

Table 4-14: Energy savings summary (HPS to 73W LED).

Section	Length, m	Energy, kWh	Energy, kWh	Energy, kWh	HPS to LED savings	Dimmed LEDs savings
		HPS	LED	Dimmed		
1)	200	10,363	4,476	2,088.97	56.81%	53.33%
2)	200	10,363	4,476	2,088.97	56.81%	53.33%
3)	200	8,883	3,837	1,790.54	56.81%	53.34%
4)	200	8,883	3,837	1,790.54	56.81%	53.33%
5)	200	8,883	3,837	1,790.54	56.81%	53.33%
6)	200	8,883	3,837	1,790.54	56.81%	53.33%
7)	150	7,402	3,197	1,545.41	56.81%	51.66%
		63,660	27,497	12,885.52		
		36,163			56.81%	53.14 %
		50,774.48				79.76%

From Tables 4-13 and 4-14, the energy consumptions under the various scenarios compared as shown under Figure 4-27.

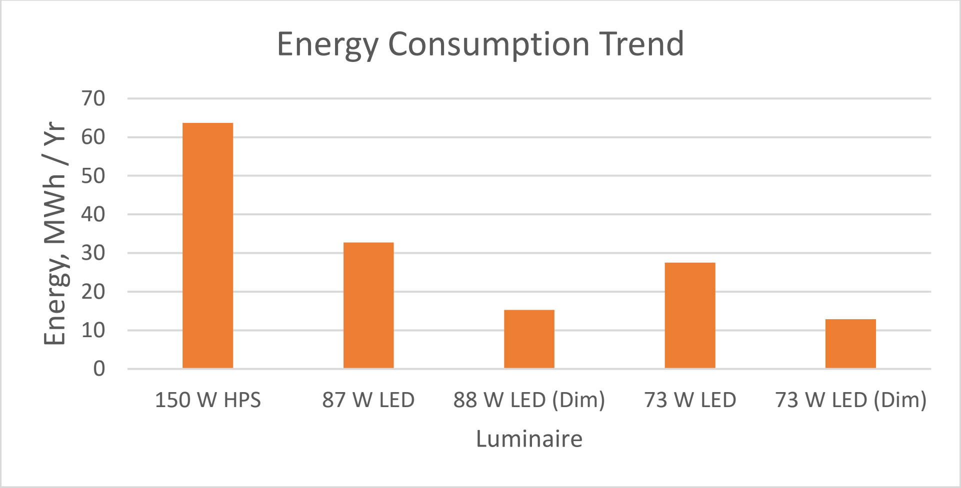


Figure 4-27: Energy Consumption Comparison.

On an overall basis, 48.52 % savings are anticipated by transitioning from HPS to 87W LED lighting. By further dimming the LED luminaires, 75.98% additional energy savings are expected. In absolute terms, 30.888 MWh of energy can be saved by transition to LEDs for the 1.35 km road.

From Tables 4-2, 4-6 and 4-11, the load profile trends were plotted as shown under Figure 4-28. Dimmed LED lighting resulted into lower loads with night progression while the load trend without dimming was constant.

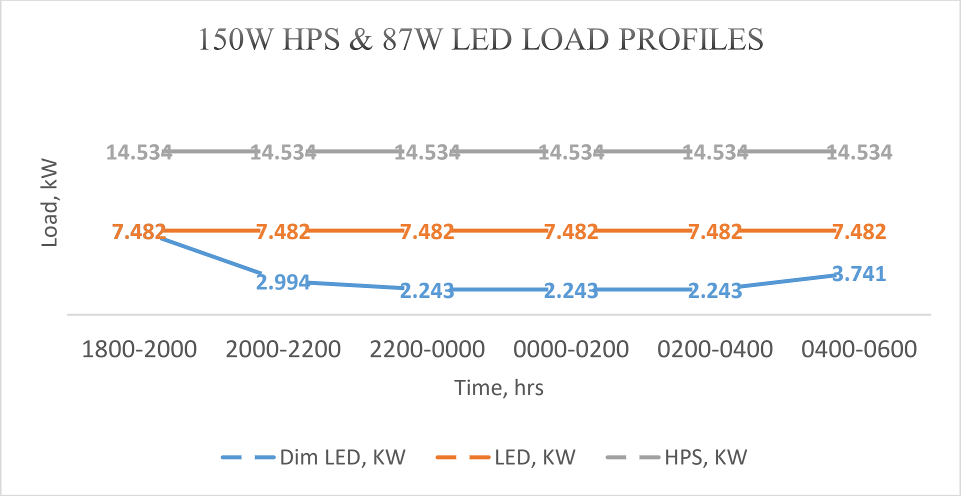


Figure 4-28: Load profile trends.

Addis Ababa had 5,915 km of roads in 2018 whereby 2,616 km had asphalt surfaces [36]. If LED luminaires are adopted instead of HPS lamps for the asphalt roads, 59.854 GWh of energy can be saved (assuming the same lighting requirements as Uganda Street). Florence Ngunju [23] estimated that Nairobi City could save 14.52 GWh of energy annually by transitioning from 250 W to 120W HPS – since no photometric studies were done to size the exact LED requirement, it is possible that more savings would have been realized in the Nairobi study.

The installed power density reduces from 10.78 watts / m to 5.55 watts / m due to the HPS to 87W LED transition – as shown under sections 4.22 and 4.3.3. This drastic reduction, 49%, indicated that LED installation is a sure way of reducing the electrical loads demanded by road lighting from the interconnected grid. With the same lighting hours, LEDs on Uganda Street would consequently result into a 49% reduction in energy costs.

LED dimming can be harnessed as a demand management measure and to ensure that high peak loads in the evenings are smoothened out.

4.5.2. Compare lighting performance with HPS and with LED

The average luminance, Lav, and overall uniformity, Uo, under the HPS lighting and 87W LED were summarized as shown under Table 4-15.

Table 4-15: HPS & LED Lighting performances.

Section	Lav, Cd/m^2			Uo		
	HPS	87W LED	73W LED	HPS	87W LED	73W LED
0+000 - 0+200	1.16 / 1.16	1.21 / 1.21	1.01 / 1.01	0.63 / 0.63	0.63 / 0.63	0.63 / 0.63
0+200 – 0+600	1.17 / 1.17	1.22 / 1.22	1.02 / 1.02	0.64 / 0.64	0.63 / 0.63	0.63 / 0.63
0+600 – 0+800	1.16 / 1.15	1.20 / 1.21	1.00 / 1.01	0.63 / 0.64	0.63 / 0.63	0.63 / 0.63
0+800 – 1+000	1.27 / 1.26	1.30 / 1.30	1.08 / 1.09	0.71 / 0.71	0.68 / 0.68	0.68 / 0.68
1+000 – 1+200	1.18 / 1.26	1.30 / 1.27	1.08 / 1.02	0.71 / 0.67	0.68 / 0.60	0.68 / 0.60
1+200 – 1+350	1.15 / 1.16	1.21 / 1.21	1.01 / 1.00	0.63 / 0.63	0.63 / 0.63	0.63 / 0.63

The various lighting performance parameters are given as RHS/LHS in each case. The minimum Lav requirement for class M4 roads is 0.75 Cd/m2 which was satisfied under all the cases. The Uo requirement is 0.4 which was also met by the recommended LEDs. It was evident however that the 87W LED achieved higher Lav values, far beyond what is required under the street lighting class.

4.6. Cost Benefit Analysis

The cost benefit analysis was undertaken assuming the HPS lamps at half-life and hence a resale value of 50%. An initial value of $ 166.01, which was the average from two studies [13] [14], was used for the HPS lamp and hence a resale value of $ 83.01 for one HPS lamp (and a total salvage value $7,138.86 for the 86 lamps installed on Uganda Street). The LED lamp capital cost was taken as $ 291.48 which was the average of the costs from two studies [14] [23] – this translated into a total initial investment of $ 25,067.28 for the entire street.

4.6.1. Maintenance Savings

The LED luminaire would last for 100,000 hours (twenty-two years), a period in which the HPS lamp would be replaced four times. The LED luminaire replacement cost's savings for a twenty-year period were hence computed as shown under Table 4-16.

Table 4-16: Maintenance Savings

	HPS	
HPS lamp cost per unit, USD	166.01	
Cost per replacement cycle, USD	14,276.86	(86 lamps)
Savings in 20 years	57,107.44	4 replacement cycles

4.6.2. Net Present Value

The energy consumption savings due to the transition to 87W or 73W LEDs were evaluated as indicated under Table 4-17.

Table 4-17: Energy savings due to HPS to LED transition.

	HPS to 87W LED	HPS to 73W LED	Details
Total Annual Savings, kWh	48,369.40	50,774.48	Table 4-13 and 4-14
Cost of power, USD per kWh	0.052	0.052	https://ethioenergybuz.com/en/blog/264-electricity-energy-tariff-in-ethiopia-current
Annual Savings, USD	2,515.21	2,640.27	

Based on a monthly labour cost of \$ 69 [37], and a technician dedicated to attend to any maintenance issues on Uganda Street (cleaning, firming up the wiring and any fault checks), the maintenance cost would be \$ 828 in the first year (an increment of 5% every 5 years was applied).

Assuming the HPS to LED transition is completed in the first year, the investment, expense, savings, and cash benefits summary for the first 22 years under LED lighting was made as shown under Table 4-18. It was assumed that the project shall be financed on a 3.125% interest rate (World Bank March 2021 rates) and hence Rd = 0.03125. The project has a positive net present value and hence shall be profitable. The NPV value for replacing the HPS with the 73W LED, would be higher (at 7024.13) than an 87W LED replacement.

Table 4-18: Costs and Benefits Summary.

Year	**Investment**	**Savings**	**Expenses**	**Salvage**	**Cash Flow, CFi**	**CFi/(1+Rd)i**
1	-25067.28	0	0	7138.9	-17928.42	-17928.42
2	0	2,515.21	-828	0	1687.21	1636.082424
3	0	2,515.21	-828	0	1687.21	1586.504169
4	0	2,515.21	-828	0	1687.21	1538.428285
5	0	2,515.21	-828	0	1687.21	1446.602905
6	0	16,792.07	-828	0	15964.07	12480.49846
7	0	2,515.21	-869.4	0	1645.81	1103.184615
8	0	2,515.21	-869.4	0	1645.81	862.4551187
9	0	2,515.21	-869.4	0	1645.81	578.1027081
10	0	16,792.07	-869.4	0	15922.67	2930.879807
11	0	2,515.21	-869.4	0	1645.81	106.4111454
12	0	2,515.21	-912.87	0	1602.34	19.06971533
13	0	2,515.21	-912.87	0	1602.34	1.232967506
14	0	2,515.21	-912.87	0	1602.34	0.014673752
15	0	16,792.07	-912.87	0	15879.2	0.000111895
16	0	2,515.21	-912.87	0	1602.34	1.03401E-10
17	0	2,515.21	-958.513	0	1556.6965	7.07876E-19
18	0	2,515.21	-958.513	0	1556.6965	4.56801E-32
19	0	2,515.21	-958.513	0	1556.6965	2.07721E-53
20	0	16,792.07	-958.513	0	15833.5565	6.19981E-87
21	0	2,515.21	-958.513	0	1556.6965	8.1336E-144
22	0	2,515.21	-1006.44	0	1508.770825	3.0867E-234
			NPV			**6361.047104**

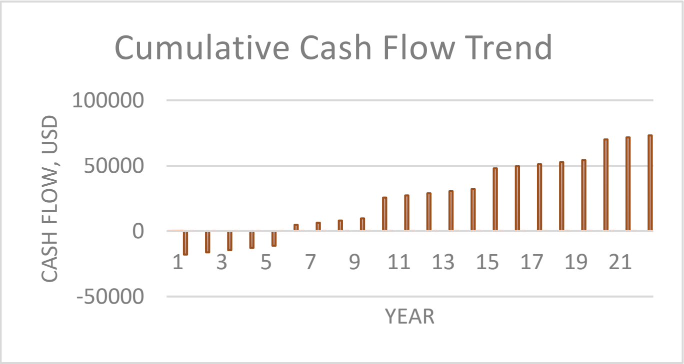
It was assumed that the project shall be financed on a 3.125% interest rate (World Bank March 2021 rates) and hence Rd = 0.03125. The project has a positive net present value and hence shall be profitable. The NPV value for replacing the HPS with the 73W LED, would be higher (at 7024.13) than an 87W LED replacement.

4.6.3. Payback Period

This is the time it takes for the cumulative cash flow to be positive which was evaluated as detailed under Table 4-19.

Table 4-19: Cumulative Cash Flow Summary.

Year	Cumulative Cash Flow
1	-17928.42
2	-16241.21
3	-14554
4	-12866.79
5	-11179.58
6	4784.49
7	6430.3



From Table 4-19, the investments costs are offset by the sixth year and hence the project payback period was obtained as six years. A 73W LED replacement would lead to the same payback period but with a higher cumulative cash flow at the end of the sixth year – compared to the 87W LED.

4.6.4. Internal Rate of Return (IRR)

The IRR is the rate of return where NPV=0. This was computed by first evaluating the NPV for Rd values greater than 3.125% as shown under Table 4-20.

From Table 4-20, the NPV would be zero for Rd values between 5.125% and 6.125%. This was summarised as follows.

Rd	NPV
5.125 %	1448.37
? = x	0
6.125 %	-189.22

Extrapolating

(x -5.125) / (6.125-x) = (0-1448.37) / (-189.22-0); X = 6.01

The IRR was therefore computed as 6.01%.

Table 4-20: NPV under various Rd values.

		Rd = 3.125 %	Rd=2.125 %	Rd=4.125 %	Rd=5.125 %	Rd=6.125%
Year	**Cash Flow, CFi**	**CFi/(1+Rd)i**				
1	-17928.42	-17928.42	-17928.42	-17928.42	-17928.42	-17928.42
2	1687.21	1636.082	1652.102	1620.369	1604.956	1589.832
3	1687.21	1586.504	1617.726	1556.177	1526.712	1498.075
4	1687.21	1538.428	1584.064	1494.528	1452.282	1411.614
5	1687.21	1446.602	1518.828	1378.459	1314.132	1253.373
6	15964.07	12480.49	13492.333	11553.232	10702.754	9922.063
7	1645.81	1103.184	1252.168	973.115	859.4123	759.887
8	1645.81	862.455	1058.293	704.246	576.1738	472.2891
9	1645.81	578.102	805.173	416.398	300.8675	218.0608
10	15922.67	2930.879	5009.011	1723.8128	1019.026	605.3997
11	1645.81	106.411	253.2943	45.0799	19.25506	8.290946
12	1602.34	19.069	77.5776	4.7515	1.199746	0.306906
13	1602.34	1.232	11.9393	0.1301	0.014036	0.001546
14	1602.34	0.014	0.5780	0.00038	1.051E-05	2.961E-07
15	15879.2	0.0001	0.0426	3.106E-07	9.1235E-10	2.831E-12
16	1602.34	1.0340E-10	1.5538E-06	7.550E-15	6.0384E-19	5.280E-23
17	1556.696	7.0787E-19	4.0578E-12	1.435E-25	3.3706E-32	9.148E-39
18	1556.696	4.5680E-32	3.9349E-21	6.761E-43	1.2702E-53	3.014E-64
19	1556.696	2.0772E-53	1.0257E-35	6.232E-71	2.7503E-88	1.77E-105
20	15833.556	6.1998E-87	2.6371E-58	2.75E-115	2.283E-143	3.49E-171
21	1556.696	8.133E-144	1.7083E-97	1.08E-189	3.965E-235	3.90E-280
22	1508.77082	3.086E-234	2.758E-159	0	0	0
	NPV	**6361.04710**	**10404.7156**	**3541.88249**	**1448.36603**	**-189.2231**

4.7. Sensitivity Analysis

Section 4.6 NPV and payback values were computed with an assumption of a constant energy cost over the 20-year LED life period. Since energy costs are subject to global fuel cost changes and local changes in energy costs (due to diminishing availabilities or newer sources), NPV and payback values have consequently been computed with a reducing or increasing energy cost.

4.7.1. Increasing energy costs.

The annual savings with a 10% increment in energy costs every five years were summarised as shown under Table 4-21.

Table 4-21: Energy cost savings with increasing energy cost.

		HPS to 87W LED	Annual Savings, USD
	Total Annual Savings, kWh	48,369.40	
Year 1	Cost of power, USD per kWh	0.052	2,515.21
Year 5	Cost of power, USD per kWh	0.0572	2,766.73
Year 10	Cost of power, USD per kWh	0.0629	3,042.44
Year 15	Cost of power, USD per kWh	0.0692	3,347.16
Year 20	Cost of power, USD per kWh	0.0761	3,680.91

4.7.2. Reducing energy costs.

The annual savings with a 10% reduction in energy costs every five years were summarised as shown under Table 4-22.

Table 4-22: Energy cost savings with reducing energy cost.

		HPS to 87W LED	Annual Savings, USD
	Total Annual Savings, kWh	48,369.40	
Year 1	Cost of power, USD per kWh	0.052	2,515.21
Year 5	Cost of power, USD per kWh	0.0468	2,263.69
Year 10	Cost of power, USD per kWh	0.0421	2,036.35
Year 15	Cost of power, USD per kWh	0.0379	1,833.20
Year 20	Cost of power, USD per kWh	0.0341	1,649.40

4.7.3. Sensitivity Trend

The cumulative cash flow under different energy costs are summarised in the Appendices (Energy cost being constant throughout the lamp life, energy cost increasing by 10% every 2 years, energy cost increasing by 10% every 5 years, energy cost reducing by 10% every 5 years and energy cost reduction by 10% every two years). These cash flow scenarios compare as shown under Figure 4-29.

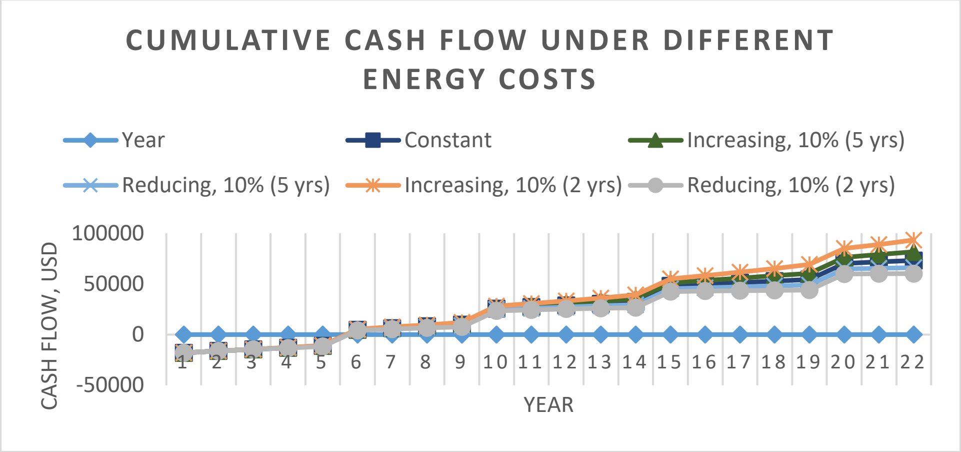


Figure 4-29: Cash flow under various energy cost scenarios.

In all the five cases, a positive net cash flow was achieved in the 6th year with the highest net cash flow being achieved where the energy cost increases every two years.

The NPV for each of the five cases was also positive as shown on Figure 4-30 indicating that the HPS to LED transition would be profitable within the prescribed energy cost changes.

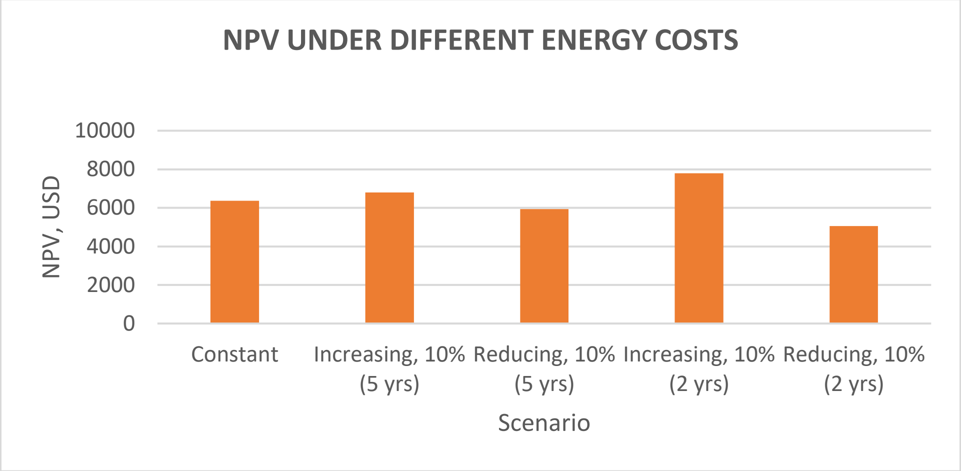


Figure 4-30: NPV under various energy costs.

The highest NPV would be achieved with the energy costs increasing at 10% every two years – The project would therefore be most profitable with higher energy costs. The lowest NPV was observed with the fastest energy cost reductions – the project would be least attractive if energy costs reduce over the project period.

4.8. Case Validation

The studies summarised under Table 3-1 indicate a maximum saving of 35% through HPS to LED transition. The energy savings due to this project were compared to previous studies as shown under Table 4-23.

Table 4-23: Uganda Street Energy Savings compared to other studies.

	% Energy Reduction	
	Step 1: HPS to LED	Step 2: Dimmed LED
Mohammed, Nour, et al, [25]	35 %	18.69 %
Philips, Durban [24]	27 %	
Fusheng Li, et al [12]	30 %	
Florence [23]	24 %	
Annika K. Jägerbrand [34]	49 %	
Uganda Street HPS to 87 W LED	**48..52 %**	**53.34 %**
	75.98 %	
Uganda Street HPS to 73 W LED	**56.81 %**	**53.14 %**
	79.76 %	

This project achieved higher savings than the previous studies cited under Table 4-23. The project benefitted from the developments made in LED technology enabling deployment of high efficacy luminaire and obtaining superior savings. This partly explains the reason minimum 48.52 % savings were obtained compared to maximum 35% in similar studies.

The traffic data analysed helped obtain the highest possible dimming schedule in keeping with EN13201 standards. Traffic volume reductions were matched with proportional LED light dimming – the highest light reduction, with an equivalent class M6 lighting, was applied for the lowest traffic levels. This was one of the reasons the obtained energy savings were higher under this project.

4.9. Chapter Four Conclusion

The HPS to LED transition models demonstrated impressive energy savings which exceeded savings documented in previous studies – this was attributed to advancements in LED luminaire technology. Dimming of the LED luminaires, based on the road traffic trends, contributed to further savings. The study established a positive economic case due to the long LED luminaire operation life.

5.0 CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1. Conclusions

Transitioning from the existing HPS lighting to 87W LED lighting, on Uganda Street, would reduce the energy consumption from 62.66 MWh to 32.772 MWh. Dimming of the LED luminaires would reduce the energy consumption further from 32.772 MWh to 15.291 MWh.

If 73W luminaire are used in place of the 87W LED luminaire, the energy consumption would drop from 62.66 MWh to 27.497 MWh. Dimming of the 73W LED luminaire would reduce the energy consumption from 27.497 MWh to 12.886 MWh.

The 87W LED achieved a higher average luminance compared to the 150W HPS lamps while the 73W luminaires' achieved luminance was slightly below that of the HPS luminaire but within the level required under M4 lighting class. Each of the evaluated scenarios satisfied the standard overall uniformity. It was however noted that LED luminaire offers superior quality lighting (higher CRI and CCT) compared to HPS whose lighting quality is poor at installation and further deteriorates with age.

The project underlined the need for comprehensive photometric designs before transition from HPS to LED lighting. Photometric designs utilize manufacturer luminaire data to assess the lighting quantity and quality – this would assure the authorities managing the lighting infrastructure that the recommended LED lighting would be adequate and reliable.

EN13201 lighting standards classify road lighting into six lighting classes and provide road lighting designers with the discretion to vary the lighting levels with changing road circumstances, which also serves as an energy management measure. Any variation to the lighting level, for instance through dimming, must be based on studies showing that the final lighting satisfies the requirements of the lighting standards.

Due to advancement in LED technology and an increase in their use in road lighting, initial LED installation costs has drastically reduced – this has gradually made the economic case for their installation more favourable. In the case of Uganda Street, the investment would be paid pack in six years with a positive NPV.

5.2. Recommendations

The 73W LED luminaire satisfies the class M4 lighting requirements of Uganda street and is recommended in favour of the 87W LED luminaire – this would achieve greater savings due to the lower consumption compared to the 87W LED luminaire.

AACRA should take advantage of the available LED technologies and roll out their citywide deployment – this would lead to huge overall energy reductions, lower the GHG emissions and ease pressure on the load required to be supplied from the interconnected grid.

Since the traffic volume and overall situation on Uganda Street is bound to change, it is recommended that the dimming schedule be reviewed and adjusted accordingly based on periodic traffic studies.

Further study on the effects of LED lamp deterioration on possible light dimming schedules, is recommended. While a constant maintenance factor is applied throughout the LED life, it is expected that the lamp performance is superior at the beginning of life – higher light dimming levels are therefore possible which could be established through further research. Studies on transition from HPS to LED and dimming, under solar power street lighting, are also recommended – of particular interest would be the possible effects of dimming on the sizing and life of the battery.

5.3. Contributions to Research

The project established the critical role of the EN13201:2015 standards in guiding the process of transition from HPS to LED road lighting. The study reiterated that such transitions must guarantee that the final road lighting conditions must never be compromised – all parameters, under EN13201-2 must be satisfied for all the road areas (the drive lanes and walkway).

The project provided a systematic approach in the application of scheduled dimming as a road lighting energy management measure. This approach was based on the evaluation of available traffic data which revealed the traffic volumes' trend, over the night-time, and hence the need to adjust the road lighting intensities proportionally. Notwithstanding the road traffic volume trends, the study helped observe that EN13201-2 acts to provide the limits of light dimming, in that the lighting levels cannot be reduced beyond the limits of class M6.

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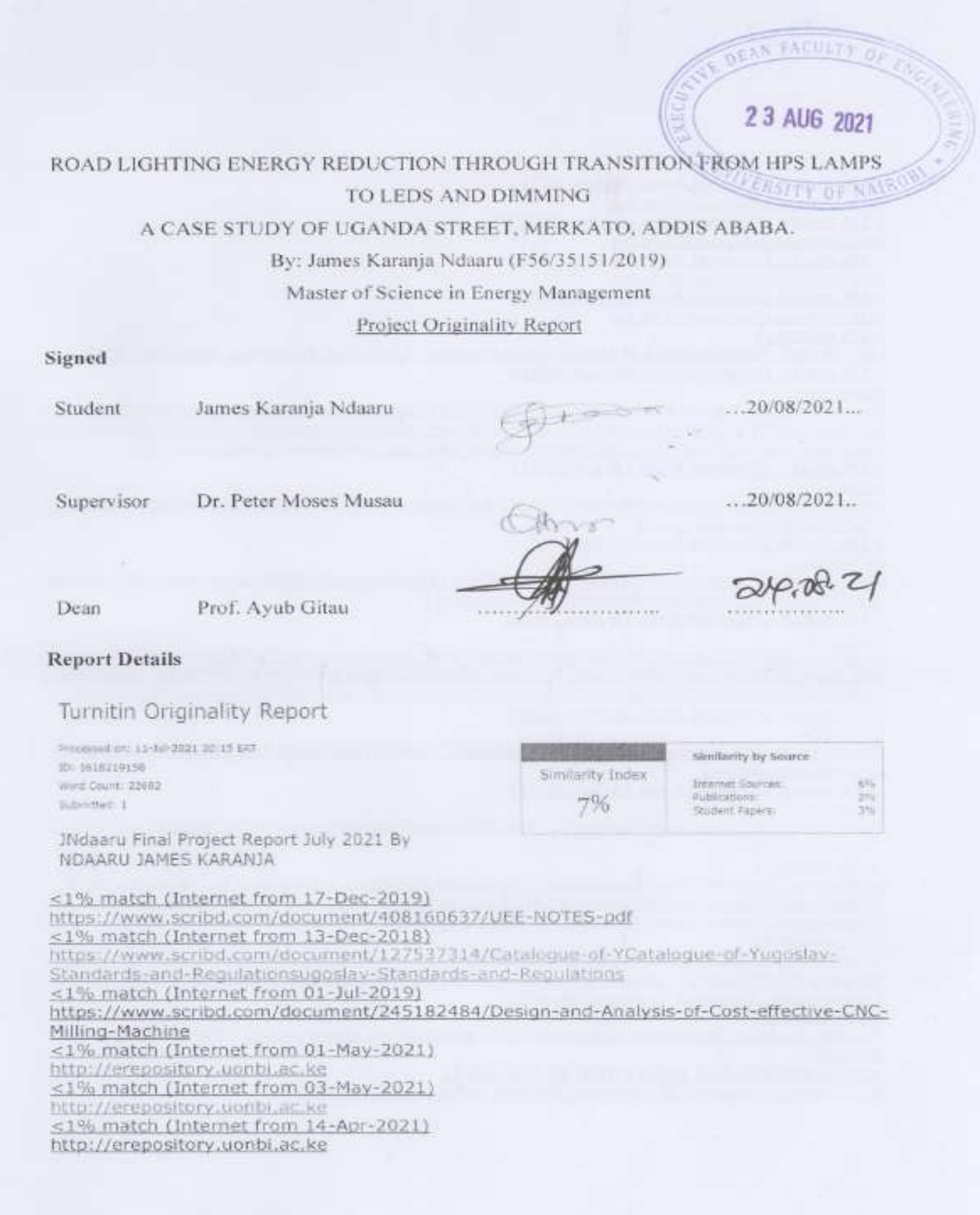
APPENDICES

Appendix A: Originality Report



EXECUTIVE DEAN FACULTY OF ENGINEERING
23 AUG 2021
UNIVERSITY OF NAIROBI

ROAD LIGHTING ENERGY REDUCTION THROUGH TRANSITION FROM HPS LAMPS TO LEDS AND DIMMING
A CASE STUDY OF UGANDA STREET, MERKATO, ADDIS ABABA.
By: James Karanja Ndaaru (F56/35151/2019)
Master of Science in Energy Management
Project Originality Report

Signed

Student	James Karanja Ndaaru	…20/08/2021…
Supervisor	Dr. Peter Moses Musau	…20/08/2021..
Dean	Prof. Ayub Gitau	24.08.21

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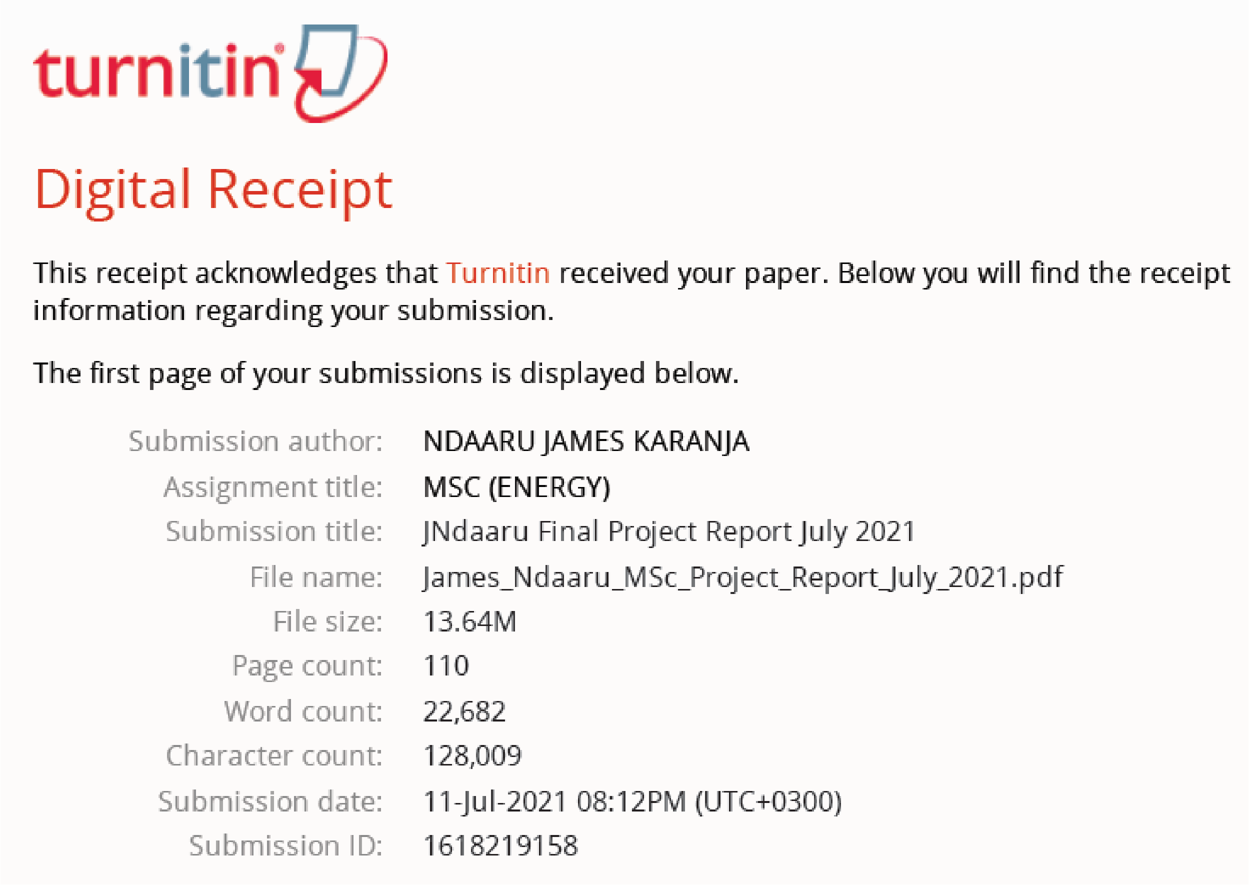

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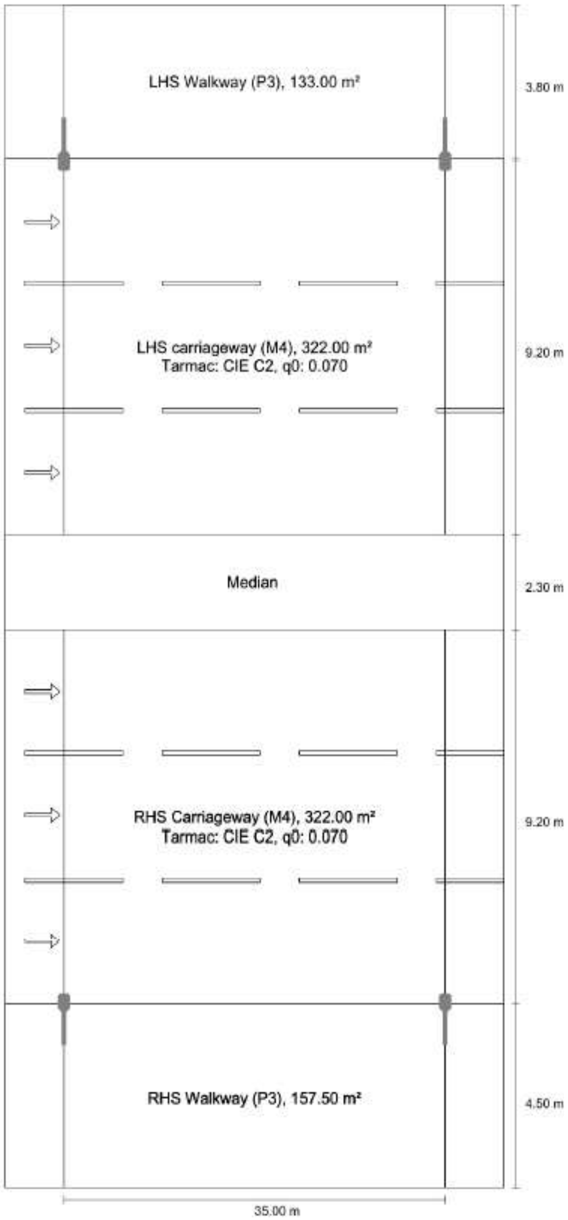
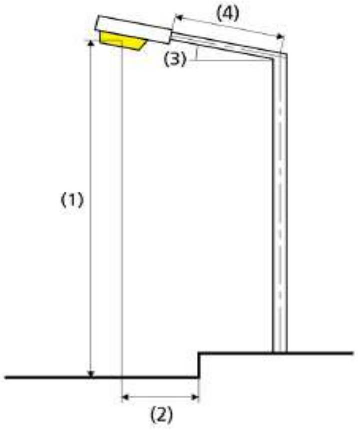
Appendix B: Lighting Simulations – Existing HPS Lighting

B1: Uganda Street: Section 1 (0+000 – 0+200)





Lamp:	1xSON-TPP150W
Luminous flux (luminaire):	12407.87 lm
Luminous flux (lamp):	17500.00 lm
Operating Hours	
4000 h:	100.0 %, 169.0 W
W/km:	9802.0
Arrangement:	both sides opposite
Pole distance:	35.000 m
Boom inclination (3):	10.0°
Boom length (4):	0.964 m
Light centre height (1):	10.000 m
Light overhang (2):	0.000 m
ULR:	0.00
ULOR:	0.00
Maximum luminous intensities	
at 70° and above	653 cd/klm *
at 80° and above	73.8 cd/klm *
at 90° and above	7.05 cd/klm *
Luminous intensity class:	G*3

Any direction forming the specified angle from the downward vertical, with the luminaire installed for use.

* Luminous intensity values in [cd/klm] for calculating luminous intensity class refer to the output flux of the luminaire, according EN 13201:2015.

Arrangement complies with glare index class D.3

Results for valuation fields
Maintenance factor: 0.82

LHS Walkway (P3)

Em [lx]	Emin [lx]
≥ 7.50	≥ 1.50
≤ 11.25	
✗ 11.70	✓ 5.29

LHS carriageway (M4)

Lm [cd/m²]	Uo	Ul	TI [%]	EIR
≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.30
✓ 1.16	✓ 0.63	✓ 0.75	✓ 12	✓ 0.70

RHS Carriageway (M4)

Lm [cd/m²]	Uo	Ul	TI [%]	EIR
≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.30
✓ 1.16	✓ 0.63	✓ 0.75	✓ 12	✓ 0.70

RHS Walkway (P3)

Em [lx]	Emin [lx]
≥ 7.50	≥ 1.50
≤ 11.25	
✓ 11.19	✓ 4.88

B2: Uganda Street: Sections 2 & 3 (0+200 - 0+600)

Results for valuation fields
Maintenance factor: 0.82

LHS Walkway (P3)

Em [lx]	Emin [lx]
≥ 7.50	≥ 1.50
≤ 11.25	
✗ 12.34	✓ 5.77

LHS carriageway (M4)

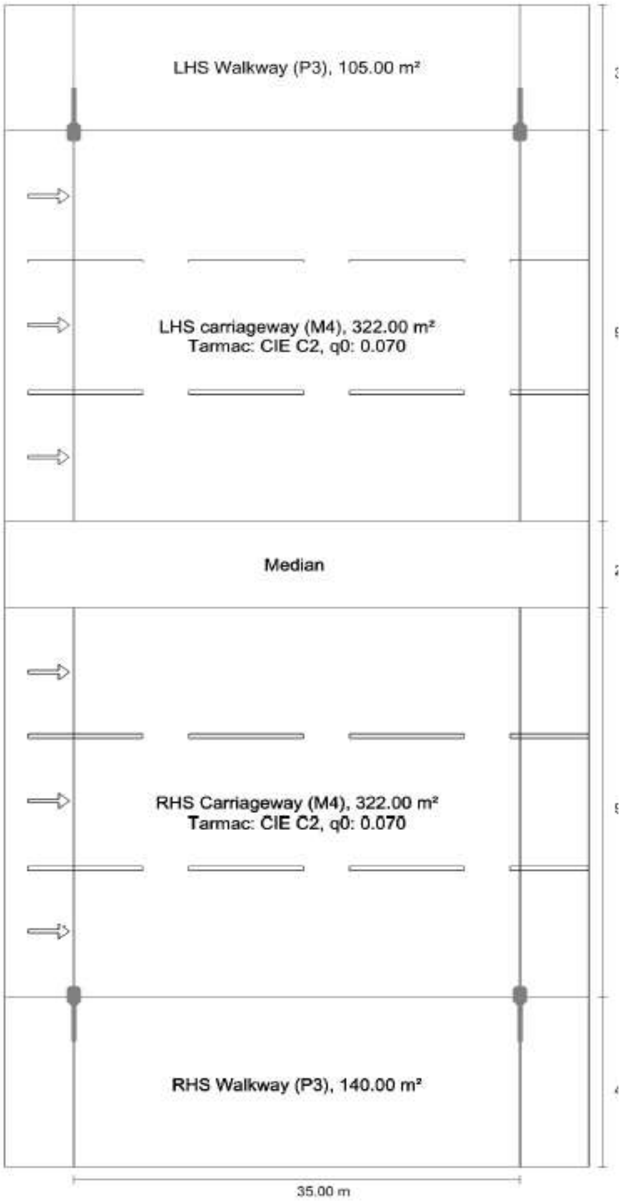
Lm [cd/m²]	Uo	Ul	TI [%]	EIR
≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.30
✓ 1.17	✓ 0.64	✓ 0.75	✓ 12	✓ 0.70

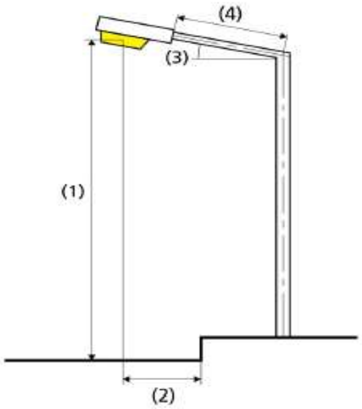
RHS Carriageway (M4)

Lm [cd/m²]	Uo	Ul	TI [%]	EIR
≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.30
✓ 1.17	✓ 0.64	✓ 0.75	✓ 12	✓ 0.70

RHS Walkway (P3)

Em [lx]	Emin [lx]
≥ 7.50	≥ 1.50
≤ 11.25	
✗ 11.58	✓ 5.20





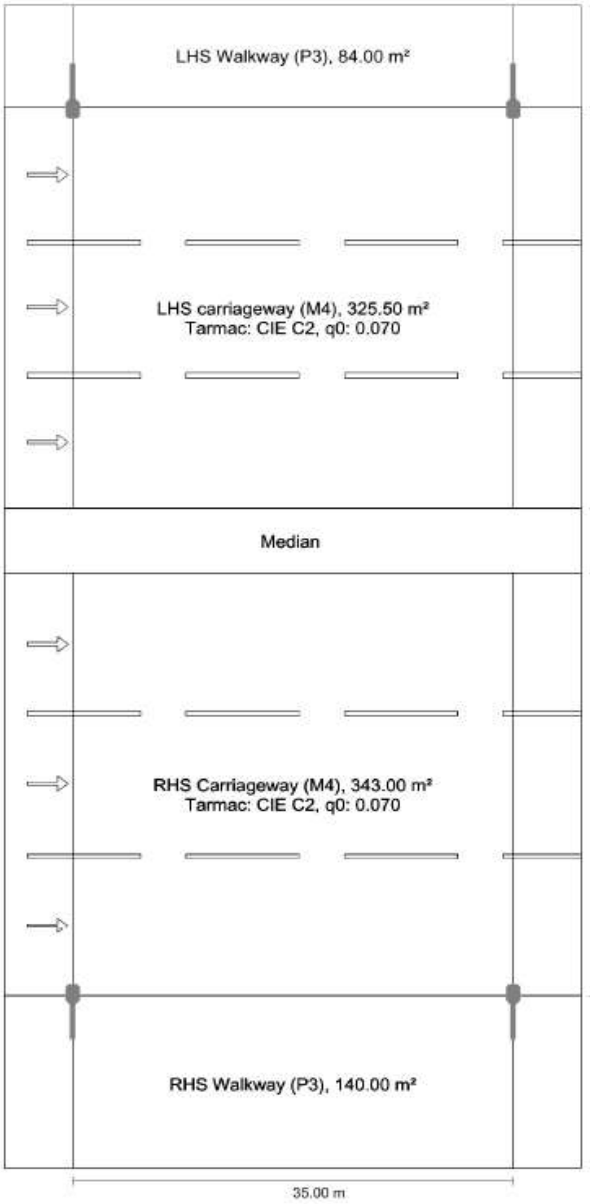
Lamp:	1xSON-TPP150W
Luminous flux (luminaire):	12407.87 lm
Luminous flux (lamp):	17500.00 lm
Operating Hours	
4000 h:	100.0 %, 169.0 W
W/km:	9802.0
Arrangement:	both sides opposite
Pole distance:	35.000 m
Boom inclination (3):	10.0°
Boom length (4):	0.964 m
Light centre height (1):	10.000 m
Light overhang (2):	0.000 m
ULR:	0.00
ULOR:	0.00
Maximum luminous intensities	
at 70° and above	653 cd/klm *
at 80° and above	73.8 cd/klm *
at 90° and above	7.05 cd/klm *
Luminous intensity class:	G*3

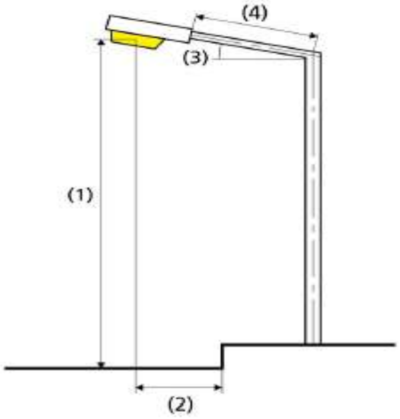
Any direction forming the specified angle from the downward vertical, with the luminaire installed for use.

* Luminous intensity values in [cd/klm] for calculating luminou intensity class refer to the output flux of the luminaire, accord EN 13201:2015.

Arrangement complies with glare index class D.3

B3: Uganda Street: Section 4 (0+600 – 0+800)



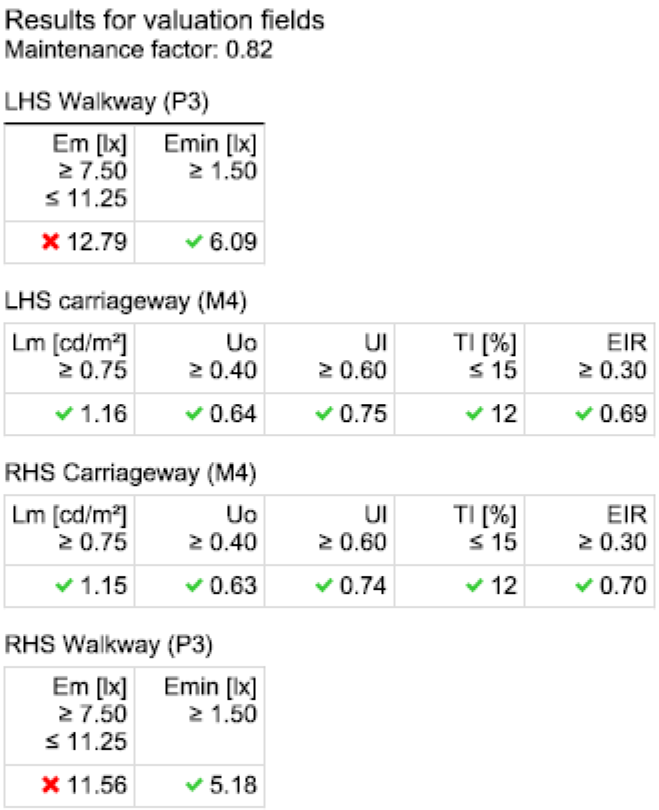


Lamp:	1xSON-TPP150W
Luminous flux (luminaire):	12407.87 lm
Luminous flux (lamp):	17500.00 lm
Operating Hours	
4000 h:	100.0 %, 169.0 W
W/km:	9802.0
Arrangement:	both sides opposite
Pole distance:	35.000 m
Boom inclination (3):	10.0°
Boom length (4):	0.964 m
Light centre height (1):	10.000 m
Light overhang (2):	0.000 m
ULR:	0.00
ULOR:	0.00
Maximum luminous intensities	
at 70° and above	653 cd/klm *
at 80° and above	73.8 cd/klm *
at 90° and above	7.05 cd/klm *
Luminous intensity class:	G*3

Any direction forming the specified angle from the downwar vertical, with the luminaire installed for use.

* Luminous intensity values in [cd/klm] for calculating luminc intensity class refer to the output flux of the luminaire, accor EN 13201:2015.

Arrangement complies with glare index class D.3



Results for valuation fields
Maintenance factor: 0.82

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 12.79	✓ 6.09

LHS carriageway (M4)

Lm [cd/m^2] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.16	✓ 0.64	✓ 0.75	✓ 12	✓ 0.69

RHS Carriageway (M4)

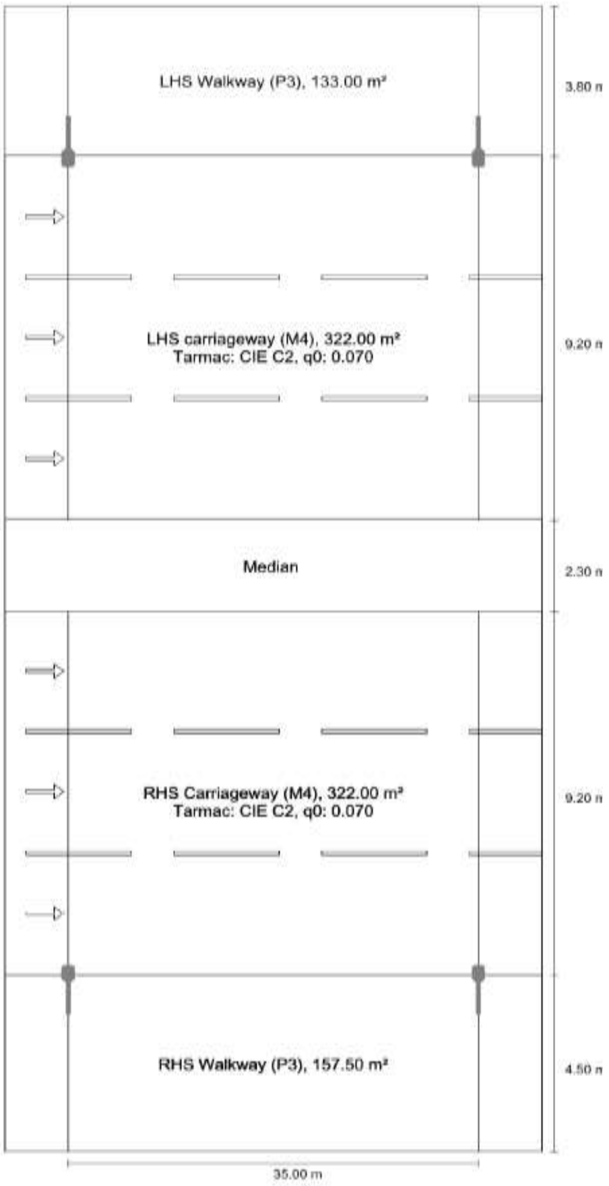
Lm [cd/m^2] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.15	✓ 0.63	✓ 0.74	✓ 12	✓ 0.70

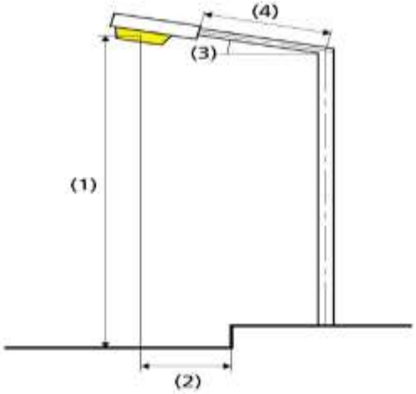
RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 11.56	✓ 5.18

Appendix C: Lighting Simulations – Recommended LED Lighting (87W)

C1: Uganda Street: Section 1 (0+000 – 0+200)



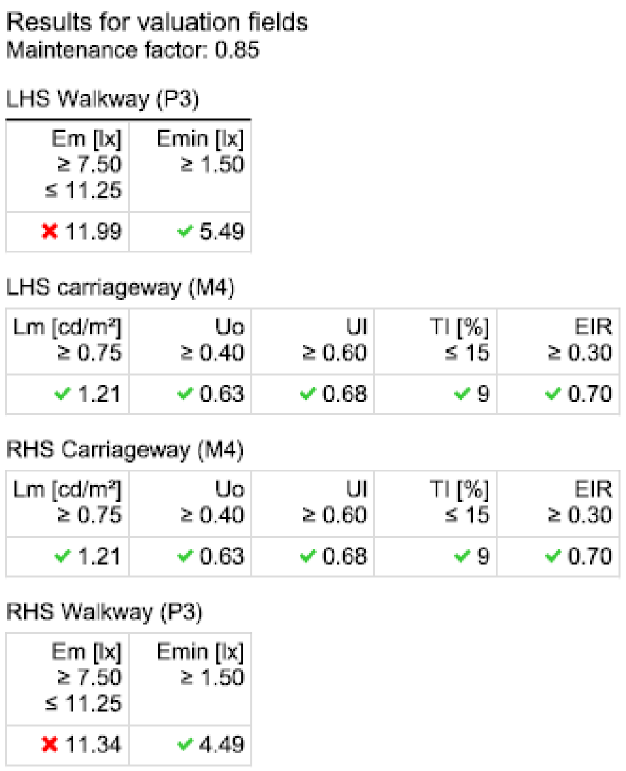


Lamp:	1xLED
Luminous flux (luminaire):	11999.33 lm
Luminous flux (lamp):	12000.00 lm
Operating Hours	
4000 h:	100.0 %, 87.0 W
W/km:	5046.0
Arrangement:	both sides opposite
Pole distance:	35.000 m
Boom inclination (3):	10.0°
Boom length (4):	0.496 m
Light centre height (1):	10.000 m
Light overhang (2):	0.000 m
ULR:	0.00
ULOR:	0.00
Maximum luminous intensities	
at 70° and above	509 cd/klm *
at 80° and above	198 cd/klm *
at 90° and above	6.95 cd/klm *
Luminous intensity class:	G*1

Any direction forming the specified angle from the downwa vertical, with the luminaire installed for use.

* Luminous intensity values in [cd/klm] for calculating lumin intensity class refer to the output flux of the luminaire, acco EN 13201:2015.

Arrangement complies with glare index class D.0



Results for valuation fields
Maintenance factor: 0.85

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 11.99	✓ 5.49

LHS carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.21	✓ 0.63	✓ 0.68	✓ 9	✓ 0.70

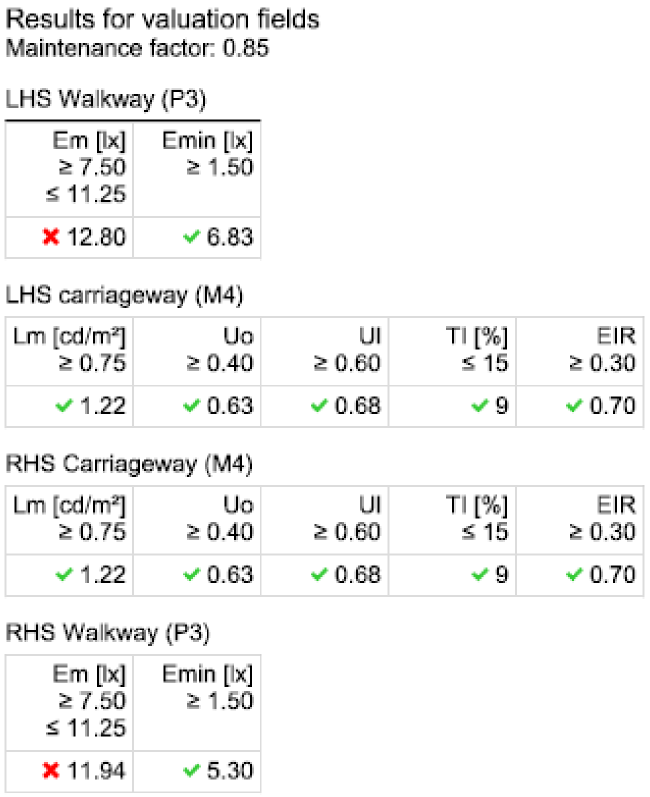
RHS Carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.21	✓ 0.63	✓ 0.68	✓ 9	✓ 0.70

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 11.34	✓ 4.49

C2: Uganda Street: Section 2 & 3 (0+200 – 0+600)



Results for valuation fields
Maintenance factor: 0.85

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 12.80	✓ 6.83

LHS carriageway (M4)

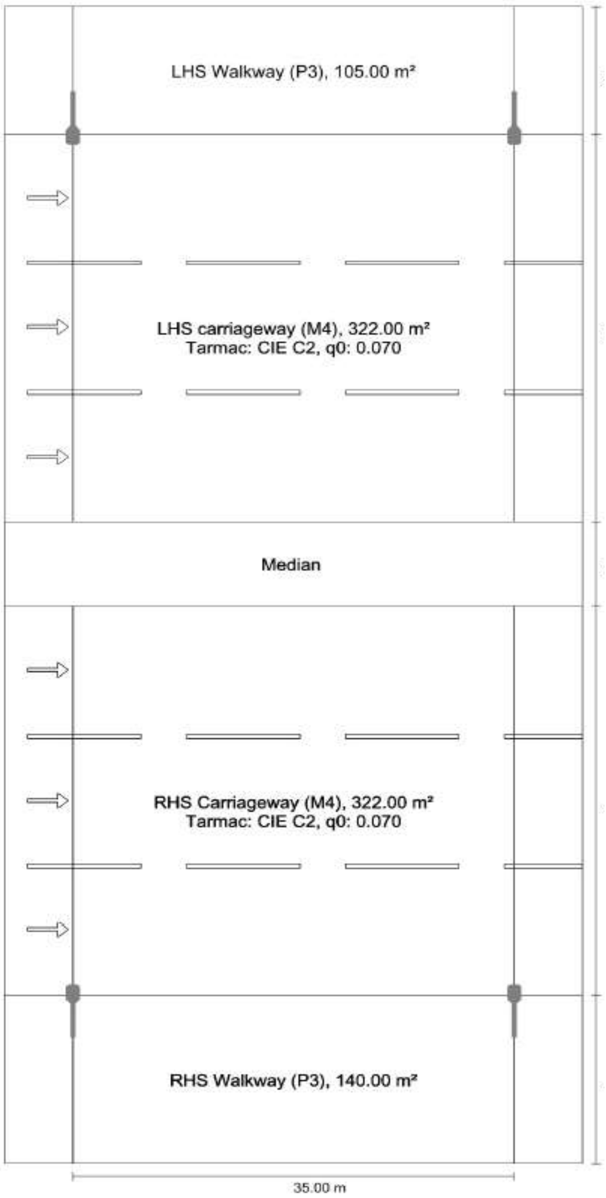
Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.22	✓ 0.63	✓ 0.68	✓ 9	✓ 0.70

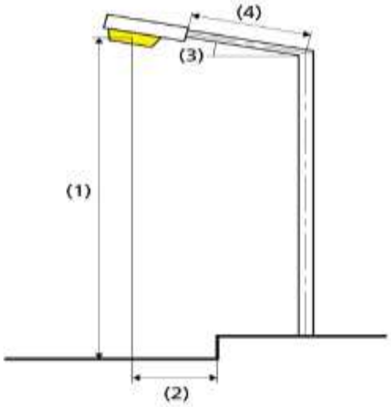
RHS Carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.22	✓ 0.63	✓ 0.68	✓ 9	✓ 0.70

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 11.94	✓ 5.30





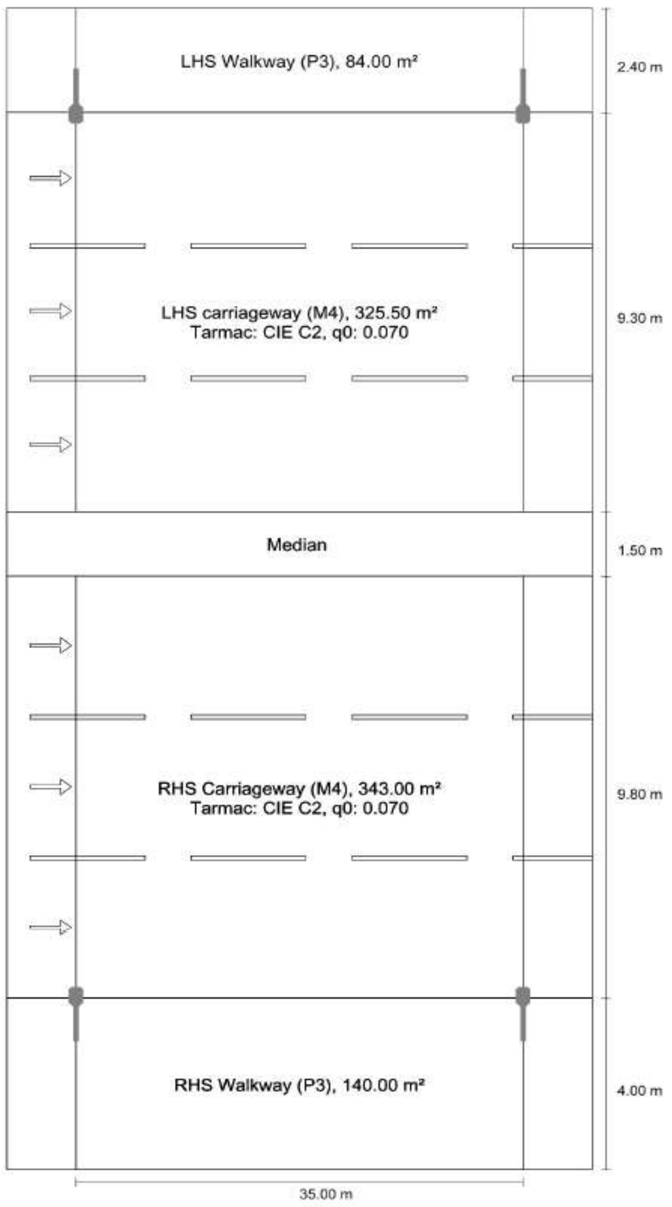
Lamp:	1xLED
Luminous flux (luminaire):	11999.33 lm
Luminous flux (lamp):	12000.00 lm
Operating Hours	
4000 h:	100.0 %, 87.0 W
W/km:	5046.0
Arrangement:	both sides opposite
Pole distance:	35.000 m
Boom inclination (3):	10.0°
Boom length (4):	0.496 m
Light centre height (1):	10.000 m
Light overhang (2):	0.000 m
ULR:	0.00
ULOR:	0.00
Maximum luminous intensities	
at 70° and above	509 cd/klm *
at 80° and above	198 cd/klm *
at 90° and above	6.95 cd/klm *
Luminous intensity class:	G*1

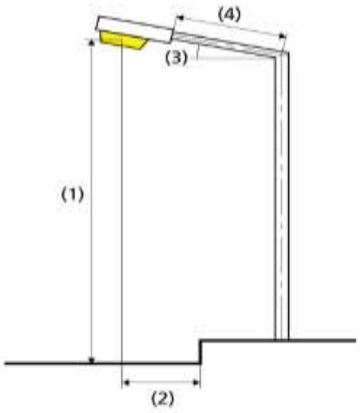
Any direction forming the specified angle from the downward vertical, with the luminaire installed for use.

* Luminous intensity values in [cd/klm] for calculating lumino intensity class refer to the output flux of the luminaire, accord EN 13201:2015.

Arrangement complies with glare index class D.0

C3: Uganda Street: Section 4 (0+600 – 0+800)



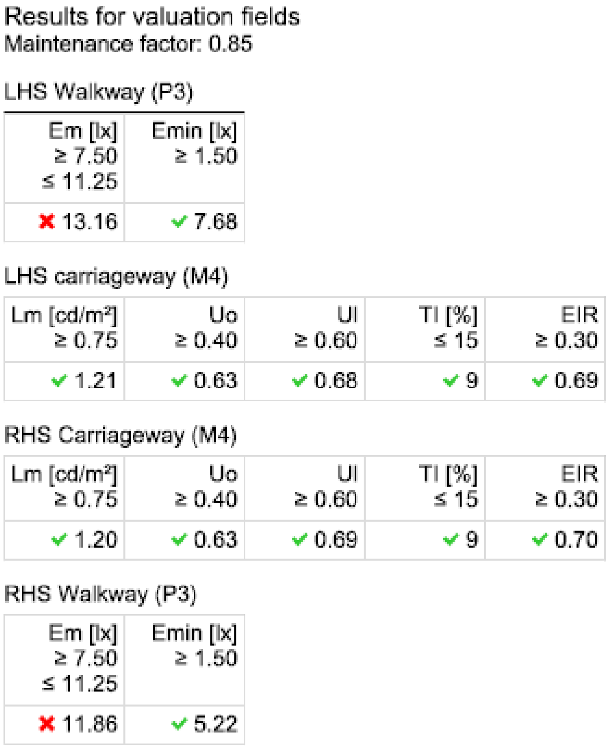


Lamp:	1xLED
Luminous flux (luminaire):	11999.33 lm
Luminous flux (lamp):	12000.00 lm
Operating Hours	
4000 h:	100.0 %, 87.0 W
W/km:	5046.0
Arrangement:	both sides opposite
Pole distance:	35.000 m
Boom inclination (3):	10.0°
Boom length (4):	0.496 m
Light centre height (1):	10.000 m
Light overhang (2):	0.000 m
ULR:	0.00
ULOR:	0.00
Maximum luminous intensities	
at 70° and above	509 cd/klm *
at 80° and above	198 cd/klm *
at 90° and above	6.95 cd/klm *
Luminous intensity class:	G*1

Any direction forming the specified angle from the downward vertical, with the luminaire installed for use.

* Luminous intensity values in [cd/klm] for calculating luminous intensity class refer to the output flux of the luminaire, according EN 13201:2015.

Arrangement complies with glare index class D.0



Results for valuation fields
Maintenance factor: 0.85

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 13.16	✓ 7.68

LHS carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.21	✓ 0.63	✓ 0.68	✓ 9	✓ 0.69

RHS Carriageway (M4)

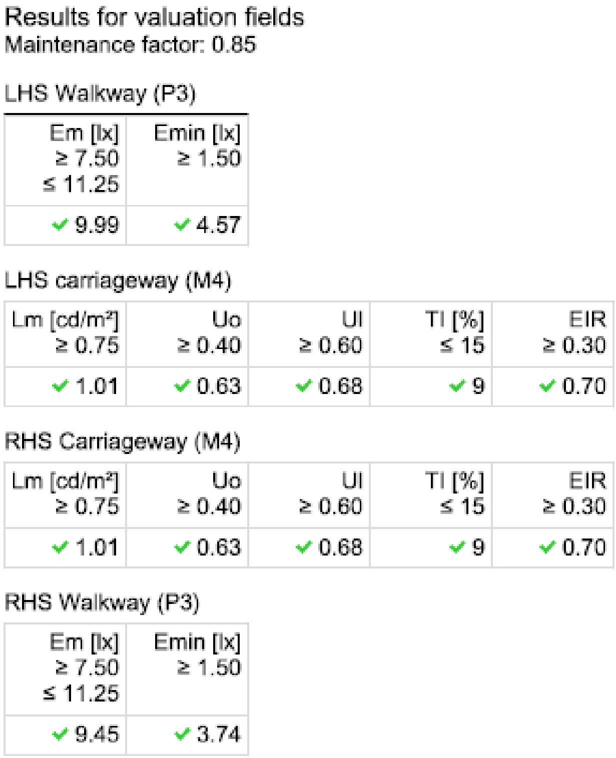
Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.20	✓ 0.63	✓ 0.69	✓ 9	✓ 0.70

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✗ 11.86	✓ 5.22

Appendix D: Lighting Simulations – Recommended LED Lighting (73W)

D1: Uganda Street: Section 1 (0+000 – 0+200)



Results for valuation fields
Maintenance factor: 0.85

LHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✓ 9.99	✓ 4.57

LHS carriageway (M4)

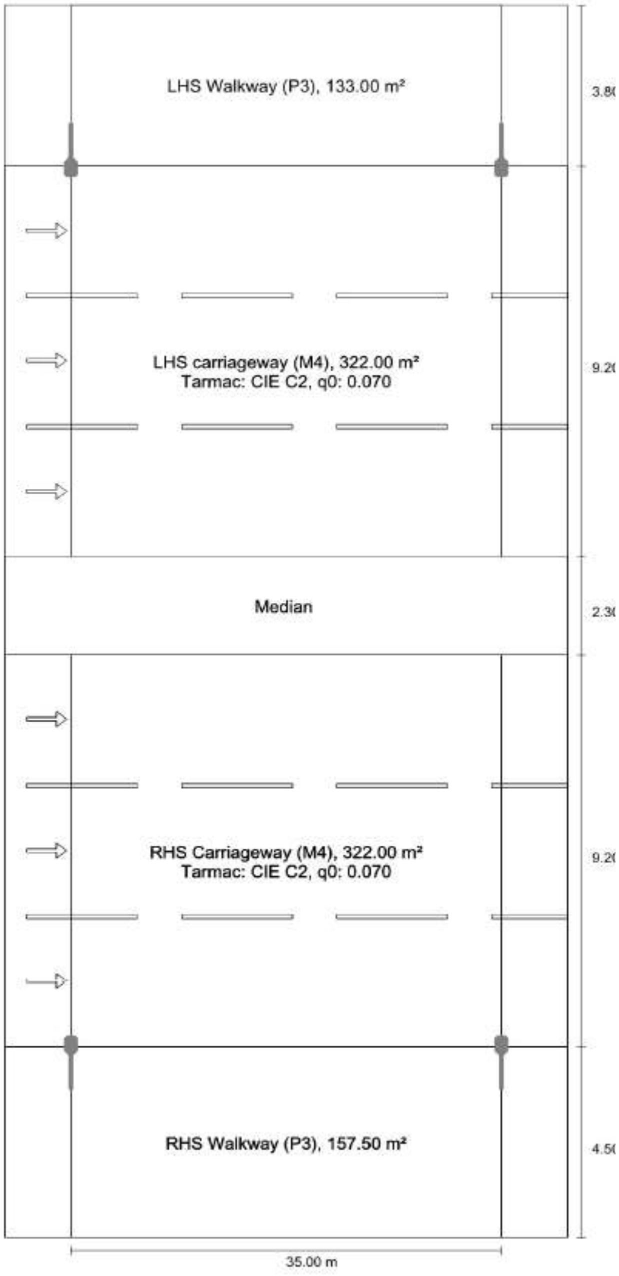
Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.01	✓ 0.63	✓ 0.68	✓ 9	✓ 0.70

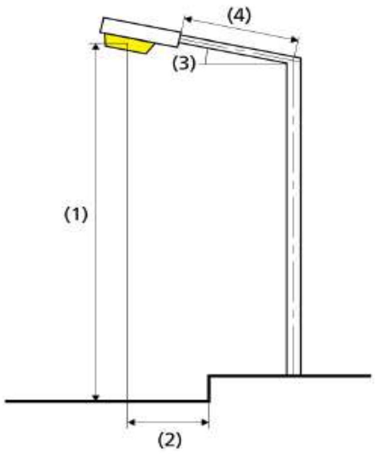
RHS Carriageway (M4)

Lm [cd/m²] ≥ 0.75	Uo ≥ 0.40	Ul ≥ 0.60	TI [%] ≤ 15	EIR ≥ 0.30
✓ 1.01	✓ 0.63	✓ 0.68	✓ 9	✓ 0.70

RHS Walkway (P3)

Em [lx] ≥ 7.50 ≤ 11.25	Emin [lx] ≥ 1.50
✓ 9.45	✓ 3.74





Lamp:	1xLED
Luminous flux (luminaire):	9999.44 lm
Luminous flux (lamp):	10000.00 lm
Operating Hours	
4000 h:	100.0 %, 73.0 W
W/km:	4234.0
Arrangement:	both sides opposite
Pole distance:	35.000 m
Boom inclination (3):	10.0°
Boom length (4):	0.496 m
Light centre height (1):	10.000 m
Light overhang (2):	0.000 m
ULR:	0.00
ULOR:	0.00
Maximum luminous intensities	
at 70° and above	509 cd/klm *
at 80° and above	198 cd/klm *
at 90° and above	6.95 cd/klm *
Luminous intensity class:	G*1

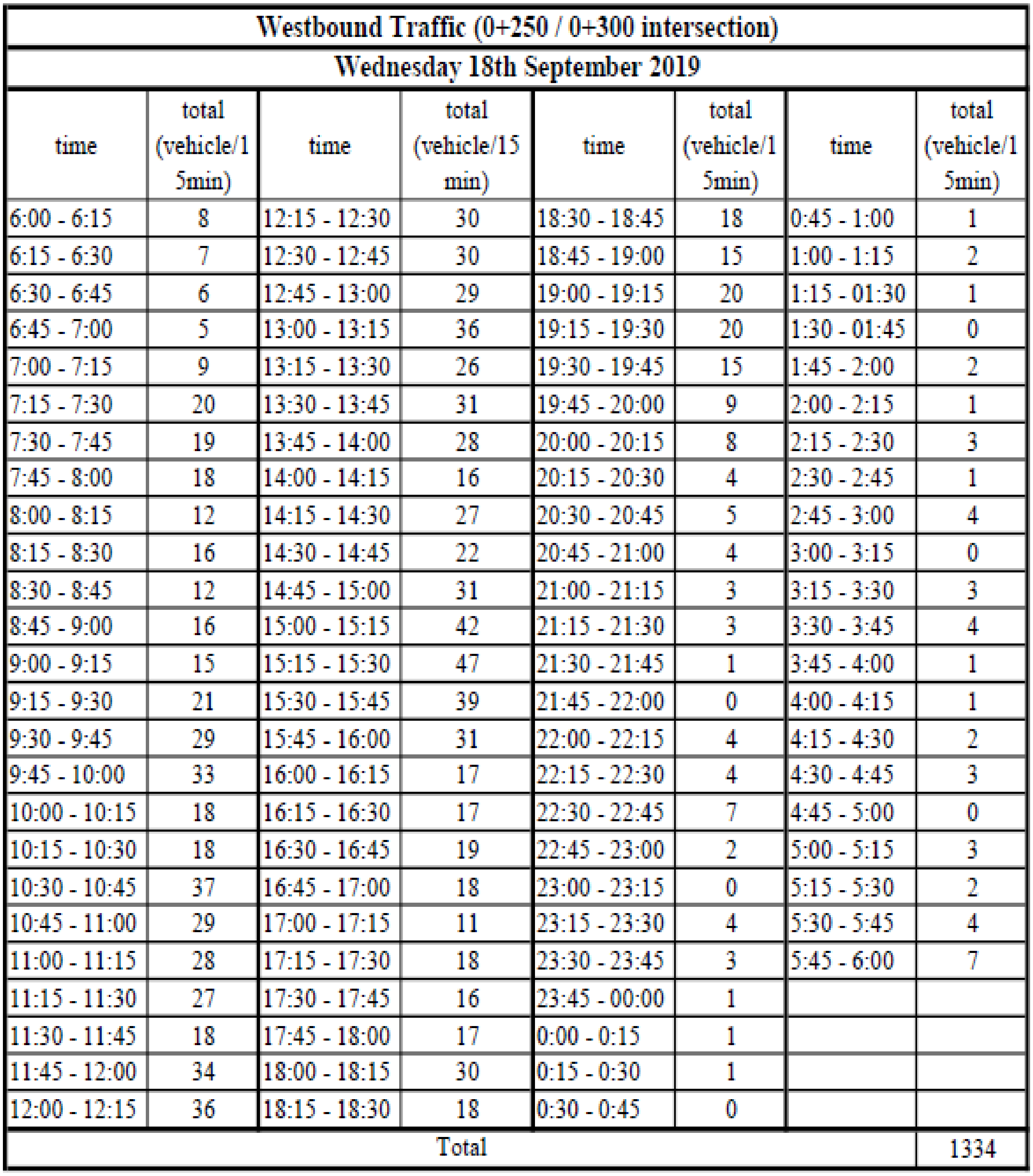
Any direction forming the specified angle from the downward vertical, with the luminaire installed for use.

* Luminous intensity values in [cd/klm] for calculating luminou intensity class refer to the output flux of the luminaire, accordi EN 13201:2015.

Arrangement complies with glare index class D.0

Appendix E: Traffic Data

E1: Westbound weekday

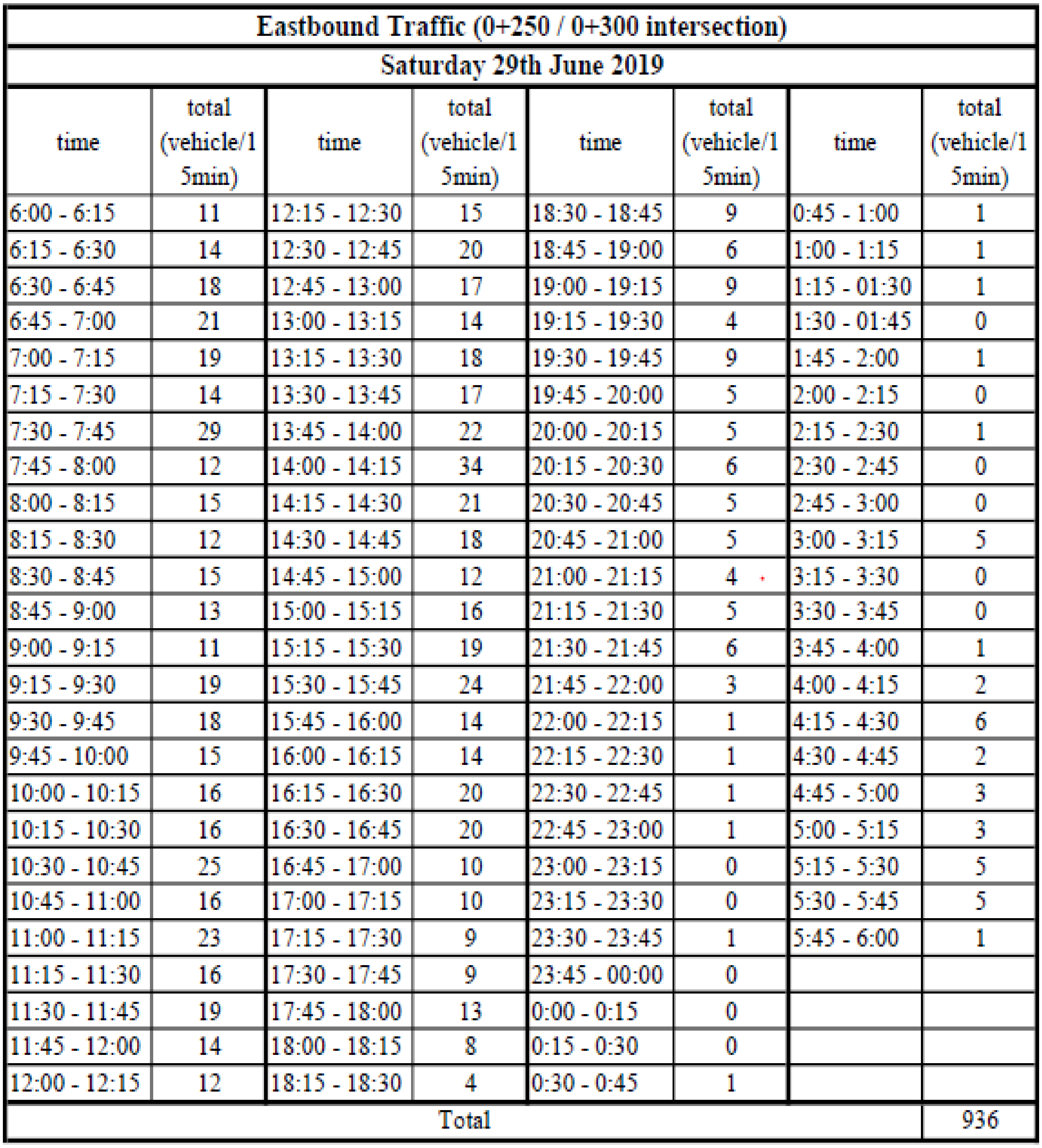


Westbound Traffic (0+250 / 0+300 intersection)

Wednesday 18th September 2019

time	total (vehicle/15min)	time	total (vehicle/15 min)	time	total (vehicle/15min)	time	total (vehicle/15min)
6:00 - 6:15	8	12:15 - 12:30	30	18:30 - 18:45	18	0:45 - 1:00	1
6:15 - 6:30	7	12:30 - 12:45	30	18:45 - 19:00	15	1:00 - 1:15	2
6:30 - 6:45	6	12:45 - 13:00	29	19:00 - 19:15	20	1:15 - 01:30	1
6:45 - 7:00	5	13:00 - 13:15	36	19:15 - 19:30	20	1:30 - 01:45	0
7:00 - 7:15	9	13:15 - 13:30	26	19:30 - 19:45	15	1:45 - 2:00	2
7:15 - 7:30	20	13:30 - 13:45	31	19:45 - 20:00	9	2:00 - 2:15	1
7:30 - 7:45	19	13:45 - 14:00	28	20:00 - 20:15	8	2:15 - 2:30	3
7:45 - 8:00	18	14:00 - 14:15	16	20:15 - 20:30	4	2:30 - 2:45	1
8:00 - 8:15	12	14:15 - 14:30	27	20:30 - 20:45	5	2:45 - 3:00	4
8:15 - 8:30	16	14:30 - 14:45	22	20:45 - 21:00	4	3:00 - 3:15	0
8:30 - 8:45	12	14:45 - 15:00	31	21:00 - 21:15	3	3:15 - 3:30	3
8:45 - 9:00	16	15:00 - 15:15	42	21:15 - 21:30	3	3:30 - 3:45	4
9:00 - 9:15	15	15:15 - 15:30	47	21:30 - 21:45	1	3:45 - 4:00	1
9:15 - 9:30	21	15:30 - 15:45	39	21:45 - 22:00	0	4:00 - 4:15	1
9:30 - 9:45	29	15:45 - 16:00	31	22:00 - 22:15	4	4:15 - 4:30	2
9:45 - 10:00	33	16:00 - 16:15	17	22:15 - 22:30	4	4:30 - 4:45	3
10:00 - 10:15	18	16:15 - 16:30	17	22:30 - 22:45	7	4:45 - 5:00	0
10:15 - 10:30	18	16:30 - 16:45	19	22:45 - 23:00	2	5:00 - 5:15	3
10:30 - 10:45	37	16:45 - 17:00	18	23:00 - 23:15	0	5:15 - 5:30	2
10:45 - 11:00	29	17:00 - 17:15	11	23:15 - 23:30	4	5:30 - 5:45	4
11:00 - 11:15	28	17:15 - 17:30	18	23:30 - 23:45	3	5:45 - 6:00	7
11:15 - 11:30	27	17:30 - 17:45	16	23:45 - 00:00	1		
11:30 - 11:45	18	17:45 - 18:00	17	0:00 - 0:15	1		
11:45 - 12:00	34	18:00 - 18:15	30	0:15 - 0:30	1		
12:00 - 12:15	36	18:15 - 18:30	18	0:30 - 0:45	0		
Total							1334

E2: Eastbound weekend



Eastbound Traffic (0+250 / 0+300 intersection)

Saturday 29th June 2019

time	total (vehicle/15min)	time	total (vehicle/15min)	time	total (vehicle/15min)	time	total (vehicle/15min)
6:00 - 6:15	11	12:15 - 12:30	15	18:30 - 18:45	9	0:45 - 1:00	1
6:15 - 6:30	14	12:30 - 12:45	20	18:45 - 19:00	6	1:00 - 1:15	1
6:30 - 6:45	18	12:45 - 13:00	17	19:00 - 19:15	9	1:15 - 01:30	1
6:45 - 7:00	21	13:00 - 13:15	14	19:15 - 19:30	4	1:30 - 01:45	0
7:00 - 7:15	19	13:15 - 13:30	18	19:30 - 19:45	9	1:45 - 2:00	1
7:15 - 7:30	14	13:30 - 13:45	17	19:45 - 20:00	5	2:00 - 2:15	0
7:30 - 7:45	29	13:45 - 14:00	22	20:00 - 20:15	5	2:15 - 2:30	1
7:45 - 8:00	12	14:00 - 14:15	34	20:15 - 20:30	6	2:30 - 2:45	0
8:00 - 8:15	15	14:15 - 14:30	21	20:30 - 20:45	5	2:45 - 3:00	0
8:15 - 8:30	12	14:30 - 14:45	18	20:45 - 21:00	5	3:00 - 3:15	5
8:30 - 8:45	15	14:45 - 15:00	12	21:00 - 21:15	4	3:15 - 3:30	0
8:45 - 9:00	13	15:00 - 15:15	16	21:15 - 21:30	5	3:30 - 3:45	0
9:00 - 9:15	11	15:15 - 15:30	19	21:30 - 21:45	6	3:45 - 4:00	1
9:15 - 9:30	19	15:30 - 15:45	24	21:45 - 22:00	3	4:00 - 4:15	2
9:30 - 9:45	18	15:45 - 16:00	14	22:00 - 22:15	1	4:15 - 4:30	6
9:45 - 10:00	15	16:00 - 16:15	14	22:15 - 22:30	1	4:30 - 4:45	2
10:00 - 10:15	16	16:15 - 16:30	20	22:30 - 22:45	1	4:45 - 5:00	3
10:15 - 10:30	16	16:30 - 16:45	20	22:45 - 23:00	1	5:00 - 5:15	3
10:30 - 10:45	25	16:45 - 17:00	10	23:00 - 23:15	0	5:15 - 5:30	5
10:45 - 11:00	16	17:00 - 17:15	10	23:15 - 23:30	0	5:30 - 5:45	5
11:00 - 11:15	23	17:15 - 17:30	9	23:30 - 23:45	1	5:45 - 6:00	1
11:15 - 11:30	16	17:30 - 17:45	9	23:45 - 00:00	0		
11:30 - 11:45	19	17:45 - 18:00	13	0:00 - 0:15	0		
11:45 - 12:00	14	18:00 - 18:15	8	0:15 - 0:30	0		
12:00 - 12:15	12	18:15 - 18:30	4	0:30 - 0:45	1		
Total							936

Appendix F: IEEE Conference Paper

2021 IEEE PES/IAS PowerAfrica

Road Lighting Energy Reduction: From HPS to LEDs - A Case Study of Uganda Street, Addis Ababa, Ethiopia

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***Abstract*— Modern technology advancements, coupled with aggressive research, has enabled the development and manufacture of superior LED luminaires. The 21st century has seen significant transition from HPS to LEDs in road lighting as a measure to reduce the installed load and the amounts paid by municipal authorities to cover energy consumption costs. This paper investigated the energy saving possibilities of replacing HPS with LED luminaires - Uganda Street, a 1.35km road in Addis Ababa, was used as the case study. *Dialux evo* was used to determine the lighting performance, under HPS and LED lighting, with reference to the requirements of CEN13201-1 and EN13201-2. Vehicular traffic data was used to recommend a part-dimming schedule. Annual energy savings of 51.31 % and 79.75 % were realized by replacing the HPS with LED lamps and by further dimming the LEDs respectively. The study findings provide confidence for city authorities to transit from HPS to LED street lighting as a measure to reduce the overall lighting peak load and achieve huge reductions in their annual energy consumptions.**

Keywords*— *HPS, LED, Energy Reduction, Dimming and Lighting Performance.

I. INTRODUCTION

Installation of functional street lighting systems is nowadays part of the infrastructure demanded by city residents globally. Street lighting enhance road visibility at night, allow business and social activities to proceed beyond the fall of darkness, create ease in the identification of people and traffic for law enforcement purposes and act to deter criminal and violence tendencies, especially in crime hot spots, related to darkness [1].

Lighting accounts for half of the overall energy consumption in cities [2] with street lighting being a key contributor. By 2015, 304 million streetlights had already been installed [3] and the number was poised to rise to 352 million by 2025. The enormous number of installed streetlights inflict significant costs to city authorities in the form of maintenance costs and energy consumption costs. Inefficient street lighting systems are still prevalent worldwide [3] leading to high installed electrical loads, greater pressure on power generations and high green house gas (GHG) emissions. In 2011, for instance, street lighting accounted for 30-60 % [4] of the GHG emissions in Australian local authorities.

Uganda Street is one of the boundary roads serving Merkato, the busiest market centre in Addis Ababa. It is estimated that 200,000 people visit Merkato everyday leading to a contribution of 20-25% revenue to Addis Ababa City [5]. The high number of business people, residents, buyers and tourists visiting this market demand that adequate street lighting be in place to support night time business and social interactions. Currently, high pressure sodium (HPS) lamps are mounted on dedicated galvanized steel lighting poles. Addis Ababa City Roads Authority (AACRA) is responsible for the management of all street lighting infrastructure in Addis Ababa and foots the costs associated with the street lighting system.

The most recent street lighting standards provide a wider classification of lighting levels allowing road lighting designers to better match the designed lighting with the requirements of the road [6]. CEN13201-1 acknowledges the use of adaptive lighting techniques, such as part night dimming, as an energy consumption reduction measure [7].

The other sections of this paper covers the energy reductions achieved in previous studies, execution of this study including scope and methodology, results, conclusion, acknowledgement and references.

II. ENERGY REDUCTION POSSIBILITIES

The European E-street project identified 36 TWh (63.7%) in annual energy savings achievable through transition from old lighting installations to newer and adaptive ones [8] – high consumption mercury vapor lamps to HPS lamps. Between 2006 and 2008, 20,000 adaptive HPS streetlights had been installed in 12 different European countries.

The Australian authorities projected 27.1% energy savings through transition from inefficient technologies (largely mercury vapor) to modern HPS lamps. With 2.28 million streetlights installed by 2011, 250 W and 400 W mercury vapor lamps had been replaced by lower wattage 150 W and 250 W HPS lamps respectively over the past decade [4].

The US Department of Energy estimated, in 2012, that by 2030, 300 TWh of energy savings would be achieved due to an accelerated transition into LED lighting technologies [9]. It was estimated that 26 million inefficient streetlights existed [10] which contributed to the dire need to move into more efficient technologies which would offer energy savings.

The city of Pittsburgh in 2011 intended to replace 40,000 HPS and HID streetlights with LED streetlights - based on proof-of-concept studies, undertaken by a consultant before

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commencing the project, the City estimated that 70% savings in energy and maintenance costs would be achieved; annual reductions would be to the tune of 1.7 million dollars in energy and maintenance cost and 6,818 metric tonnes of carbon dioxide [11].

In 2014, mercury and HPS lamps were prevalent in Nairobi City with only 4% of installed street lights being LED [12]. HPS lamps accounted for the greatest installation share, 82.3%, and consisted of 150 W, 250 W and 400 W luminaires. If the 250W HPS lamps would be replaced with 120 W LED lamps, 14.52 GWh would be saved annually. The lamp distribution in 2014 was summarised in Table 1.

Table 1: Nairobi City Street Lighting Lamps Summary [12].

Type of lamp	Number	Frequency
High Pressure Mercury Vapour	3,250	10.5 %
Metal Halide	450	1.5 %
High Pressure Sodium (HPS)	25,500	82.3 %
Low Pressure Sodium Vapour	-	-
Low Pressure Mercury Tubes	425	1.4 %
Energy Efficient Tubes	125	0.4 %
LEDs	1,250	4 %

The City of Kigali, in a baseline survey, estimated that replacement of HPS with LED luminaire would lead to 60% in energy consumption [13].

The studies previously conducted [11] [12] did not elaborate the basis for the choice of the given LED luminaire wattage, and lumen output, as being suitable to replace the existing HPS luminaire. For instance replacing the 250 W HPS with 120W LED, in Nairobi City [12], did not ascertain that the original lighting performance (lighting level as defined under EN13201-2) would not be compromised.

III. STUDY EXECUTION

A. Project Area

Four primary arterial streets circle the Merkato market area and connect it to the rest of Addis Ababa City. Uganda Street is a 1.35km dual road to the South of the market area as shown on Figure 1.

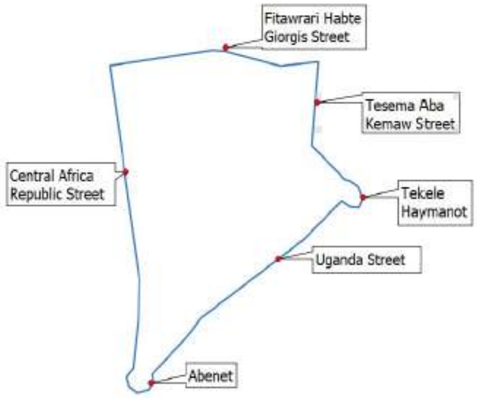

Figure 1: Study Area – Uganda Street in Merkato.

The Uganda street cross-section from right to left is typically as follows: right hand side (RHS) walkway, RHS drive lanes, median / green space, left hand side (LHS) drive lanes and LHS walkway. The existing lighting poles are erected on, each side of, the walkway. The outermost lane is in some sections designated a freight or bus-stop area, allowing the movement of people to and from the market area.

B. Drive Lanes' Lighting Classification

Drive lanes belong to class M lighting according to CEN13201-1. Six categories exist under class M namely M1 to M6 where M1 has the highest requirements. The lighting category of a road is determined by weighting nine factors detailed under CEN13201-1. This was carried out for Uganda Street as shown under Table 2.

Table 2: Drive lanes' lighting class selection.

Parameter	Option (selected)	Description	Weighting Value
Design Speed	Moderate	40<v≤70 km/h	-1
Traffic volume	High	>65 % maximum capacity (multilane routes)	1
Traffic composition	Mixed		1
Separation of carriageway	Yes		0
Junction density	Moderate	≤3 intersection/km	0
Parked vehicles	Present		1
Ambient luminosity	Moderate	Normal situation	0
Navigational task	Easy		0
Sum of weighting value, VWS			2
Lighting class = 6 - VWS			4

The pedestrian walkway similarly belongs to class P and the lighting category was evaluated as P3 according to CEN13201-1 as shown on Table 3.

Table 3: Walkways' lighting selection.

Parameter	Option (selected)	Description	Weighting Value
Travel Speed	Low	v≤40 km/h	1
Use intensity	Busy		1
Traffic composition	Pedestrians and cyclists		1
Parked vehicles	Not present		0
Ambient luminosity	Moderate	Normal situation	0
Sum of weighting value, VWS			3
Lighting class = 6 - VWS			3

C. Methodology

The entire road was divided into seven sections (Section 1 to 7) with distinct cross sections – the cross-section variations were however minor, majorly observed with the median and walkway widths. Dialux evo was used to simulate the existing street lighting case and the recommended LED lighting case(s). EN13201-2 was used to determine the lighting performance in both cases. Determination of a suitable LED luminaire as a replacement to the HPS lamp is an iterative process – the luminaire wattage and lumen output were adjusted until the required level of lighting was achieved (to M4 and P3 for drive lanes and walkways respectively). Traffic data was also tabulated to form the basis of recommending a suitable night dimming schedule.

IV. RESULTS

EN13201-2 requires the evaluation of the following areas for the main drive lanes; the average luminance, Lm, the Overall Uniformity, Uo, the Longitudinal Uniformity, Ui, the Threshold Increment, Ti, and the Edge Illumination Ratio, EIR.

A. Section 1 (0+000 – 0+200), LHS

The road lighting performance was carried out for the existing case, HPS, and for two LED cases – the selected luminaire flux levels were 17,500, 12,000 and 10,000 lumens, respectively. The lighting performance for section 1 was summarised on Table 4.

Table 4: Drive lanes' lighting performance, section 1.

	Lm (Cd/m2)	Uo	Ui	Ti (%)	EIR
M4	≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.30
HPS, 150 W	1.16	0.63	0.75	12	0.70
LED, 87 W	1.21	0.63	0.68	9	0.70
LED, 73 W	1.01	0.63	0.68	9	0.70

The simulation analysis, summarised in Table 4, indicated that an 87W LED luminaire satisfied class M4 lighting requirement providing a level and quality of lighting comparably equivalent to that of the HPS lamps – the average luminance under the lower wattage LED was however higher. It was also noted that an even lower LED luminaire, 73W would still satisfy class M4 lighting for this road – the average luminance would however fall short of the HPS level.

B. Sections 2 &3 (0+200 – 0+600), RHS

These sections differ from Section 1 in that the median and walkways are narrower. The simulation results, summarised on Table 5, however, pointed to a conclusion similar to Section 1 – 87 W LED would achieve the current HPS lighting; 73W LED would also meet M4 lighting but at reduced average luminance.

The 73 W LED luminaire would achieve the greatest load reduction and is recommended – despite the lower initial average luminance level (compared to the HPS lamp), the LED luminaire offers higher operational life than HPS lamps. The overall effect is that the lighting achieved through HPS lamps deteriorates faster, in quality and quantity, compared to the lighting from LED lamps. At the end of life, which is faster for HPS lamps, the average luminance due to HPS lighting would be lower than that of LED lighting.

Table 5: Drive lanes' lighting performance, section 2 & 3.

	Lm (Cd/m2)	Uo	Ui	Ti (%)	EIR
M4	≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.30
HPS, 150 W	1.17	0.64	0.75	12	0.70
LED, 87 W	1.22	0.63	0.68	9	0.70
LED, 73 W	1.02	0.63	0.68	9	0.70

C. Energy Savings Under LED

A total of 86 HPS lamps are currently installed on Uganda Street. The achieved energy savings were computed as summarized under Table 6.

Table 6: HPS to LED energy savings.

	HPS, 150 W	LED, 87 W	LED, 73 W
Number	86	86	86
Operation, hrs	4,380	4,380	4,380
Load, kW	14.53	7.48	6.28
Energy, MWh	63.66	32.76	27.51
	30.90		
	36.15		

The energy consumption is based on 12 hours per night, 365 days an year. Due to the HPS lamps' poor efficiency, the input wattage is 169 W and has been applied in Table 6.

D. Traffic Data and Dimming Schedule

24-hour vehicular traffic data was obtained and used to construct an understanding of the nighttime road use trend. The data was obtained for a weekday and for a weekend in September and June 2019, respectively. The weekday vehicular traffic trend was presented under Figure 2.

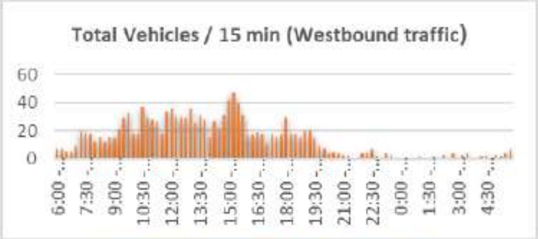

Figure 2: Westbound traffic, weekday.

The weekend eastbound traffic trend was presented as shown under Figure 3.

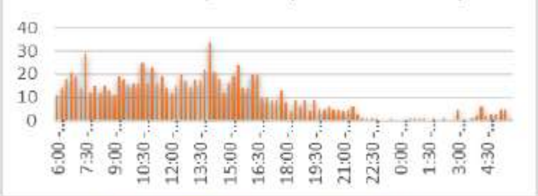

Figure 3: Eastbound traffic, weekend.

The average night-time traffic for both westbound and eastbound traffic calculated for every two hours was summarized under Table 7.

Table 7: Average night traffic.

	Weekday		Weekend		
	West	East	West	East	
Time (hrs)	% of highest				% Average
1800-2000	100	77	100	100	94
2000-2200	17	38	28	67	38
2200-0000	23	23	14	11	17
0000-0200	7	23	10	11	13
0200-0400	13	38	10	56	29
0400-0600	23	100	17	56	49

The nighttime traffic reduction proregression was presented as shown under Figure 4.

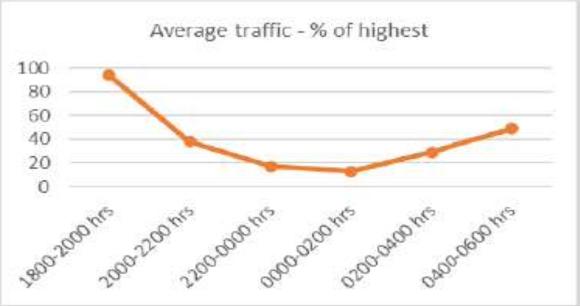

Figure 4: Nighttime traffic progression trend.

From the traffic data analyzed, traffic dipped to less than half between 2000 hrs and 0400 hrs and then recovers to half for the morning hours. From this trend it is recommended that all the luminaire, on Uganda Street, be dimmed as shown on Table 8.

Table 8: Recommended dimming schedule.

Time (hrs)	Average traffic	Recommended lighting level
1800-2000	94 %	100 %
2000-2200	38 %	40 %
2200-0000	17 %	30 %
0000-0200	13 %	30 %
0200-0400	29 %	30 %
0400-0600	49 %	50 %

E. Dimmed-LED Energy Savings

The energy consumption based on the night-time dimming schedule recommended under Table 8 was calculated by Equation 1.

Energy = Installed load x dimmed level x operating hours
Equation 1

The energy consumption was computed for each of the distinct dimming periods and then aggregated to obtain the total consumption for one night as summarized under Table 9.

Table 9: Dimmed-LED Energy Savings.

Time (hrs)	Load, kW	Dimmed level	Energy, kWh
1800-2000	7.48	100 %	14.96
2000-2200	7.48	40 %	5.98
2200-0000	7.48	30 %	4.49
0000-0200	7.48	30 %	4.49
0200-0400	7.48	30 %	4.49
0400-0600	7.48	50 %	7.48
Total daily			41.89

Given 365 days in an year, the resulting annual consumption is 15.29 MWh (41.89 kWh x 365). If a 73 W is used, the consumption was computed as 12.89 MWh.
The nighttime dimmed load/energy profile was plotted as shown under Figure 5.

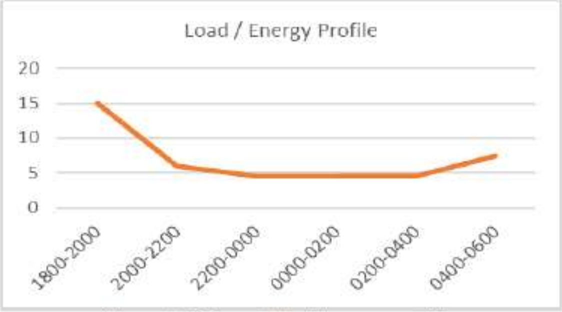

Figure 5: Dimmed load/energy profile.

F. Savings Summary

The savings achieved through transition from HPS to LED street lighting were summarized under Table 10.

Table 10: Energy savings summary.

	HPS, 150 W	LED, 87 W		LED, 73 W	
		100 %	Dimmed	100 %	Dimmed
Annual Energy, MWh	63.66	32.76	15.29	27.51	12.89
Savings, MWh, %	30.90 MWh, 42.02 %				
	48.37 MWh, 75.98 %				
	36.15 MWh, 51.31 %				
	50.77 MWh, 79.75 %				

Through immediate transition from the current HPS lamps to 87 W LEDs, 30.90 MWh of annual energy savings would be realized for the 1.35km of road. The potential energy savings, for the entire city of Addis Ababa, would be to the scale of TWh given the thousands of principal arterial and secondary arterial streets which are currently served by HPS lighting.

The graphical presentation of the consumptions under each case appeared as shown under Figure 6.

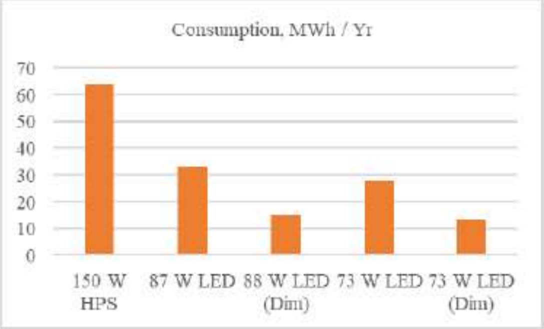

Figure 6: Energy Consumption - HPS & LED Cases.

V. CONCLUSION

The transition from 150W HPS to 73W LEDs led to the reduction of the peak load from 14.53kW to 6.28kW for Uganda street and 51.31% reduction in annual energy consumptions. Dimming of the LEDs would achieve even greater savings (79.75%).

Replacement of high wattage HPS lamps with lower wattage LED luminaires provide a strong case for city authorities to reduce their annual energy consumption burdens. The choice of the LED luminaire must however be verified based on photometric computations to ensure that the road lighting levels are not reduced or compromised in relation to the EN13201 standard.

Dimming of the LED streetlights would further provide extra savings but must be based on traffic volume checks. Since the traffic volumes vary from time to time, it is recommended that frequent studies be made to inform the dimming pattern accordingly.

The adopted dimming pattern should not lead to lighting levels lower than the lowest class under EN13201, namely M6 and P6 for the drive lanes and walkways respectively – the average luminance and the horizontal illuminance, for instance, should not be lower than 0.3 Cd/m^2 and 2 lux respectively.

ACKNOWLEDGEMENT

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Appendix G: Amendments on report

Section	**Change done**
5.2 Recommendations	HPS to LED transition under solar street lighting included for further study.
Appendix A	Originality Report updated to July 2021
Appendix F	IEEE Conference Paper added