FACTORS AFFECTING THE PERFORMANCE OF SOLAR STREET LIGHTS ON SELECTED STREETS OF LUSAKA DISTRICT, ZAMBIA

BY

KABUNDA KAREN

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Declaration

I, Kabunda Karen, declare that this dissertation is my original work and that, to the best of my knowledge, it has never been produced or presented for any academic prizes at the University of Zambia or any other institution. Professor P. Jain and Dr. R. Rajan expertly supervised it. I also declare that all material obtained from other people and sources has been properly cited.

Karen Kabunda

Student

December 2023

Date

Approval

As part of the prerequisites for the award of a Master of Science in Physics degree, the University of Zambia has validated Karen Kabunda's dissertation.

Examiner 1

Name: ………………………..Date: ..………………………………

Signature: ....

Examiner 2

Name: ……………………………………....................Date: …………………………………

Signature: ....

Examiner 3

Name: ……………………………………........................Date: ………………………………

Signature: ....

Supervisor: ....Date: ....

Signature: ....

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Dedication

I owe my success thus far to God Almighty, his Grace, and Mercies, as well as to my cherished mother Margaret Zulu, and my late father Mr. Joseph Kabunda, who persistently motivated me to pursue my education.

Abstract

Well-illuminated streets play a vital role in enhancing the security and well-being of residents in cities and towns. Investing in solar street lighting can reduce costs spent on grid electricity bills. It can also enhance safety and security at the same time uplift the economy of, women and men who sell/work during late hours. Investment in this area will not only align with the call for gender responsiveness in urban planning in Africa but also help in achieving the sustainable development goal (SDG) 7 which stresses ensuring that there is access to clean and affordable energy by 2030. This study focused on the performance of solar street lights within some selected streets of Lusaka, Zambia, with particular emphasis on factors affecting their performance. The research investigated battery types, switching systems, shading, inclination, and orientation effects on the sampled solar street lights. Systematic sampling selection of street lights was done based on the Yamane Taro formula with a 90% confidence interval for the sample size. The primary data were collected through fieldwork measurement observations and questionnaires. Voltage and current readings were taken in the morning and evening for analysis. The primary data was analysed using a statistical package for social science (SPSS) and Python. The study revealed that the choice of switching system, charging system, and battery type significantly influence the performance of solar street lights in Lusaka. Lithium-ion batteries and ultra-capacitors outperformed lead-acid batteries, mainly due to their efficiency and reliability. Flooded lead acid batteries had low efficiency, and lower maintenance requirements and were mainly exposed to vandalism. Physical inspections also identified issues with charge controllers, particularly affecting the lithium-ion batteries and ultra-capacitors. The results revealed that many charge controllers had failed thus allowing the batteries to overcharge in most cases to the extent that they swell and burst. The study showed that majority of the solar street lights are oriented in the northeast, with some facing northwest in roads like Lumumba, great north and Mosi-O-Tunya. Solar panels in the northwest along Lumumba road and great north road exhibited an average power output of 89 W while those oriented in the northeast had the average power of 84 W showing the solar panels in northwest generally outperformed those in the northeast. Furthermore, the orientation and inclination of solar panels were found to impact performance. Poorly oriented and inclined panels led to incomplete battery charging and limited night-time illumination. In conclusion, this research underscores the importance of selecting the right components and installing and ensuring proper maintenance for solar street lighting systems.

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I want to use this opportunity to express my gratitude to you, Father, for watching out for me and showing greater concern than I could. I am appreciative of your continuous assurance that you won't desert me. If I could have flown, I would have gone to the gate of heaven to praise the Almighty God. Even if I can't see your face, Lord, I shall prostrate at your feet in a burst of overwhelming thanks.

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List of Abbreviations

AC	Alternating current
AFCON	Asia foundations and construction limited
Am	Air Mass
ANOVA	Analysis of Variance
A-si	Amophous silicon
AVIC	Aviation Industry Corporation of China
BMS	Battery management system
cdTe	Cadimium-Telluridec
CIS	Copper indium selenide
C-Si	Monocrystalline solar panel
DC	Direct current
DC	Direct current
DoD	Depth of discharge
ESD	Energy storage device
Ff	Fill factor
GW	Gigawatts
Isc	Short circuit current
IV	Current voltage
Jsc	Short circuit current density
K	Kwacha
KWh/m^2	Kilowatt hour per meter squared
LA	Lead acid battery
LCC	Lusaka city council
LED	Light-Emitting Diodes
LI	Lithium-ion battery
M	Meter

MPP	Maximum power point
NASA	National Aeronautics and Space Administration
Pc-Si	Polycrystalline solar panel
PV	Photovoltaic
PWM	Pulse Width Modulation
QUALI	Qualitative
QUAN	Quantitative
RDA	Road Development Agency
SSL	Solar street lights
SoC	State of charge
STC	Standard test conditions
Tc	Temperature coefficient
UC	Ultra capacitors
USD	US dollar
Voc	Open Voltage
ZESCO	Zambia Electricity Supply Corporation

CHAPTER 1

1.0 INTRODUCTION

1.1 Overview

The foregoing chapter covers the background information on the use of solar energy. The chapter further discusses the following; statement of the problem, purpose of the study, research objectives, research hypothesis, significance of the study, structure of the dissertation, and limitations of the study.

1.2 Background

Energy is a fundamental cornerstone for humanity's survival and economic advancement. The energy landscape varies across nations shaped by geographic and demographic factors. While certain African countries rely heavily on hydroelectric and fossil fuel-based power, some countries in Europe have embraced renewable energy sources and nuclear energy [1]. Solar energy, which is an abundant resource in Africa, has captured the attention of researchers worldwide. The growing interest in adopting solar energy has led to an impetus in research efforts. The studies aimed not only to provide a better understanding of the potential of solar power but also to highlight the urgent need to transition towards renewable energy resources [1,2].

The pursuit of sustainable energy initiatives and the goal of diversifying a country's energy mix go hand in hand. The first step involves assessing the energy source potentials of that country [1, 3, 4]. However, in most developing countries like Zambia, the availability of solar energy resource information is limited due to the lack of widespread metrological stations for collecting weather data across the country [1]. This lack of data not only limits research opportunities but also poses a substantial lack of understanding of solar energy capabilities in Zambia. In Zambia, a nation abundantly endowed with diverse resources, the potential of solar energy stands out as a promising alternative for energy production. Zambia receives about $2100\ \text{kWh/m}^2$ of solar energy with 2000 – 3000 hours of sunshine per year according to the data set obtained from the National Aeronautics and Space Administration (NASA) Atmospheric Science Data Centre using Surface Metrology and Solar Energy [5].

There are a variety of energy technologies that have been developed to take advantage of solar energy. These include passive solar heating and daylighting, photovoltaic systems, solar hot water, and solar air conditioning systems.

Solar energy can not only be used in large-scale applications but can also be used in small-scale systems such as homes, traffic lights, and street lighting. With the use of solar energy, this study aims at determining and analysing factors affecting the performance of solar street lighting systems in Zambia, Lusaka.

Well-lit streets bring confidence to many residents in the cities and towns; the sense security of cities and towns plays a pivotal role in fostering economic growth and ensuring the well-being of their dwellers. Unfortunately, Africa has the highest rate of fatalities from road traffic injuries in the world [6]. Enhanced visibility emerges as a critical factor in mitigating the risk, particularly for pedestrians who heavily rely on walking as their primary mode of transportation. Compounded by insufficient public services such as the use of hydroelectricity to power street lights has many disadvantages, such as rising crime rates, underscoring the urgent need for urban interventions [7]. Therefore, investing in solar street lighting can improve costs spent on electricity bills, safety, and security, especially for women and men who sell along the streets during late hours. Investments in this area align with the call for gender-responsive urban planning in the global South and African countries [8, 9]. An additional dimension to consider is the role of street vendors in supporting livelihoods and economies though the controlled street vending is allowed else were it is illegal in Zambia. Poor lighting conditions limit their trading activities to daylight hours, imposing constraints on their income potential. [10]

Beyond immediate gains, there exist substantial co-benefits for social cohesion and community empowerment. The active involvement of communities in service provision and safeguarding emerges as a potential catalyst for sustainable engagement with municipal authorities. Such collaborations can pave ways for joint financing initiatives and even improve revenue collection through taxpayers.[11]

Environmental and system factors are important to consider when it comes to the installation of solar street lighting systems. These factors include temperature, energy conversion efficiency, shading, and the orientation, and inclination of the solar panel. Zambia being in the southern hemisphere, solar panels should be installed facing true north. The angle of tilt of a solar panel is also important and is dictated by the latitude at which it is installed.

It is important to ensure that buildings and trees in the vicinity do not shadow the panel to utilise maximum exposure of the panel to solar radiation. Other factors to consider in the solar street light installation are efficient charging mechanisms, types of batteries, configuration of switching mechanisms, and challenges in terms of deployment, maintenance, and safety protocols.

1.3 Statement of the problem

Proper functioning and optimal performance of street lighting in any city or town is not only an indicator of how well the city or town is organized but also provides a sense of security to its residents. In Lusaka, a significant step has been made with the deployment and installation of approximately 4000 solar street lights since the year 2013 by the Lusaka City Council. However, no study has been conducted to determine the factors affecting the performance of solar street lights installed in the streets of Lusaka. By examining the determinants of their performance, this study seeks to find out potential challenges, propose recommendations, and contribute to the advancement of effective street lighting in Zambia.

1.4 Aim of study

The primary aim of this study was to investigate the technical specifications and factors affecting the operational performance of the solar lighting systems that have been implemented within specific streets of Lusaka.

1.5 Objectives

The objectives of the study were to:

(i) determine how shading, orientation and inclination affect the performance of solar street lights within Lusaka,

(ii) investigate the diverse battery technologies employed in Lusaka’s solar street lighting systems,

(iii) assess the effects of switching mechanisms on the overall performance of the lights, and

(iv) identify and characterize challenges of security/ vandalism and maintenance that impact the continuous operation of these lighting systems.

1.6 Hypothesis

The hypothesis used in this study is a null hypothesis which states that: all the solar lights deployed and installed in the streets of Lusaka perform efficiently and optimally under implementation conditions.

1.7 Significance of study

Results obtained in this study will provide information and data that can be used by Lusaka City Council (LCC)and the road development agency (RDA)for effective deployment of new street lights thereby streamlining the implementation processes and enhancing urban infrastructure planning. The results of this study may be extended to other cities and towns in Zambia that may be considering implementing of solar street lights. One direct societal impact is anticipated through the potential reduction of night time street crimes. The research outcomes will be instrumental for policy makers informing evidence-based decisions and enabling the formulation of strategies that promote efficient urban lighting systems aligning with Zambia's broader energy and urban development objectives.

1.8 Structure of the dissertation

The first chapter provides an introduction to the study, the problem statement, the aim and the objectives of the study, the research hypothesis, and the broader significance of the research. In Chapter two a review of existing literature on the factors affecting the performance of solar street lights from various research and case studies has been presented. Chapter three outlines the research methods, measurement techniques, and instruments employed coupled with a description of the study location in Lusaka. The presentation of analysis of the results from the study is done in Chapter four. Results and discussion of the study in line with the objectives are given in Chapter five. The final Chapter (six) provides the conclusions and recommendations drawn from the study for future work.

1.9 Limitations of the study

The study is wholly confined to the factors affecting the performance of solar street light in Lusaka. The study was carried out on four roads due to little time. The other reason why the researcher carried out the study at the four selected roads is that machinery used for the measurements of the orientation and inclination was mostly used by the Lusaka city council engineers and thirdly the newly implemented rules by the police to protect the solar street lights from vandalism, especially in the evenings with roads like Mosi- O- Tunya road. For the same reason, the researcher was given access to solar street lights that operated on flooded lead acid batteries on a single road to ensure the components' safety, as several of them had sealed battery boxes. Only two solar street lights installed at LCC Yard, for solar street lights along Ring road, were made available for the researcher to study due to their unique design, including a battery, LED fitting, charge controller, and solar panels mounted in a single sealed fitting. As a result, opening the lights in the field was prohibited to prevent system damage. However, the orientation, inclination and lux where measured see appendix for the results

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Overview

This chapter reviews the literature related to the factors affecting performance of solar street lights in other countries and cities. The reviewed literature underscores the critical importance of, proper installation of solar street lights, considering factors like orientation, inclination, and shading to maximize power output. The implementation of solar street lights especially in sub-Saharan Africa has brought so much change to both the citizens and the municipal council. Crucially, national governments should advocate for collaborative efforts between municipal authorities' local communities and other stakeholders to collectively devise and execute green infrastructure projects and essential services such as solar-powered street lighting. This approach holds the potential to unlock numerous co-benefits across society, the economy, and the environment.

2.2 Solar panel orientation, inclination, and shading effects

2.3 Solar panel orientation

The efficiency of a solar power system is determined by two pivotal factors which are: orientation and location. To achieve maximum power output, it is crucial to ensure that solar panels are oriented in the optimal direction. A solar panel will utilize most of its power when the Sun's rays hit its surface perpendicularly. Therefore, meticulous attention to the correct orientation and appropriate tilt is paramount, as these make the panels be exposed to the highest intensity of sunlight for the greatest period [12]. In the southern hemisphere, solar panels should be oriented north, otherwise south.

In countries situated in the northern hemisphere like China, Canada, United States, Europe, America, and India, the ideal orientation for photovoltaic (PV) panels is south. Conversely, in countries located in the southern hemisphere, such as Indonesia, Brazil, New Zealand, Australia, South Africa, and Zambia, optimal performance is achieved when PV panels are installed facing northwards. This geographical consideration underscores the significance of tailoring solar panel orientation to regional solar patterns for enhanced energy yield.

solar tracking systems that follow the Sun's movement have been proven to considerably enhance energy production, however, it is noteworthy that in Zambia, the majority of solar systems that street lights adhere to have a fixed orientation for their panels, and solar tracking systems are not used for solar street lights by the municipal council because of their high cost. Figure 1 shows two fixed panel orientations within the streets of Lusaka.

Figure 1: Fixed system of solar panels to ensure power output is maximized

In Dave's research [12], findings indicated the significance of accounting for the variance between magnetic north and true north when installing solar panels. Magnetic north, as indicated by a compass, points toward the Earth's north magnetic pole, while solar panels are optimally oriented towards solar or geographic north, aligning with the direction toward the North pole. Consequently, solar panels situated in the northern hemisphere must face the true south direction to ensure optimal sunlight exposure and, subsequently, maximize energy efficiency. This understanding of directional alignment is crucial for precise solar panel positioning, contributing to enhanced performance in solar energy systems.

The optimal orientation of solar panels may vary depending on their specific application. Consideration of a slight deviation from due south or due north can prove advantageous. For instance, solar panels intended for residential use may benefit from facing slightly southwest or northwest. The rationale behind this lies in the fact that while some panels capture more energy when oriented due south or due north, the usability of the energy is enhanced when it is generated later in the day. This fine-tuned adjustment enables solar panels to generate more electricity during peak hours of demand by aligning energy production more effectively with consumption patterns [13].

2.4 The angle of tilt / inclination

The angle of tilt or inclination of a solar panel plays a crucial role in its installation and energy production. The angle at which a solar panel should be set to produce the most energy in a given year is determined by its geographical latitude. Some studies have reported that the tilt or inclination of solar panels is relative to the location, period, and duration. Gevorkian [14] advocates a general guideline where the optimal tilt angle aligns with the geographical latitude, ensuring an efficient annual energy output. For instance, if the solar array is situated at 50° latitude, the recommended tilt angle is likewise 50°. Applying this principle to Lusaka, with a geographical latitude of 15° south, suggests an optimal tilt angle within the same range. Furthermore, Dave [12] emphasizes that solar panels located closer to the equator benefit from a more vertical inclination to either the north or south, while those nearer the poles should tilt towards the equator for increased efficiency.

The influence of climatic and environmental factors on solar panel output, with or without correct tilt, is also noteworthy. In northern climates, low-tilt panels may accumulate snow during winter, potentially obstructing sunlight. A study conducted in Edmonton and Alberta Canada, [15] revealed that annual energy loss due to snow accumulation varies from 1.6% at an optimal tilt (53°) to 5.3% at a low tilt (15°). Additionally, solar panels with low tilt are more prone to "soiling" by dirt and debris, partially obstructing sunlight [15]. These considerations highlight the multifaceted impact of tilt on solar panel performance, emphasizing the need for careful assessment based on geographical location and environmental conditions.

2.5 The effect of shading on solar panels

The performance of a photovoltaic (PV) module or array; where modules are interconnected cells forming larger units, is significantly affected by partial shading conditions. Shading from passing clouds, trees, or buildings can cast shadows on modules, resulting in notable consequences for the overall power output of the system. In their study conducted in Germany on improving photovoltaic power output, Strache et al., [16] revealed that shading has the potential to compromise a PV system's output by up to 20%.

Kumari *et al.*, [17] further highlighted that even if just one cell is shaded, it can compromise the power output of the entire set of interconnected cells. This compromise occurs because a shaded solar cell, in the presence of unshaded cells, operates like a diode in the reverse direction, dissipating substantial power and leading to local overheating. Shading within modules also impacts the current-voltage (I-V) characteristics of the PV string, creating multiple local Maximum Power Points (MPP), maximum power point is a point on the current-voltage (I-V) curve of a solar module under illumination, where the product of current and voltage is maximum. This, in turn, increases the likelihood of the system not operating at the global maximum power point. To address these issues, most solar panel manufacturers incorporate bypass diodes within the modules. Bypass diodes, connected in parallel with a solar panel or string of panels, serve a crucial role by redirecting current around partially shaded panels or eliminating the hot-spot phenomena. This is significant as hot spots can potentially damage PV cells and even pose a fire risk if the incident light on the surface of PV cells within a module is not uniformly distributed. The integration of bypass diodes in PV modules is an essential measure to prevent the application of high reverse voltage across cells during shading events, ensuring the reliability and safety of solar panel systems.

2.6 Components of a solar street light

Frering *et al.*,[5] highlighted that street lighting is an integral part of the complementary infrastructure along roads, adaptable to the placement on the left, right, or in the centre of a dual-carriageway road. In a study on solar street lighting systems, Liu [18] identifies key components, including solar cell panels, LED lights, lamp posts, and battery boxes.,

Usually, solar street lighting systems operate automatically, illuminating at night and powering off in the morning, offering ease of maintenance at an affordable cost. An indispensable component in solar street lighting is the Battery Management System (BMS) [19]. The BMS plays a crucial role in cutting off and discharging the battery, and monitoring each cell individually. It employs a transistor switch and a properly sized discharge resistor in parallel with each cell. When the BMS detects that a particular cell is nearing its charge limit, it redirects excess current to the next cell in a top-down fashion, ensuring efficient battery management. The integration of these components contributes to the seamless functioning and sustainable operation of solar street lighting systems.

2.7 Solar panel

A solar panel is a device that converts light energy from the Sun into electricity in direct current (DC) form. Zanjani [20] illustrates this functionality by highlighting that street lights can effectively utilize solar cell panels, absorbing sunlight and converting it into electrical energy through the photovoltaic process. The photovoltaic process involves the conversion of absorbed sunlight energy into electric energy by a photovoltaic (PV) cell. Markvart *et al.*, [21] elaborate on the mechanism, explaining that solar cell panels initiate the process by converting sunlight into DC, which is subsequently stored in a battery. The photovoltaic effect, initially noted by the French physicist Edmond Becquerel in 1839, serves as the foundation for the theory underlying their functioning. When the semiconductors, absorb photons which are light particles, and release electrons, creating an electric current, this phenomenon is known as the photovoltaic effect. Numerous solar cells, which are usually composed of silicon, make up solar panels and the photons from the sun are absorbed by the silicon atoms in the solar panel. Some of the silicon atoms' electrons become "excited" and break loose from their atoms when photons are absorbed and transfer their energy to them. As a result, electron-hole pairs are formed, in which the electron can go freely and leaves a positively charged "hole" in its place. Thereafter an electric field is produced between the layers of silicon by the solar cells construction. The divided electrons and holes are propelled toward the opposing sides of the cell by this electric field, which functions as a force. Positively charged holes travel towards the rear surface of the solar cell, whereas free electrons are compelled to flow towards the front due to the electric field. A full circuit is created by joining the metal contacts on the front and rear of the solar cell. To create an electric current that may be utilized to power electrical devices, this permits electrons to move from the front surface to the back surface. Vaishak *et al.*, [22], in their study, categorize well-known PV panels into amorphous, polycrystalline (Pc-Si), and monocrystalline (c-Si) types. This variety in panel types offers different efficiency and cost considerations, providing flexibility in adapting solar street lighting systems to diverse requirements and conditions.

2.7.1 Monocrystalline solar panels

Monocrystalline solar cells are identifiable by their deep black colour (although some bluish reflections can be observed depending on the light) and cut edges. Monocrystalline (c-Si) solar panels are made from single crystalline silicon, endowing them with a unique advantage. Due to their composition of single silicon crystals, electrons flow through the cell with greater ease, resulting in superior photovoltaic (PV) cell efficiency compared to other panel types. The efficiency and power capacity of monocrystalline solar panels are notably high, ranging from 17% to 28.89%, although some sources suggest a slightly broader efficiency span of 15-25% [22].

The elevated efficiency of monocrystalline solar panels translates to a reduced space requirement for a given power capacity. In practical terms, this means that a smaller number of monocrystalline solar panels are needed to achieve the same power output as polycrystalline or thin-film panels. Consequently, monocrystalline solar panels often boast higher power output ratings, underscoring their effectiveness in optimizing energy generation within limited spatial constraints. Figure 2 shows a sample of monocrystalline solar panel.

Figure 2: Monocrystalline solar panel

2.7.2 Polycrystalline solar panels

Polycrystalline (Pc-Si) solar panels are composed of solar cells made from multiple fragments of silicon crystals melted together, imparting a distinctive speckled blue appearance. Figure 3 shows a sample of a polycrystalline blue appearance. These solar panels are cheaper than monocrystalline solar panels as they are made using cheap waste silicon. However, it is worth mentioning that certain studies suggest polycrystalline solar panels exhibit slightly lower heat tolerance compared to their monocrystalline counterparts [23]. Practically this implies that in high-temperature conditions, polycrystalline solar panels may perform marginally less efficiently, potentially affecting their overall lifespan. According to Vaishak *et al.*, [22], the energy conversion efficiency of polycrystalline solar panels typically falls within the range of 13% to 16%. This highlights the trade-offs in selecting polycrystalline panels, as one weighs their cost-effectiveness against factors such as heat-resilience and overall performance under diverse environmental conditions

Figure 3: Polycrystalline solar panel

2.7.3 Thin films solar cells

In a study conducted by Chopra *et al.*, [24], thin film solar cells were investigated and the results showed that thin films are beginning to be deployed in significant quantities and could potentially provide more cost-effective electricity compared to monocrystalline (c-Si) wafer-based solar cells. Thin films solar cells consist of successive thin layers, ranging from 1 to 4 μm thick-deposited on to an economically viable substrate like glass polymer, or metal. The three primary types of thin-film solar cells that have been commercially developed are; amorphous silicon multi-Junction thin-film Silicon that consists of A-Si cell with additional layers of A-Si and micro crystalline silicon (A-Si/μc-Si), Cadmium -Telluride (CdTe), Copper-Indium-Selenide (CIS), and Copper-Indium-Gallium-Diselenide (CIGS). While thin-film solar cells exhibit conversion efficiencies between 10-15%, making them less efficient in converting sunlight to electricity compared to crystalline solar cells, their potential for lower-cost electricity deployment is a promising aspect highlighted in the research [24]. They however, have instability problems that have to resolved.

2.7.4 Characteristics of solar panels

The main parameters that are used to characterize the performance of solar panels are the peak power P_{max}, the short-circuit current density J_{sc}, the open circuit voltage V_{oc}, and the fill factor FF. The open-circuit voltage (V_{oc}) is the voltage at which no current flows through the external circuit. It is the maximum voltage that a solar panel can deliver whereas short-circuit current (Jsc) is the current density that flows through the external circuit when the electrodes of the solar panel are short circuited [25] meaning the current density flowing through the solar cell while the voltage across it is zero. The fill factor is an important measurement and can be used to evaluate the efficiency of solar cells. Therefore, it is defined as the ratio of the maximum power from solar cell to the product of the open circuit voltage and the short circuit current.

2.8 Energy storage technologies

Currently, there exists a multitude of energy storage technologies, a prominent one being electrochemical energy storage technology. The electrochemical energy storage systems encompass devices such as batteries and supercapacitors, exhibiting significant versatility across various applications and offering flexibility in terms of capacity [26]. Batteries and supercapacitors or ultra-capacitors play an important role in storing electricity generated by solar panels. Batteries, characterized by a high energy-density to power-density ratio, excel in providing sustained power over extended durations. However, they exhibit limitations in efficiently supplying peak power demands, responding sluggishly to dynamic loads, and having low charge rates [27,28]. On the other hand, supercapacitors boast high power density-to-energy density ratios and rapid charge rates. The distinctive chemical compositions of each technology determine the unique characteristics and performance attributes of the respective energy storage devices. In a comprehensive study by Townsend *et al.*, [29], three types of Energy Storage Devices (ESD) were scrutinized: lead-acid batteries (LA), lithium-ion batteries (Li), and ultra-capacitors (UC). The research presented a comparative analysis of these energy storage device technologies, particularly focusing on their degradation over time and found that degradation of the energy storage devices can largely be attributed to overcharging, over discharging, environmental temperatures, charging too frequently and not charging frequently enough. These degradations were found to be sensitive and can be resolved through monitoring by a battery management system.

2.8.1 Lead acid batteries (LA)

According to Dhundhara *et al.*, [30], lead-acid batteries are the oldest and the first type of rechargeable battery type ever developed [31]. Despite their historical significance, lead acid batteries possess a relatively low energy density, a short life cycle, and a high discharge rate. However, there are cost-effectiveness positions them as the most economical choice among rechargeable batteries [32]. There are two types of lead acid batteries namely: sealed and flooded lead acid batteries. The former, being maintenance-free, is more expensive than the latter, which requires periodic electrolyte top-ups. This distinction in maintenance need contributes to the cost differential between sealed and flooded lead acid batteries. Choosing between these types means balancing initial costs with ongoing maintenance needs, emphasizing the detailed factors involved in selecting lead-acid batteries.

2.8.2 Lithium-ion batteries (Li)

Lithium-ion batteries are commonly used and highly recommended for solar street lighting because of their high energy densities and long-life span. However, lithium-ion batteries are more expensive as compared to lead-acid batteries [30,33].

2.8.3 Supercapacitors (SC) /ultra capacitors (UC)

Supercapacitors and Ultracapacitors are electrical energy storage devices similar to batteries, capable of storing and releasing electrical energy. Advancements in technology have positioned them as integral components of energy storage systems particularly in PV systems where the use of supercapacitors is becoming more and more common. According to Koenig *et al.*, [34] an ultra-capacitor is a capacitor characterized by ultra-high capacitance but with a lower voltage limit. It is an energy storage device (ESD) that effectively combines the features of electrolytic capacitors and rechargeable batteries. In comparison to the former, ultracapacitors can store 10-100 times more energy per unit volume.

Research by Yoong *et al.*, [35] found that UC's exhibit very low internal resistance, thus allowing minimal restrictions when providing or receiving power. As opposed to batteries, UC functions best in intermittent high-power applications but may not be as well-suited for continuous average-power requirements. Notably they have an almost infinite life span, a low self-discharge rate, but come with a relatively higher cost compared to batteries. [36].

Table 1 Lead acid, lithium-ion, and ultra-capacitor comparison [29].

	LA	**Li**	**UC**
Energy density (Wh/kg)	35–40	50–220	2.5–55
Power density (W/kg)	69–154	50–5100	5000–10,000
Cycle life	800	3000	>50,000
Self-discharge rate (%pm)	<3	<2	>54 *
Operating temperature (°C)	40–+60	50–+85	40–+70
Cost (USD **/kWh)	55–168	385–1005	103 k–220 k
Cost per cycle	0.07–0.32	0.14–1.13	0.22–5.19

The comparison in Table 1 indicates that Li technology surpasses LA technology in most categories, with the notable exception being cost. However, when considering factors such as the number of cycles and the specific type of LA or Li technology, the overall cost of Li can become less than that of LA over its usable lifetime. In contrast, ultra-capacitors (UC) exhibit contrasting behaviour, showcasing higher energy and power density but also featuring a significantly higher initial procurement cost and cost per cycle.

2.9 Charge controller

Satpathy *et al.*, [37,38] in their review define a charge controller as a device that regulates the current and voltage flowing from the power source, in this case, the solar panel, into the battery bank. This regulation is essential to prevent overcharging of the batteries. Previous studies have identified two primary types of charge controllers; Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT) [39,40].

PWM controllers accept the power that is available from the source and adjusts the voltage to meet the battery's requirements. Given that solar panels typically have higher voltages than batteries, PWM controllers play a crucial role in maintaining the voltage during the charging process. Additionally, Markvart *et al.,* [21] highlight the presence of an energy flow controller before energy is stored in the battery. This controller, regulates the system and is programmed with specific times for the lights to be turned on and off, as demonstrated by Lawder *et al.*,

[19]. This controlled and timed operation ensures efficient energy utilization in solar street lighting systems.

A critical component in solar power systems is the Battery Management System (BMS), responsible for overseeing the charging and discharging cycles of the battery, ensuring optimal functionality [19]. The BMS plays a crucial role in regulating the current supplied to the battery, ensuring it receives the maximum current that the source is rated to supply [41].

During the charging process, the required voltage increases, consequently drawing more power from the source. The challenge lies in efficiently utilizing the maximum power of the source, which is achievable if the battery demands a voltage matching the maximum voltage supply of the source [42]. This is where the Maximum Power Point Tracking (MPPT) system comes into play as a buffer. The MPPT system evaluates the voltage required by the source and adjusts the current usage according to the maximum power available. In practical terms, MPPT assesses the voltage of the solar panel relative to the battery's voltage, making precise adjustments to optimize the panel's voltage for maximum charging efficiency. By aligning these voltages, MPPT consistently delivers the maximum available power [43].

2.10 Light emitting diodes (LEDs)

The light-emitting diode (LED) serves as the primary light source in integrated lighting systems. According to Kiong, [44] in his study on the cost-effective of solar-powered LED, LED lamps have a longer lifespan and electrical efficiency several times superior to incandescent lamps, and notably surpassing the majority of fluorescent lamps, certain LED chips can emit more than 100 lumens per watt.

In contrast to incandescent lamps and unlike most fluorescent lamps, such as fluorescent tubes and Compact Fluorescent Lights (CFL) bulbs, LED lights come to full brightness instantly without the need for a warm-up time. Additionally, the lifespan of fluorescent lighting is affected by frequent switching on and off. Despite their initial cost, LEDs present a cost-effective solution in the long run. they can convert around 70-90% of the energy they consume into visible light, with very little wasted as heat. LEDs are the preferred option for energy-conscious individuals and companies since they are substantially more energy-efficient than other kinds of light-emitting devices. They not only save electricity costs but also lessen carbon emissions and electricity demand, which promotes environmental sustainability. Figure 4 shows some examples of the LED lamps used in solar street lights within some selected streets in Lusaka, Zambia.

Figure 4: Types of LEDs used for Solar Street lights in Lusaka Zambia

2.11 Advantages and disadvantages of solar street lights

As highlighted by Ambhore *et al.*, [45], solar street lights offer several notable advantages. Firstly, solar energy, being sourced from the sun, is a sustainable power supply, especially in the sub-Saharan Africa, Zambia in particular has the sunshine in available during the day most of the year resulting in substantial reductions in electricity bills. The utilization of solar energy in daily operations translates to significant savings over time. Additionally, the maintenance requirements for solar systems are minimal, contributing to their long-term cost-effectiveness.

The adoption of alternative and efficient off-grid technologies, such as solar-powered street lighting, holds the potential to reduce electricity costs, which often constitute a substantial portion of municipal budgets. Beyond economic advantages, solar street lighting brings about social and environmental benefits as well as improved safety and extended trading hours for controlled street venders are among the socio-economic advantages. Furthermore, the use of renewable energy aligns with environmental sustainability goals, contributing to the reduction of carbon footprints.

Solar street lights operate independently of the utility grid, leading to reduced operation costs. As wireless lights, they do not rely on electricity providers, contributing to greater autonomy and flexibility. Another notable advantage lies in their enhanced efficiency, translating to increased durability. Unlike traditional street lights, solar street lights do not require daily on-off cycles, minimizing wear and tear. This characteristic not only enhances their lifespan but also ensures continuous functionality irrespective of external conditions or power interruptions. The consistent and reliable performance of solar-powered street lights underscores their superior efficiency compared to their traditional counterparts.

While solar-powered street lights offer remarkable benefits, it is crucial to acknowledge certain drawbacks. Despite being eco-friendly, low-maintenance, sustainable, efficient, and safe, their initial installation cost is a notable disadvantage, being comparatively expensive. Additionally, solar street lights pose challenges in extreme weather conditions. Accumulation of snow or dust combined with moisture on the horizontal PV panels can hinder or even halt energy production, impacting their reliability during adverse weather.

Another consideration is the heightened risk of theft, attributed to the comparatively higher equipment costs associated with solar street lights [46]. Ensuring security measures in place becomes imperative to mitigate this risk. Furthermore, the dependency on direct sunlight underscores a limitation of solar street lights. It is essential to guarantee unobstructed access to sunlight, ensuring that the solar panels are not shaded by shadows or obstructed by taller structures during the installation process. A thoughtful approach considering these factors is crucial for a well-informed decision regarding the integration of solar street lights.

2.12 Review of solar street lighting adoption in african countries

Many countries in Africa are actively embracing the adoption of solar street lighting. For example, cities such as Jinja and Kampala in Uganda have emerged as pioneers in sub-Saharan Africa, to recognise the advantages of solar-powered street illumination. In Uganda, Zimbabwe, Malawi, South Africa, Tunisia, Morocco, Botswana, Djibouti, Benin, Cameroon, Nigeria, and Zambia are transitioning from conventional street lighting to solar powered street lighting. In a comprehensive study conducted by Gouldson *et al.*,[47] they found Uganda to be transitioning from conventional to solar street lighting systems because they have proven to be cheaper to build and operate.

Municipal decision-makers in towns such as Jinja and Kampala made it apparent that they preferred solar street lights due to the anticipated long-term financial gains and the avoidance of large electricity bills. This change is driven by the expectation of better economic conditions in the future, with chances for more investments being presented by the savings from lower electricity bills. This strategic approach allows for a wider implementation of well-lit streets, thereby extending the numerous benefits to a larger population of urban residents. The trend seen in the African cities mentioned above highlights the growing recognition of solar street lighting as a sustainable and economically viable solution throughout the continent. Municipal authorities, realizing the potential for redirected funds, could channel these savings towards various endeavours, including covering installation costs.

The move to solar-powered street lighting is a comprehensive strategy with significant socio-economic and environmental effects, not just a change in technology. Installing solar street lighting has clear environmental benefits, but it also acts as a means of promoting diversity and initiating positive changes. The increased safety it offers, especially for vulnerable populations like women and children, stands out in terms of its social impact. As a result, there are fewer traffic accidents, making cities safer. Furthermore, extending company hours boosts economic activity and creates a more active nighttime economy. Economically speaking, switching to solar-powered street lighting results in significant energy cost reductions. When vital social services like health and education are funded with these savings, it becomes a valuable resource.

As affirmed by the World Bank [48], the adoption of solar-powered street lighting emerges as a transformative solution with profound implications, touching on social inclusivity, economic empowerment, and environmental sustainability. It exemplifies how innovative technologies can serve as catalysts for positive change within urban landscapes.

Drawing insights from the experience of Kampala and Jinja, the potential benefits of implementing solar street lighting extended beyond Uganda, reaching across various countries in sub-Saharan Africa. The world bank in 2010 [48] cited an example that, the transition to solar-powered street lights, replacing conventional ones, showcased a remarked reduction in installation costs by approximately 21 million USD for every 1,000 km of new road. Moreover, the electricity consumption reduced by 40 percent and the maintenance costs dropped by 60 percent.

The World Bank estimation of requiring between 60,000 and 100,000km of new roads for intra-continental connectivity in Africa presents a unique opportunity. Illuminating these roads networks with solar-powered lighting not only serves as a cost-effective alternative but also opens avenues to shift from grid-based electricity consumption to the generation and utilization of between 96 and 160 GW of distributed renewable energy. This transformative shift represents (more than a doubling of current energy generation in sub-Saharan Africa, presently standing at just 92 GW) [49]. Figure 5 shows solar street light of jinja city Kampala.

Figure 5: Solar-powered street lights in Kampala, Uganda. [49]

According to Marianne [50], other African cities, including Lagos in Nigeria and Nairobi in Kenya also implemented solar street lights at large scales, particularly in the formal sector. The primary motivations cited for this shift are enhanced safety and the facilitation of extended operating hours for street vendors and traders. Research has also highlighted the positive impact on road and public safety in the cities. Marianne [50] in her work alludes that in many major African cities, the implementation of conventional grid-operated street lighting faces challenges, especially in areas with informal settlements. Therefore, the proposed solution is to opt for the installation of low-cost and easily maintained solar street lighting systems.

Research on the performance of solar street lights is limited, however, a number of authors have pointed out significant challenges warranting further investigation. At the African University of Science and Technology, Nigeria, Fashina *et al.*, [51] conducted a study involving the installation of over 35 solar street lights installed in 2012 to enhance security during blackouts. Within the first year, 11 lights were found to be malfunctioning due to issues such as faulty batteries, damaged charge controllers, poor cabling, and LED light-related problems. Similarly, 2012, Oladeji *et al.*, [52] assessed more than 2000 solar street lights installed in 2008/2009 across five states in Nigeria. The findings revealed that over 50% of the solar street lights were non-functional. Common issues contributing to this included damage from rain and misalignment of PV panels involving both tilt angles and azimuth angles. These findings underscore the need for a comprehensive understanding of the challenges affecting the reliable operation of street lights.

In 2016, Mcmorran *et al.*, [53] conducted an assessment of solar street lights in Himachal Pradesh, India. They found out that out of the 62 installed solar street lights, a substantial number 42 were non-functional. This included 14 out of 25 at Bhimakali Temple,12 out of 21 in Mandi's slums and nearby villages, and the entirety of the 16 lights at Parashar Lake. The communities in these locations reported that the lights were never officially maintained by the relevant municipal authorities. Dust on PV panels in the Sahel region can reduce maximum PV power output by up to 78% within just a year [54]. Recognizing the importance of proactive maintenance, Kama *et al.*, [55] suggested a remote monitoring system for solar street lights in Senegal to notify municipalities of maintenance and cleaning requirements, addressing issues promptly to ensure sustained functionality.

Nixon *et al.*, [56] in their research on the analysis of standalone solar street lights found challenges in maintaining optimal performance in all PV-battery systems. They underscored issues such as battery and PV degradation, which pose hurdles to sustained efficiency. To mitigate these challenges, they suggested implementing intelligent control mechanisms for the solar charger and AC/DC loads. This strategic control aims to maintain a healthy State of Charge SoC and enhance monitoring for early fault detection. However, it is essential to acknowledge that such measures increase system complexity, cost, the risk of component failures, necessitate parts that might be challenging to procure locally. This involves judiciously combining advanced modern components with market-established products and systems within host communities. The approach ensures a pragmatic and effective strategy for addressing the unique challenges associated with solar street light systems in diverse settings

The experience obtained from cities like Jinja, Freetown, and countries like South Africa, and Dakar imparts a valuable lesson in which the integration of solar-powered street lighting stands as an initial stride on the extended journey toward sustainable urban development. The approach aligns harmoniously with the pursuit of the Sustainable Development Goal Seven (SDG 7), emphasizing the imperative of ensuring universal access to clean and affordable energy. The success stories arising from projects implemented in these cities underscore the potential of solar-powered street lighting not only as an illuminating solution but as a catalyst for broader sustainable urban development initiatives.

With the ever-changing technology, Ghana has recognized the extensive need for installing solar street lights. The country has initiated programs across its cities, aiming to facilitate the effective implementation and installation of solar street lights. These endeavours align with the Ghanaian policy framework for street lighting emphasizing collaborative efforts between the private and government sectors to address the nation’s street lighting requirements. Therefore, the Ghanaian government through the Ministry of Energy is channelling all its efforts towards the installation of street lights, driven by the overarching goal of enhancing security and promoting road safety during nighttime in specific areas of interest [57]. This concerted effort seeks to achieve universal access to street lighting, public safety and contributing to the socio-economic development of the citizens.

2.13 Security and vandalism

Hualiang *et al.*, [58], in their work defined vandalism as the process that degrades the value of a property either through disfigurement, or graffiti but also through the destruction of properties among others. Numerous studies have emphasized how vandalism of street lights is intertwined with broader issues, including heightened crime rates and increased motorist accidents.

Existing studies have often employed repetitive methods to gauge the impact of design variables on identified problems. Vandalism, regarded as a distinct social issue, has been isolated in research efforts, lacking integration with other concerns such as crime types, the age of individuals involved, targets of the acts, and the underlying motives [59].

CHAPTER 3

3.0 RESEARCH METHODOLOGY AND MATERIALS

3.1 Overview

This chapter provides a comprehensive overview of the chosen research methodology, offering insights into the rationale behind each decision. The study adopted a mixed-method approach, incorporating both qualitative and quantitative methods, aligning with the diverse data collection instruments employed. Research design, population, sample size, research instruments, data collection and sampling procedure, and data analysis, are explained.

3.2 Research approach

The methodological approach that was employed in this study was a mixed-method approach to comprehensively investigate some factors influencing the performance of solar street lights within selected streets of Lusaka. Teddlie *et al.*, [60] defined a mixed method as "a type of research design in which Qualitative (QUAL) and Quantitative (QUAN) approaches are used in types of questions, research methods, data collection, and analysis procedures and inferences. By combining qualitative and quantitative research, the mixed-method approach is chosen to mitigate methodological biases and enhance the overall understanding of the phenomena under investigation.

The qualitative aspect of the study adopts a descriptive approach, focusing on meaning and understanding. It involved collecting information from electrical engineers at the Lusaka City Council, delving into their opinions regarding the technical specifications and models of the installed solar street lights within selected streets of Lusaka. This qualitative approach provides depth and context to the findings. Conversely, the quantitative approach is applied to the technical part of the research, facilitating the quantification of the problem. This involves generating numerical data to derive usable statistics contributing to a more comprehensive analysis of the factors affecting the performance of solar street lights within selected streets of Lusaka. This mixed-method strategy aimed to provide a complete and detailed understanding of the research topic.

3.3 Research design

This research employed non experimental research design which is used to conduct quantitative research where there is no manipulation done to any variable in the study. In simple words, variables are measured as they occur naturally, without interference of any kind by the researcher. Mertler [61] points out of manipulation may exist because the variables maybe naturally “manipulated” before the study was undertaken or because it was not possible, or feasible, for the researcher to manipulate the particular variable. Of the types of nonexperimental research design this study used both a descriptive study design and an observational study design. Kerlinger [62] emphasizes that the descriptive study design is not only limited to mere fact findings but can lead to the development of essential principles of knowledge and solutions to significant problems. Orodho [63] describes descriptive study designs as a method of collecting information through interviews or questionnaires administered to the sample and individuals. In addition to the descriptive design, quantitative observational design was also used which is the process of carrying out research in an objective and controlled fashion so that precision is maximized and specific conclusions can be drawn regarding a hypothesis statement. Leedy *et al.*, [64] pointed out that it focuses on a particular aspect of behaviour that can be quantified through some measure.

3.4 Study location

Lusaka is a district situated in the Lusaka province of Zambia. It is located in the south-central at latitude-15.4^{o}S and longitude 28.3^{o}E. Lusaka district shares boundaries with districts namely; Chongwe in the East, Chibombo and, Chisamba in the North, and Chilanga in the South and west.

The ministry of local government through the municipal council workers provides numerous services to the citizens. In Lusaka these services include street lighting, waste management and sanitary administration, road construction, maintenance, and drainage among others. Among these initiatives is the ambitious project of installing solar street and traffic lighting systems together with the maintenance of both old and new ones. This endeavour aims not only to contribute to environmental sustainability but also to alleviate the financial burden on the council. Currently spending over K150,000 monthly on electricity bills to ZESCO for 17,000 conventional street lights, the LCC seeks a transition to solar-powered alternatives for cost efficiency.

This transformative project not only underscores the commitment of Lusaka City Council to innovation but also sets a precedent for embracing renewable energy solutions. Figure below illustrates the streets in Lusaka that have embraced solar technology for their street lighting needs, marking a significant step toward a more sustainable and cost-effective future for the district. Figure 6 shows study area and its location.

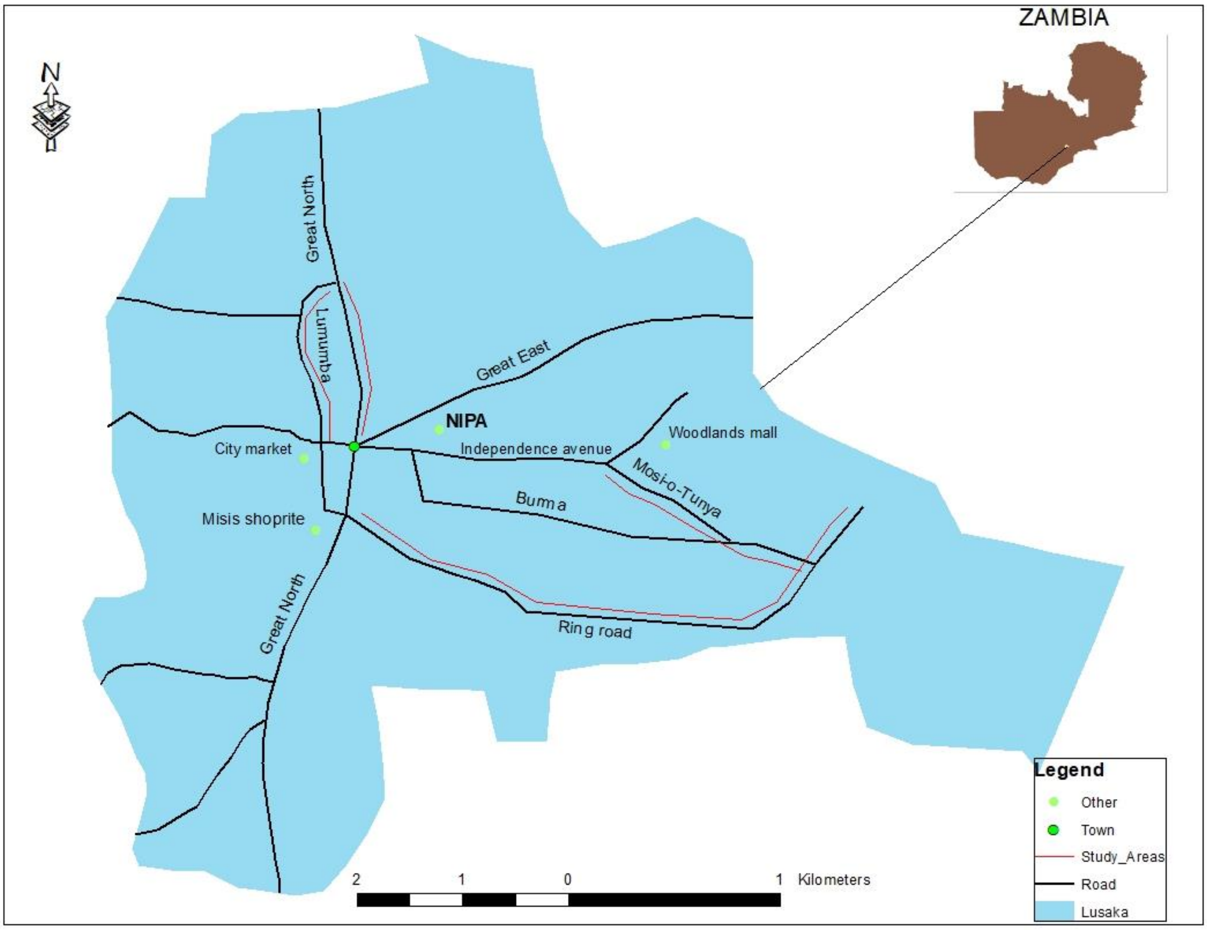


Figure 6: Location of the study area

3.5 Study population

The study was conducted within the jurisdiction of the Lusaka City Council (LCC) in selected streets of Lusaka district focusing on street lights powered by solar energy. The study population encompassed both the solar-powered street lights and individuals affiliated with the electrical engineering department at the LCC office. The selection of the study population was based on the total number of solar street lights installed within the selected streets of Lusaka.Questionaires were distributed to the engineering department of the Lusaka city council.

3.6 Sample size and sampling technique

A sample size of 364 solar street lights was obtained using the Yamane Taro formula (1), [65] derived from the total population of 4000 installed solar street lights. Employing a 90% confidence limit for each road under study, specific sample sizes were calculated for the selected streets: eighty-two (82) along Lumumba Road, forty-seven (47) along Great North Road Lusaka district, eighty-one (81) along Ring Road, and ninety-five (95) along Mosi-O-Tunya Road. These roads were purposely chosen with the assumption that they furnish the necessary information for the study. A systematic sampling technique was then employed for each solar street light under observation. Lauren [66] defines a systematic sampling technique as a probability sampling method in which researchers select members of the population at a regular interval determined in advance. For example, if the population order is random or random-like (e.g., alphabetical), then this method will give you a representative sample that can be used to conclude your population of interest. A total of 464 solar street lights with 80W solar panels and a pole height of 8 meters were installed along Lumumba Road, Great north comprised of 90 solar street lights with 120W solar panels and a pole height of 10 meters,. Ring Road had 435 solar street lights, all with a pole height of 8 meters, while Mosi-O-Tunya Road had a total of 1900 solar street lights with a pole height of 12 meters. To determine the appropriate sample sizes for each road, the Yamane Taro formula (1) was applied, taking into account the population of each road and a margin of error (e).

$$n = \frac{N}{1+Ne^2} \tag{1}$$

where; n = sample size, N = population of study, and e = margin error in calculation

Lumumba road 80 W solar panels

$$n = \frac{N}{1+Ne^2}$$

$$n = \frac{464}{1+464(0.1^2)}$$

$$n = \frac{464}{1+464(0.01)}$$

$$n = 82 \text{ solar streetlights}$$

Great North road 120 W solar panels

$$n = \frac{N}{1+Ne^2}$$

$$n = \frac{90}{1+90(0.1^2)}$$

$$n = \frac{90}{1+90(0.01)}$$

$$n = 47 \text{ solar streetlights}$$

Ring road 100 W solar panels

$$n = \frac{N}{1 + Ne^2}$$

$$n = \frac{435}{1 + 435(0.1^2)}$$

$$n = \frac{435}{1 + 435(0.01)}$$

$$n = 81 \text{ solar streetlights}$$

Mosi o. Tunya road 330 W solar panels

$$n = \frac{N}{1 + Ne^2}$$

$$n = \frac{1900}{1 + 1900(0.1^2)}$$

$$n = \frac{1900}{1 + 1900(0.01)}$$

$$n = 95 \text{ solar streetlights}$$

A comprehensive survey was undertaken to investigate the factors affecting the performance of the solar street lights within the selected streets of Lusaka. The study focused on the Great-North Road, Mosi-O-Tunya road, Lumumba road, and the Ring road (Tokyo way), all of which utilize solar street lighting. To ensure accuracy, the study design prioritized the collection of precise information on the models and technical specifications of the solar components. The data-gathering process was conducted at the electrical engineering department of the Lusaka city council yard and involved obtaining details on battery types, switching systems, panel sizes, and charging mechanisms.

3.7 Data collection method

During the data collection process, various research instruments were utilized for each, with a primary focus on questionnaires. A semi-structured questionnaire was administered to the electrical engineering department of LCC, chosen for its ease of response and suitability for collecting qualitative data. The questionnaire addressed key aspects such as the types of solar panels installed in Lusaka, the varieties of batteries employed for energy storage, and the preventive measures implemented by the Lusaka City Council against vandalism.

In addition to questionnaire-based data collection, the study involved the measurement of panel orientation and inclination. Morning and evening voltages, along with currents were measured and tabulated to assess their impact on solar street light performance. An inclinometer was used to measure the inclination or tilt angle of solar panels, while magnetometer was used to measure the orientation of the solar panels. Figure 7 show research instruments that were employed in this study.

(a) (b)

(c) (d)

Figure 7: A picture of magnetometer (a), luxmeter (b), inclinometer (c) and, multimeter (d)

All angles of orientation were measured with reference to the North direction as illustrated in Figure 8. A multimeter was used for voltage and current measurements. See appendix 11 for the raw data

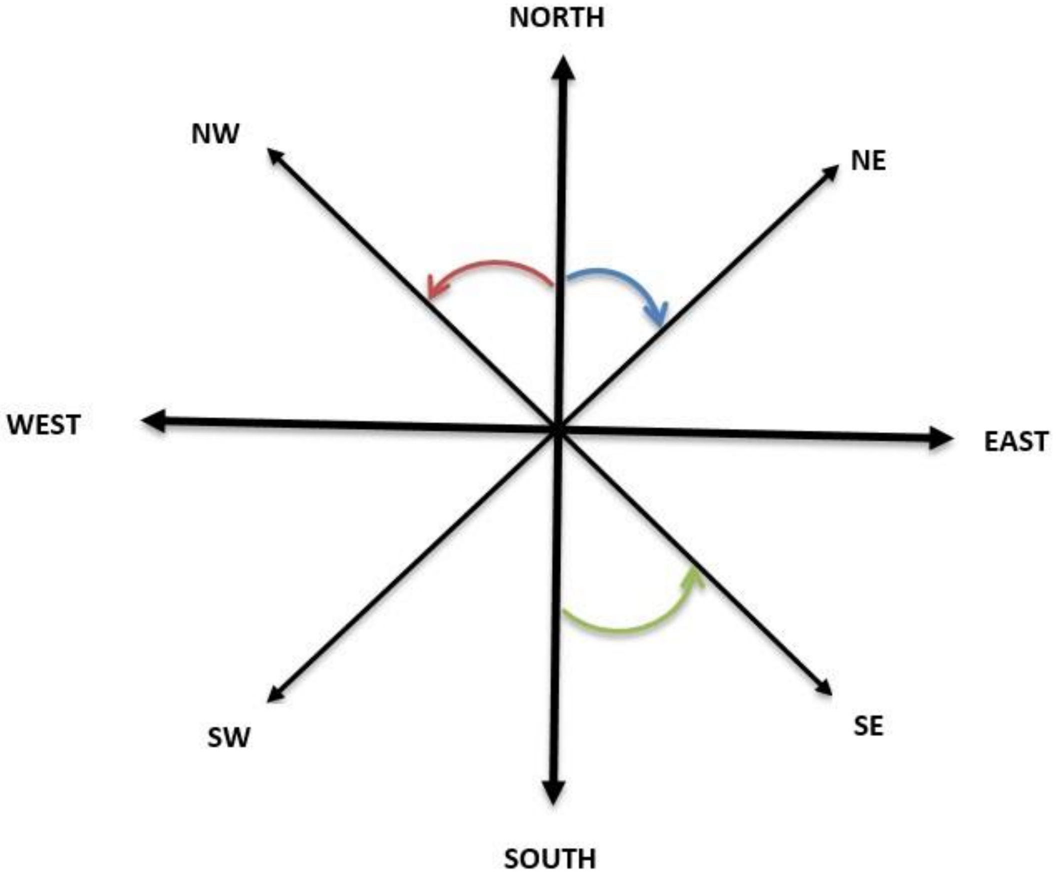


Figure 8: A drawing of a compass showing different directions and angles.

3.8 Data analysis

Ibrahim [67] defines data analysis as the systematic process of performing specific computations and assessments to draw out pertinent information from data. Since it is a process, several steps may be involved before certain conclusions and suggestions are reached, such as determining whether data is deemed raw instead of information. In this work, most of the data was analysed qualitatively. Before data analysis took place, the data had to be edited to identify and correct any irregularities. Since the solar street lights were already erected at fixed inclinations distant from Lusaka's latitude and could not be adjusted, nothing was done to correct the abnormalities in their inclination that were discovered along the ring road (see Appendix (II). Secondly, further irregularities were subsequently detected in the voltage and current readings of solar street lights situated along Lumumba Road, and these were addressed by repeating the measurement. However, for the first objective of determining how inclination, orientation, and shading influenced the performance of solar street lights, a quantitative analysis was conducted using the Python programming language. Descriptive statistics were generated through frequency tables and bar charts using the computer software called Statistical Package for Social Sciences (SPSS).

CHAPTER 4

4.0 RESULTS AND DISCUSSION

4.1 Overview

This chapter presents the findings and a comprehensive discussion of the findings derived from research and data analysis conducted on data collected from the Lusaka City Council (LCC) yard and within the selected streets of Lusaka City. This chapter present presented in Chapter Four, which sought to investigate the technical specifications and factors influencing the performance of solar street lights within some selected streets of Lusaka. Below are the objectives under which the discussions will fall: impact of shading, orientation and inclination on the performance of solar street lights within Lusaka, understanding the various battery technologies employed in Lusaka's solar street lighting systems, and evaluating the effects of switching mechanisms on overall performance, and identifying and characterizing the challenges related to security, vandalism, and maintenance.

In this chapter, the research hypothesis will be critically examined in light of the revealed insights. The discussion will offer a thorough understanding of the details and complexities linked to the performance of solar street lights within Lusaka.

4.2 Technical specifications and models of the components of the solar street lights

This section presents an inventory of models and technical specifications of the components used for the solar street lights studied.

4.2.1 Types of solar panels installed

Lusaka's solar street lighting infrastructure incorporates two distinct types of solar panels, as detailed in Table 2, along with their respective quantities and percentages.

Table 2: Types of solar panels studied

Types of solar panels	Frequency	Percent
Polycrystalline silicon	96	34.91
Monocrystalline silicon	179	65.09
Total	275	100.0

There are two different kinds of solar panels in use, as shown in Table (2). These solar panels are classified as monocrystalline silicon (m ci) and polycrystalline silicon (p ci). The data indicates that monocrystalline solar panels, totalling 179 installations, constitute the majority, representing 65.09% of all solar panels used. In contrast, polycrystalline solar panels, amounting to 96 installations, constitute the minority, making up 34.91% of the total solar panels deployed.

4.2.2 Solar panels' electrical and physical parameters

Results generated for different types of solar panels with their specific maximum power rating are presented in figure 9.

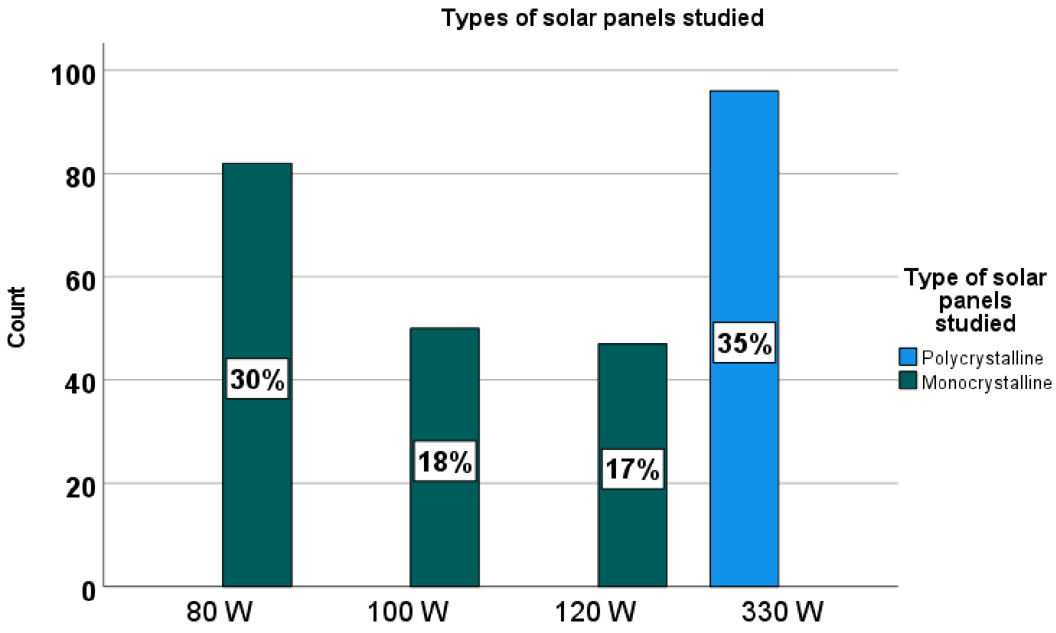


Figure 9:Types of solar panels installed

Lusaka City Council has implemented a variety of solar panels with different power ratings as illustrated in the bar chart. Notably, the most common solar panel type, with the highest maximum power rating of 330 W, was polycrystalline silicon, constituting 35%. The monocrystalline silicon solar panels had three different types of maximum power ratings. Among the monocrystalline silicon solar panels, the 80 W variant emerged as the most prevalent, constituting 30% of the total. Following closely was the 100 W solar panel, representing 18% while the lowest power rating among the monocrystalline solar panels accounted for 17% with a maximum power rating of 120 W.

4.2.2.1 Technical specifications of the 80 W, 120 W, and 330 W Solar panels

The technical specifications of the 80W, 120W, and 330 W solar panels utilized within some selected streets of Lusaka's street lights were compiled from the Lusaka City Council's electrical engineering department yard except for the 100W solar panel which didn’t have the specifications available at LCC yard.

Tables 3 and 4 provide an overview of the electrical and physical parameters of the monocrystalline silicon solar panels under Standard Temperature Conditions (STC) with $F=1000W/m^2$, Am=1.5, and $T_c=25°C$, respectively.

Table 3: Technical specifications of 80 W monocrystalline solar panels

Solar panels electrical parameters		**Physical parameters**	
Maximum power (P_{max})	80 W	Solar cell material	Monocrystalline
Tolerance of P_{max}	±3%	Cell arrangement	4 x 9 in series
Voltage at Pmax (V_{mp})	18 V	Module net weight	5.4 kg
Current at P_{max} (I_{mp})	4.44 A	Module dimension	670 x 770 x 30 mm
Open circuit voltage (V_{oc})	21.6 V		
Short circuit Current (I_{sc})	5.04 A		
Maximum series fuse	15 A		
Maximum system voltage	700 V DC		

Table 4: Technical specifications of 120 W monocrystalline solar panels

Solar panels electrical parameters		**Physical parameters**	
Maximum power (P_{max})	120 W	Solar cell material	Monocrystalline
Tolerance of P_{max}	±3%	Cell arrangement	4 x 9 in series
Voltage at P_{max} (V_{mp})	18 V	Module net weight	8.4kg
Current at P_{max} (I_{mp})	6.67 A	Module dimension	670 x 1130 x 35 mm
Open circuit voltage (V_{oc})	21.6 V		
Short circuit Current (I_{sc})	7.57 A		
Maximum series fuse	15 A		
Maximum system voltage	700 V DC		

Table 5 outlines the electrical parameters and physical parameters for a 330W polycrystalline silicon solar panel at Standard Test Condition (STC) F=1000W/m^2, Am=1.5, T_c=25ºC respectively.

Table 5 Technical specifications of 330 W polycrystalline silicon solar panels

Solar Panels Electrical Parameters		**Physical Parameters**	
Maximum power (P_{max})	330.0 W	Application class	A
Open circuit voltage (V_{oc})	46.70 V	Dimension	1960 x 990 mm
Short circuit current (I_{sc})	9.26 A	Material	Polycrystalline silicon
Maximum power voltage (V_{mp})	37.95 V	Module net weight	22.50 kg
Maximum power current (I_{mp})	8.70 A		
Maximum system voltage	1500 V DC		
Maximum series fuse rating	15 A		

Tables (3), (4), and (5) show a comprehensive overview of the electrical and physical parameters defining the technical specifications of both monocrystalline silicon and polycrystalline silicon solar panels for the 80 W, 120 W and 300 W. The 100 W monocrystalline solar panel was not available at LCC yard and hence its electrical and physical parameters could not be shown in this current research. The main parameters used to characterize the performance of solar panels are the peak power or maximum power (P_{max}), short-circuit current (I_{sc}), the open circuit voltage (V_{oc}), and the fill factor (FF).

4.3 The orientation on performance of solar panels

Data was collected (refer to Appendix II) from 275 solar street lights for selected roads of Lusaka, namely; Great North road, Ring road, Mosi-O-Tunya road, and Lumumba road. However, due to insufficient information for voltage and current measurements for solar street lights in Ring road data, information for 50 was filtered out bringing 225 for analysis. Figures 10, 11, and 12 display the data analysis results.

The data obtained for these roads include the orientation, inclination, morning and evening voltages, and currents. However, shading details were not recorded as most of the solar street lights studied were strategically installed without any building or tree covering them.

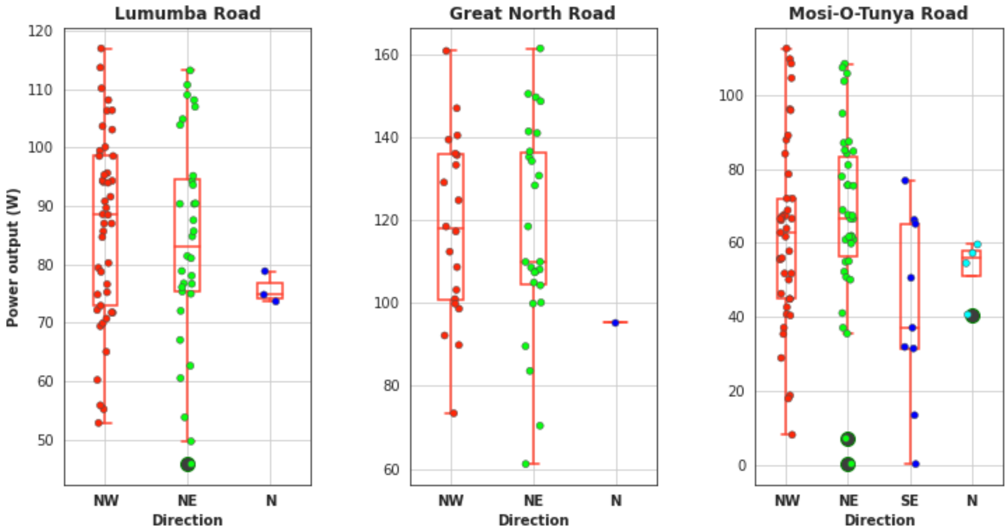


Figure 10: Box plot of the power output against the orientation for three roads

The box plots in figure10 illustrates the distribution of solar street lights' orientation and its effect on performance in different directions. The study focused on the three roads Lumumba road, Great North road, and Mosi-O-Tunya road. As earlier mentioned in the methodology, the roads were purposely chosen as they operated on the solar panels and not grid connected. However, Ring road was not part of the analysis because of limited data to analyze hence it was cleaned out. A plot of the power output against various directions (north, northwest, northwest, and southeast) was generated to show the performance variations based on orientation. The power output that was used for the plot was calculated using the measured voltages and the currents using Equation 2.

$$P = IV \qquad (2)$$

where P is the electrical power, I is the current, and V is the Voltage

The box plot presented figure 10 illustrates the performance of solar street lights having panels in different orientations across three distinct roads. The study showed that the majority of solar street lights are orientated in the northeast, with some facing northwest direction on roads like Lumumba road, and Great North road and Mosi-O-Tunya road. As illustrated, a limited number of solar street lights were oriented towards the north (N) direction and southeast (SE) directions. Solar panels oriented in the northwest along Lumumba road and Great North road exhibited a different trend in average power output of 89 W, while those oriented in the northeast showed an average power output of 84 W. These findings suggest that solar panels facing northwest generally outperformed those facing northeast.

The results of the study highlight the significance of orientation, in influencing the performance of solar street lights in Lusaka. Solar panels situated along the Great North road and Lumumba road demonstrated higher power production these where the ones found to be oriented in the northwest direction, followed closely by those in the northeast direction. A one-way ANOVA test was performed for each direction on the three roads to assess the significant difference in power outputs. The F-statistics (F-value) is a statistical measure to test the null hypothesis (H0), the associated P-value indicated the level of significance in the F-statistic test. Notably, these solar panels road despite being installed in the northwest, and northeast, showed no significant difference in power output, as confirmed by the ANOVA test in table 6. The results revealed that along Lumumba road and Great North road, there was no significant difference between the directions, as indicated by the F-statistics and their associated P-values. Lumumba road showed an F-statistics of 0.661 with a P-value of 0.519, .and Great North road showed an F-statistics of 0.426 with an associated P-value of 0.656. Both roads exhibited high p-values, suggesting no significant difference in power output, based on the orientations found within these two streets there was minimal energy loss whether a solar panel faced north, northeast and northwest direction. Therefore, failed to reject the H_0. This was also confirmed from the median of the box plots obtained in Figure 10 to mean that the energy loss showed minimal variation regardless of whether the solar panels were oriented in the north, northeast, or northwest. Zeeshan's [68] study illustrates that the extent of deviation from the North or South has a direct impact on energy production.

Table 6: Analysis of variance on the effects of orientation on a solar panel

Road	**F-statistics**	**P-value**
Lumumba road	0.661	0.519
Great North road	0.426	0.656
Mosi-o-Tunya	2.851	0.042

Solar panels along Mosi-O-Tunya road on the other hand exhibited a different trend as can be seen in figure 10, with panels facing northeast producing more power than those facing northwest. This distinction is evident in the medians of the two directions: in the northeast, the median was 68W, surpassing the northwest where the median was less than 64 W. Interestingly, some solar panels on this road were oriented southeast yielding an average power production of 38 W, indicating poor performance. In contrast to the other two roads, Mosi-O-Tunya road presented a distinct scenario where solar panels oriented northeast direction outperformed those in the northwest direction. Panels oriented in the southeast direction yielded lower power output, demonstrating a significant difference in power generation. However, in Mosi-O-Tunya road, the one-way ANOVA test was tested showing the F-statistics of 2.851 and the associated P-value of 0.042. since the P-value 0.042 was less than the level of significance 0.1, the H_0 was rejected. This indicates a significant difference in power output for each direction along Mosi-O-Tunya road, suggesting that the orientation of the solar panels in this road influences power output differently. This is notably evident in the performance patterns of the solar panels oriented in the southeast direction along Mosi-O-Tunya Road, showing their lower efficiency. So, a shift towards the southwest or the northwest results in a minor decrease in energy output, turning towards the west leads to a moderate drop, while turning towards the south or north results in the most substantial decline in energy production depending on the hemisphere of the place of installation. Figure 11 represents the average power output in the morning and evening as a function of the angle of orientation of solar street lights studied in the selected streets of Lusaka.

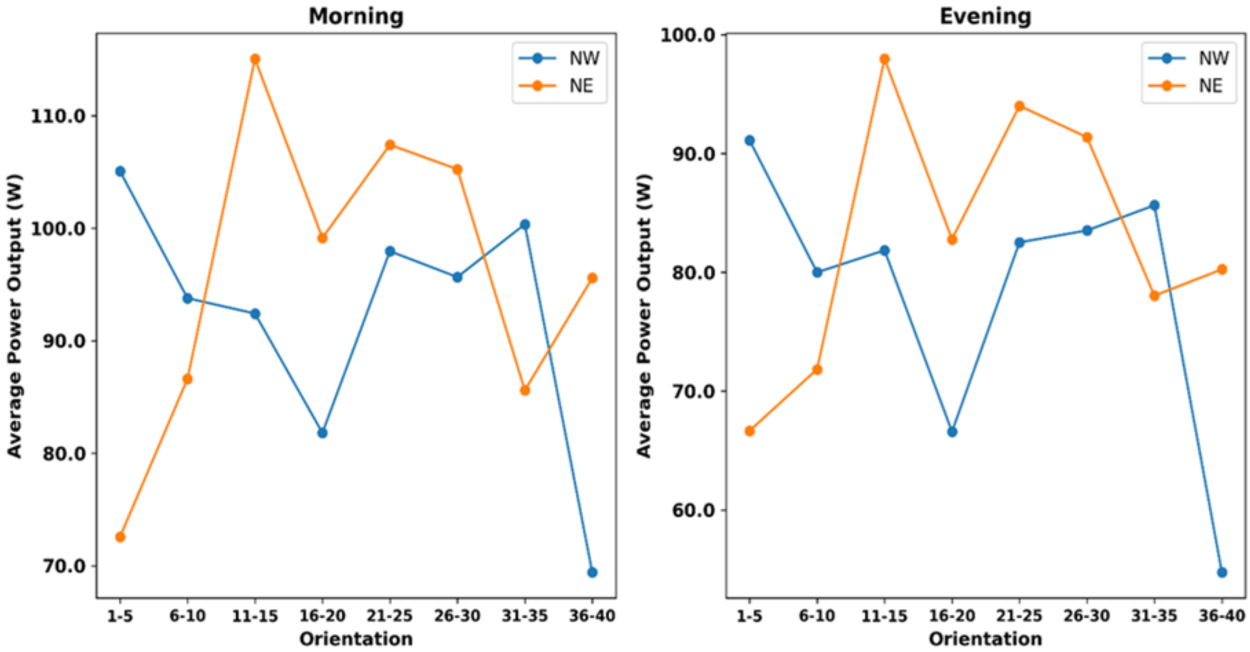


Figure 11: Average power output against the angle of orientation

Angles of orientation were measured with respect to the North direction, as depicted in Figure 8. The impact of the angle of orientation on power output is shown graphically in Figure 11.

The analysis of the sampled data reveals that the solar panels studied operated optimally when oriented toward the northeast at angles of 11^o to 15^o. Conversely, solar panels in the northwest generated the most power when they were oriented between 1^o and 5^o. The efficiency and effectiveness of performance increased as panels were oriented closer to the North. This can be seen from the peak power obtained in Figure 11.

Numerous studies have demonstrated that a solar panel's orientation or azimuth angle won't significantly affect power generation as long as it is within ±20 degrees to the north or south. This agrees with the finding of the study that solar panels oriented at angles of 1^o-5^o northwest and 11^o-16^o generated optimal power output. On the other hand, if conditions allow, 20^o to the north or southwest will cause the peak solar power generation to occur after midday, allowing for the production of more electricity during the winter.

In the study it was observed that along Great North road 94% of the solar panels were aligned optimally, in Lumumba road 58.9% and Mosi-O-Tunya road at 87.5% of the solar panels were aligned optimally bring a total of the solar streetlights studied 78.7% in general.

Furthermore, the performance of the solar panels was found to be influenced by the type of solar panels used. The material composition is crucial impacting how efficiently the panels absorb solar radiation. The box plot analysis revealed the utilization of two types of solar panels on Lusaka's streets. Monocrystalline solar panels were employed on both Lumumba and Great North roads, while polycrystalline solar panels were used on Mosi-O-Tunya Road for street lights. The findings of the study align with previous research, such as Hidayanti’s [69], which highlights the superior efficiency of monocrystalline solar panels compared to polycrystalline counterparts. Hidayanti reported efficiency rates of 9.22% for monocrystalline panels and 7.94% for polycrystalline, a 3% higher performance for the former. This study agrees with these results, observing that monocrystalline solar panels outperformed their polycrystalline counterparts in terms of efficiency. This distinction in performance was reflected in the Anova test results, reinforcing the significance of panel material in influencing solar street light efficiency.

Energy loss during the evening was observed to be primarily attributed to a voltage drop that occurred when the load was in operational, while the circuit's charge remained constant. This phenomenon resulted in energy loss, indicating that the power drop was correlated with the depletion of the battery.

$$E = VQ \tag{3}$$

The relationship between energy (E), voltage (V), and charge (Q) is defined by the equation 3.

4.4 Inclination/tilt angle of solar panel

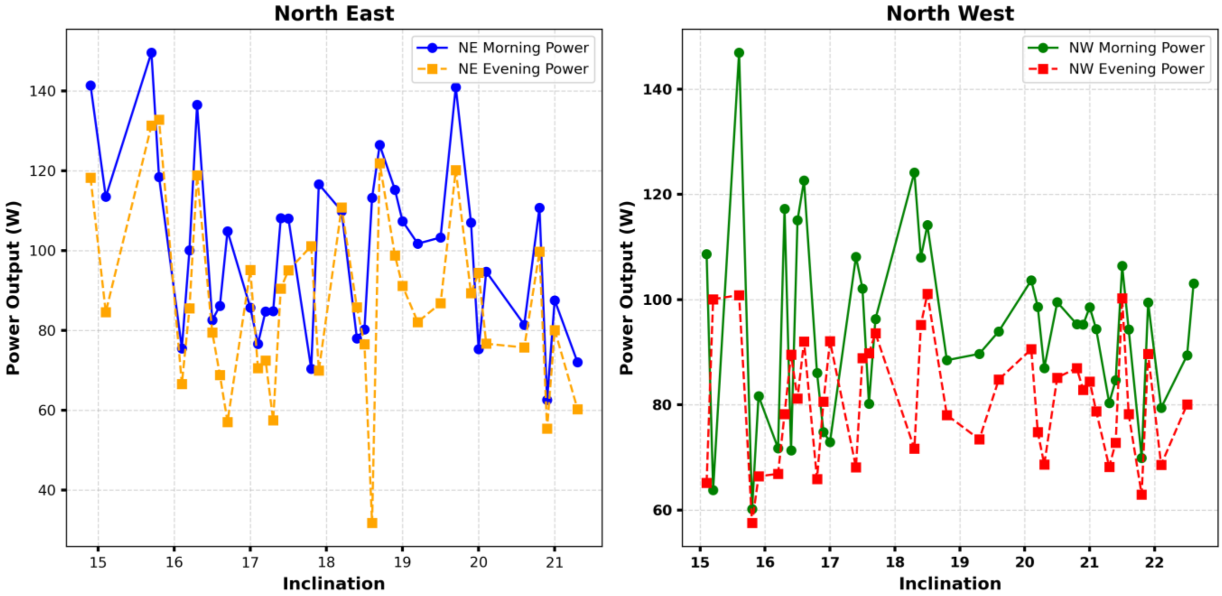


Figure 12: Effects of inclination/tilt angle on the power output

Figure 12 illustrates the correlation between power generated and inclination or tilt angle of solar panels. This graph assists in identifying the inclination values that result in higher power output. The data reveals a range of inclinations where power values are relatively higher compared to other inclination or tilt angles, suggesting an optimal inclination or tilt angle for power generation in solar panels studied.

From figure 12, it is evident that within the range, 15^{o}, 16^{o},17^{o}, and 20^{o} the solar panels in the northeast demonstrated higher power output, and northwest inclination at 15^{o} and 16^{o}. Notably, it was observed that as tilt angle deviated further from the geographical latitude of Lusaka, the power generated by solar panels decreased. This reduction in power not only affected the night-time illumination of solar street lights but also affected the charging efficiency of energy storage devices (ESD) due to reduced stored energy. In summary, the optimal inclination or tilt angle is crucial for maximizing power generation in solar panels, influencing both illumination at night and the efficiency of energy storage systems.

Soulayman's study [70] supported these findings, emphasizing that the optimum tilt angle of a solar panel depends on the geographical latitude with the study's results aligning with this principle. Most of the solar panels investigated had tilt angles of 15^{o}-18^{o}, close to the latitude of Lusaka.

Gevorkian’s study [14] contributes valuable insights by proposing a fundamental guideline for maximizing annual energy production through solar panels. The study suggests setting the solar panel tilt angle equal to the geographical latitude for optimal performance. In practical terms, if a solar array is located at a latitude of 50^o, the recommended tilt angle would be 50^o. Applying this principle to Lusaka, with a geographical latitude of 15^o south, it logically follows that the optimal tilt angle or inclination should fall within the same range. This aligns with our study's findings, where solar panels with tilt angles ranging from 15° to 22° were observed to produce optimal power output within the specific geographical context of Lusaka. Thus, Gevorkian's guideline provides a theoretical foundation that resonates with the empirical evidence obtained in our investigation, reinforcing the importance of appropriate tilt angles for solar street light efficiency.

4.5 The effects of orientation and inclination on the performance of solar street lights

It was observed that a misaligned angle of orientation and inclination negatively affected solar street light performance, including reduced power generation, insufficient night-time illumination and decreased charging efficiency [69,71]. These consequences pose a safety risk to the citizens. Insufficient exposure to sunlight resulted in certain solar panels failing to generate the required amount of electricity.

Consequently, these solar panel collected less energy from the sun, which prevented the ESDs from fully charging or not charging at all, thereby diminishing charging efficiency. The consequence of this limitation was evident in the compromised performance of solar street lights, as they were unable to illuminate adequately due to the restricted energy supply.

This scenario not only hampers the effectiveness of street lights during the night but also has broader implications, leading to increased prices of Energy Storage Devices (ESDs). Particularly, poorly oriented and inclined solar panel angles were identified as contributing factors to diminished lighting effects in solar street lights [69]. The prevalence of flickering and poorly illuminated regions, notably observed in the case of AFCON solar street lights, poses ongoing safety risks. This underscores the critical importance of proper solar panel orientation and inclination for ensuring optimal functionality and safety within the solar street lighting infrastructure.

The study emphasizes the importance of selecting the correct orientation angle during the installation process to ensure optimal performance. The solar panel should be installed facing south if in the northern hemisphere or north if installed in the southern hemisphere to generate the most electricity per unit time. However, according to Zeeshan's study [68] southeast, southwest, northwest and northwest facing solar panels generally produce about less than 8% less power output than those that face in the north and south depending on the hemisphere of that location. He later added that east or west panels will produce approximately 15% less power output than those in the south and the north.

Further, the study underscores the importance of strategic placement, avoiding shadows caused by surrounding buildings and trees. Fortunately, the examined solar street lights within some selected streets of Lusaka were well-placed, with minimal shading caused by factors like bird droppings and dust particles.

4.6 Battery types and how the switching system affected their performance

4.6.1 Energy storage types

Investigation into energy storage devices (ESD) revealed three types of commonly used in Lusaka for solar street lighting, as outlined in Table 7

Table 7: Types of energy storage and their distribution percentages

Types of energy storage	Frequency	Percent (%)
Flooded Lead acid battery [FLA]	96	34.90
Lithium-ion battery [Li]	50	18.20
Ultra-capacitors [UC]	129	46.90
Total	275	100.0

Figure 13 provides insights into the required energy storage capacity for each device, measured in Amp hours (Ah) for batteries and Farads for capacitors. Ah signifies the number of hours for which an ESD can supply current at the nominal voltage of the battery, matching the discharge rate. This metric offers a valuable measure of the charge stored in a battery, influencing the overall performance of the solar street lighting system.

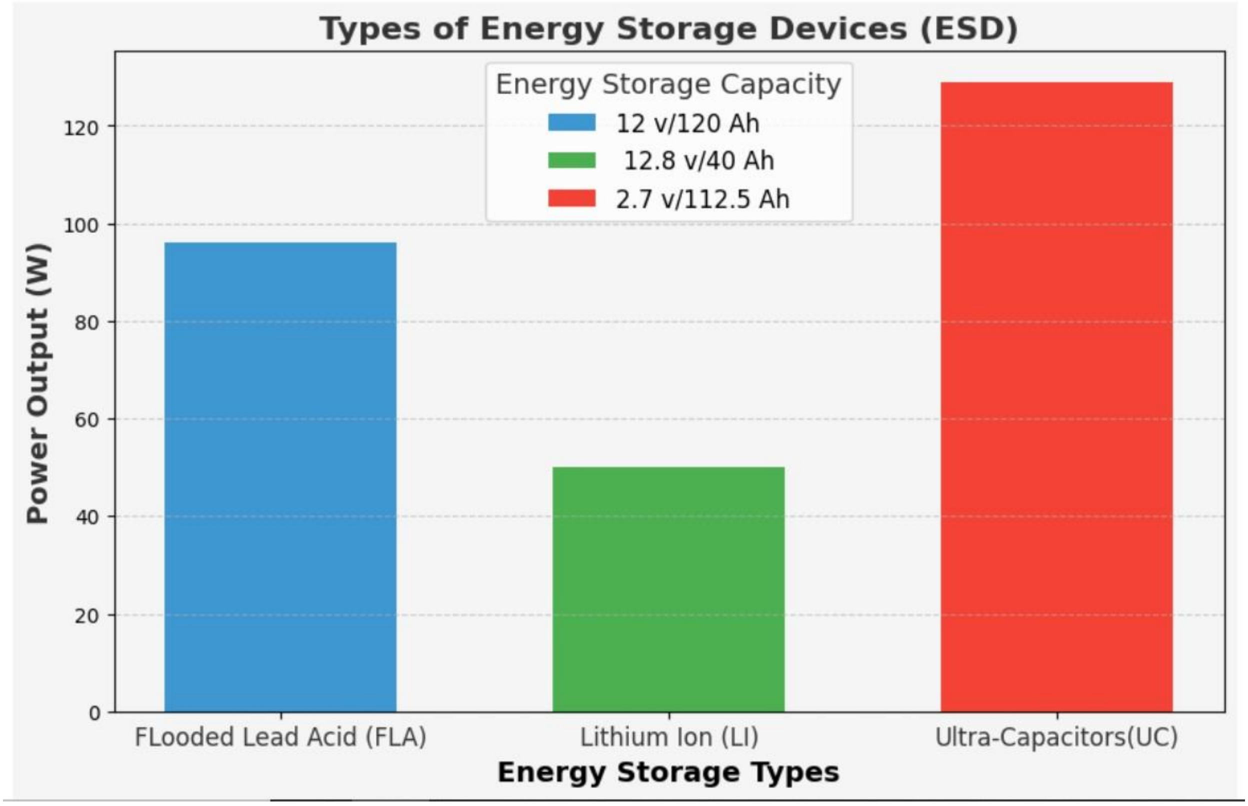


Figure 13: Energy storage capacity for the three types of ESD installed

4.6.2 Conversion from farads to ampere hour

In the analysis, ultra-capacitor/supercapacitor with a capacitance of 300,000Farads and a rating of 2.7 V was considered. The conversion from Farads to Ampere Hour (Ah) involved several steps.

Utilizing the formula for electrical energy:

$$E = \frac{1}{2}CV^2 \tag{4}$$

E is the electrical energy, C.is the capacitance and V is the voltage and

$$P = \frac{E}{t} \tag{5}$$

where t is the time and P is the power, the following steps were applied:

Substituting (4) into (5)

$$P = \frac{CV^2}{2t} \tag{6}$$

$$P = IV \tag{7}$$

where I is the current

$$P \times t = 0.5 \ \times CV^2$$

Substituting (5) into (4)

$$I \times V \times t = 0.5 \ \times CV^2 \qquad (8)$$

$$\frac{It}{3600} = \frac{0.5CV}{3600}$$

Where It is the ESD capacity in ampere hour

$$ESD\ capacity = \frac{(0.5 \times 300000 \times 2.7)}{3600}$$

$$= 112.5 \text{ Ah}$$

If all the charge can be used, then in every hour, the load will consume112.5 Amps per hour.

For a specific scenario with an 80W solar panel and with a single 12W LED lamp using three supercapacitors each with a capacity of 112.5Ah the total capacity for this the system was calculated as;

$$ESD\ capacity = 112.5 \text{ Ah} \times 3$$

$$ESD\ capacity = 337.5 \text{ Ah}$$

Similarly, for a 120W solar panel with four supercapacitors, the total capacity was

$$ESD\ capacity = 112.5 \text{ Ah} \times 4$$

$$ESD\ capacity = 450.0 \text{ Ah}$$

These calculations provide insights into the data obtained from the systems employing ultra-capacitors/supercapacitors for energy storage capacity in Ah within selected streets of Lusaka along the Lumumba road and the great north road..

The visual representation of energy storage devices in Figure 13 shows their respective energy storage capacities, while Figure 14 provides a visual depiction of these devices.

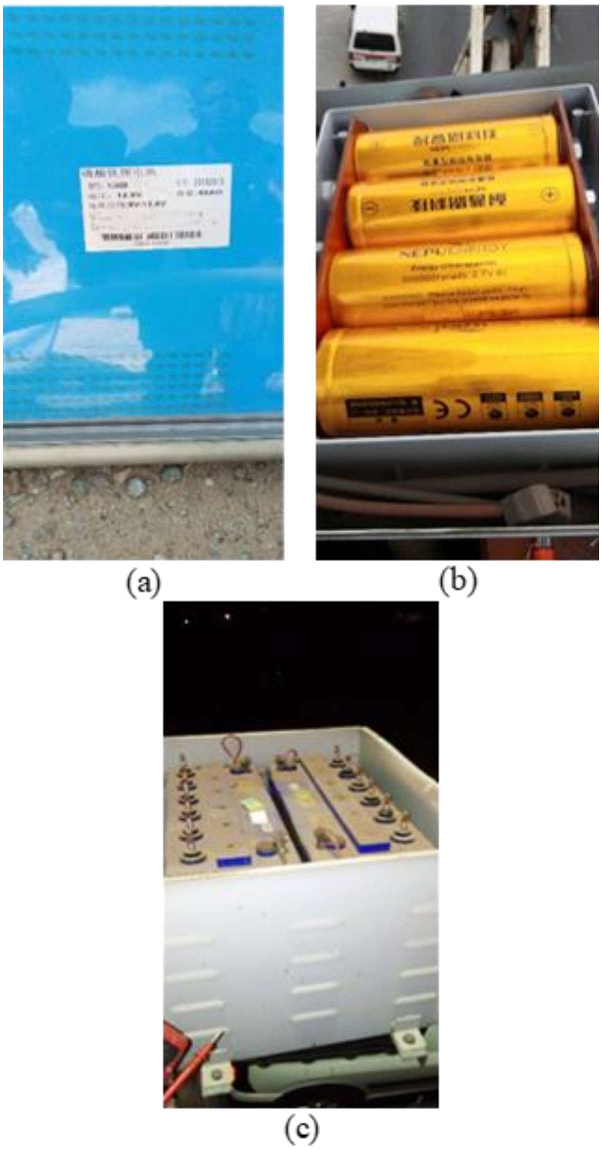


Figure 14:Types of ESDs in picture form where a is Li, b is UC, and c is FLA

The Flooded lead acid [FLA] batteries were used in Mosi-O-Tunya road, lithium-ion batteries [Li] in Ring road and ultra-capacitors [UC] in both Lumumba and Great North road. Upon analysis, the study found superior performance from Li and UC compared to FLA batteries. Several factors contributed to this: both UC and Li were maintenance-free energy storage devices, enhancing their reliability. Li exhibited high energy density, while UC demonstrated a high-power density to energy density, contributing to their efficiency. Both Li and UC boast long life cycle.

In contrast, FLA exhibited a relatively low energy density, a short cycle life and a relatively high self-discharge rate; however, they were identified as the most economical ESD option. The statistical analysis, represented by the Anova test, yielded a p-value <0.01, less than the significance value indicating a significant difference in performance among the various ESDs. Hence the hypothesis was rejected. These results were consistent with Townsend's study [29] on the comparative review of the Lead-Acid, Lithium-Ion and Ultra-Capacitor technologies and their degradation mechanisms findings which also showed that there was a significant difference between the energy storage devices.

According to Sangharsh *et al.*,[72] a thorough research and survey were conducted to assess the existing situation of solar street lights in Kathmandu, Dhulikhel, and Lalitpur municipalities. However, the study found that the majority of these installations are currently operating minimally. Similarly, in Dhulikhel, solar street lights are non-functional due to their reliance on lead acid batteries, resulting in below average performance and a lifespan of only a few months to a maximum of one year. Consequently, the municipal authorities opted to power these lights through the Nepal Electricity Authority line.

Parallel to these findings, this study identified a comparable situation in Lusaka, particularly in areas such as Kalingalinga, Mutendere, Kabulonga, a part of Chilenje and Woodlands where solar street lights equipped with flooded lead-acid batteries are minimally operational. LCC electrical engineers anticipate a potential blackout scenario in these areas within the next 3-5 years. This projection is attributed to maintenance challenges and heightened vulnerability to vandalism experienced by solar street lights relying on flooded lead-acid batteries.

In contrast, solar street lights in Jawalkhel, Lalitpur installed in 2019 and powered by lithium-ion batteries, continue to function effectively to date. This aligns with the study's findings, where solar street lights equipped with lithium-ion batteries and the Ultra capacitors have demonstrated sustained functionality since 2013. These particular energy storage devices were identified as maintenance-free, efficient, and highly reliable, contributing to their prolonged operational success.

Additionally, lux measurements were made with the luxmeter depicted in figure 7(b). The brightness between the light source and the lit region was precisely measured by the luxmeter. The solar street lights on Lumumba Road had an 8-meter pole height and a measured lux range of 4–6. The study also showed that, at a pole height of 10 meters, the measured lux of the solar street lights along Great North Road was 6-7. Roads like Mosi-O-tunya Road and Ring Road had measured lux values of 15–17 at a height pole of 12 meters, while the former displayed measured lux values of 4-6 at 8 meters. Nonetheless, several solar street lights had lux values that were higher than those shown in Table 8 because of light pollution from surrounding shops.

Additionally, it was noted that all of the Solar street lights with lower lux levels aside from the one in Table 8 had flickering and dimming lights.

Table 8: Lux measured with different height poles

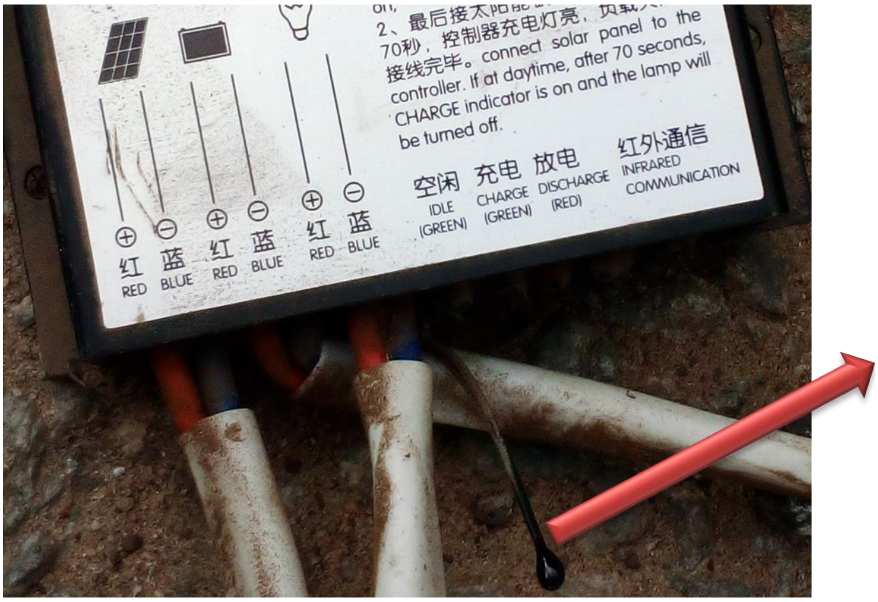
Roads	Pole height (m)	Measured Lux
Lumumba road	8	4-6
Great North road	10	6-10
Ring road	8	4-6
Mosi-O-tunya road	12	15-17

4.6.3 Effects of the switching system on the overall performance

Solar street lights in Lusaka are equipped with a vital component known as a charge controller, responsible for both charging and discharging functions. The charge controller acts as the central decision-making unit in the solar street light system, determining when to activate or deactivate automatically. Serving as the system's 'brain,' the solar charge controller is pivotal in managing light power, working time, and the charging and discharging processes. It also has an embedded photosensor that is responsible for switching on and off of the LED lamp.

This study revealed that the charge controller is key to the overall performance of solar street lights in Lusaka. It governs various aspects, including:

- **Charging and discharging:** The charge controller manages the charging and discharging of the battery, ensuring optimal energy utilization.
- **Lighting control:** It regulates the switching on/off of lights, incorporating functionalities for dimming and efficient light management. This light control is managed by a photocell sensor embedded in the charge controller going to the load side as shown in the figure 15.



Photocell sensor

Figure 15: Solar charge controller with an embedded photocell sensor

- **Battery protection:** The charge controller safeguards the battery by preventing overcharging and undercharging, enhancing the battery's longevity.

- **Nighttime operations:** During the night, the charge controller protects the battery from deep discharging and disconnecting loads when the battery voltage reaches a specified Depth of Discharge (DOD) value. It also prevents reverse currents through PV panels at night.

Furthermore, the charge controller continuously charges the battery during the day, utilizing energy from solar panels until the battery is fully charged. The stored power is then monitored and utilized at night to illuminate LED street lights using a photosensor. The study identified various types of charge controllers employed in solar street lights in Lusaka. Figure 16, 17, and 19, show the different types of charge controllers which are commonly used but Lcc has recommended the use of the charge controller in figure 18 as it can be easily be repaired when accessing the electronics of the controller.

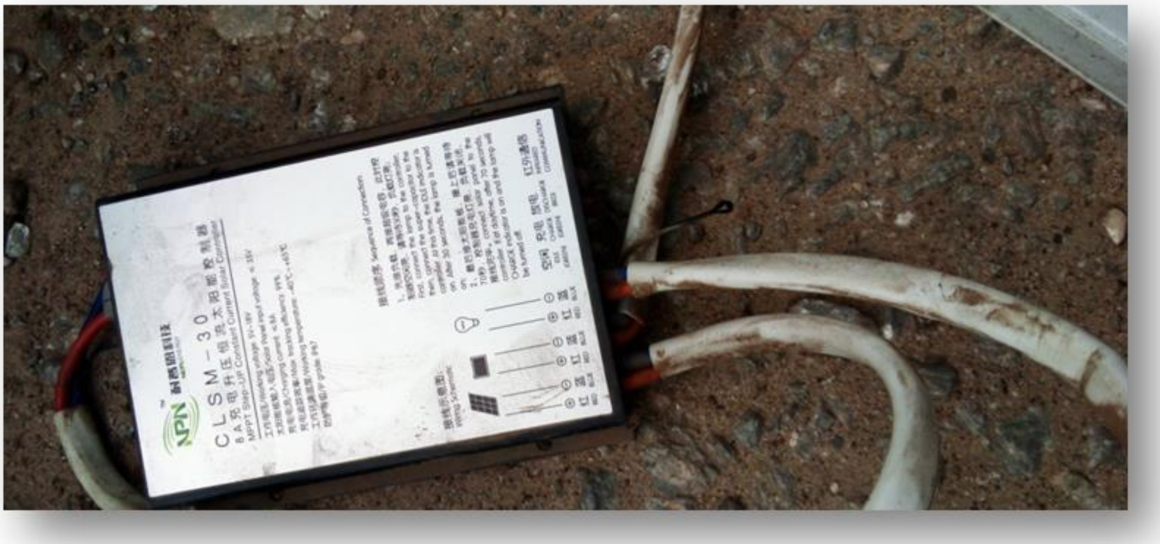


Figure 16:MPPT Step-Up constant current solar controller

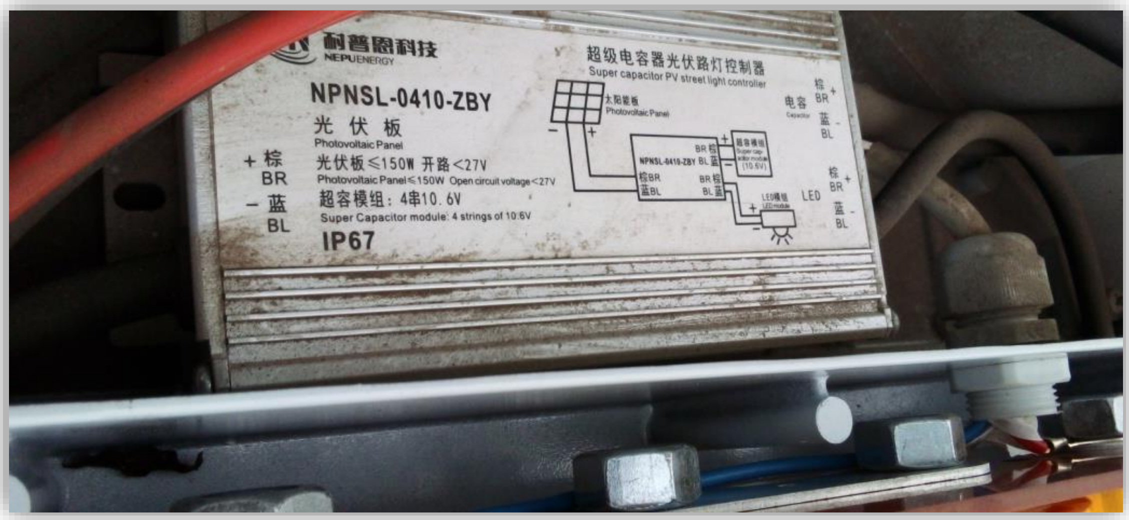


Figure 17:Super Capacitor PV Street light controller

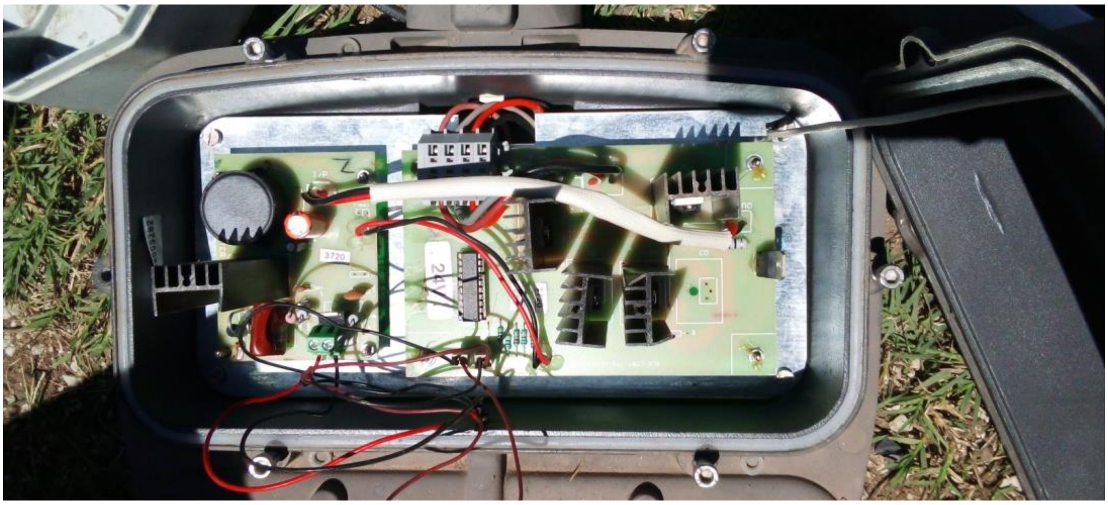


Figure 18: Unsealed MPPT charge controller

Figure 19: MPPT solar charge controller with Step-Up LED driver

The examination of solar street light components revealed a concerning issue with faulty charge controllers in some instances. Upon close inspections, it was evident that several charge controllers faced challenges in effectively managing charging voltage originating from the solar panels. This inability to regulate the charging process resulted in issues such as swelling and bursting, particularly notable in lithium-ion batteries (Li) and ultra-capacitors (UC) energy storage, where malfunctioning charge controllers contributed to operational failures.

Furthermore, in the evening the switching system from the photocell sensors exhibited inefficiencies, hindering its ability to illuminate the connected load, some photocell sensors were unable to illuminate specific loads due to malfunctions in the switching system that were embedded to these sensors. The malfunctioned photocell sensors were due to incorrect and loose wiring, secondly dirt and dust accumulation on the sensor also affected the switching system. This aligns with findings from Fashina *et al.,* [51], in their investigation at the African University of Science and Technology in Nigeria, discovered issues such as broken charge controllers, shoddy cabling, and LED lighting problems within the first year of installing 35 solar street lights in 2012. Moreover, the evaluation of over 2000 solar street lights in in five states of Nigeria in 2012 revealed that more than half of them were inoperable due to faulty charge controllers and shoddy cabling [52].

Figure 20 provides a visual representation of the status of solar street lights on three roads, except Ring road These findings underscore a significant challenge associated with the charge controllers in solar street lights, particularly concerning the switching mechanism found on the photosensors and charging mechanism. Municipal councils often face difficulties in servicing these controllers, especially for solar street lights operating on lithium-ion batteries and ultra-capacitors. The limited accessibility of electronics in these systems further exacerbates maintenance challenges, as illustrated in figures 16,17, and 19 for solar street lights with lithium-ion batteries, ultra-capacitors, and charge controllers, respectively.

A detailed analysis of Eighty-two (82) solar street lights along Lumumba road analysed in 2022 revealed that only seventy-seven (77) were found to be in good working order that five units faced issues attributed to malfunctioning charge controllers and photocell sensors, impacting the switching and charging systems. Similarly, along Mosi-O-Tunya road, out of the 95 solar street lights studied, 81 were in good condition, while 15 exhibited malfunctioning switching and charging systems, affecting their overall functionality.

A night count conducted on solar street lights along Ring road, collaboration with the electrical engineering department of Lusaka City Council, identified 10 out of the 81 studied solar street lights with faulty charge controllers.

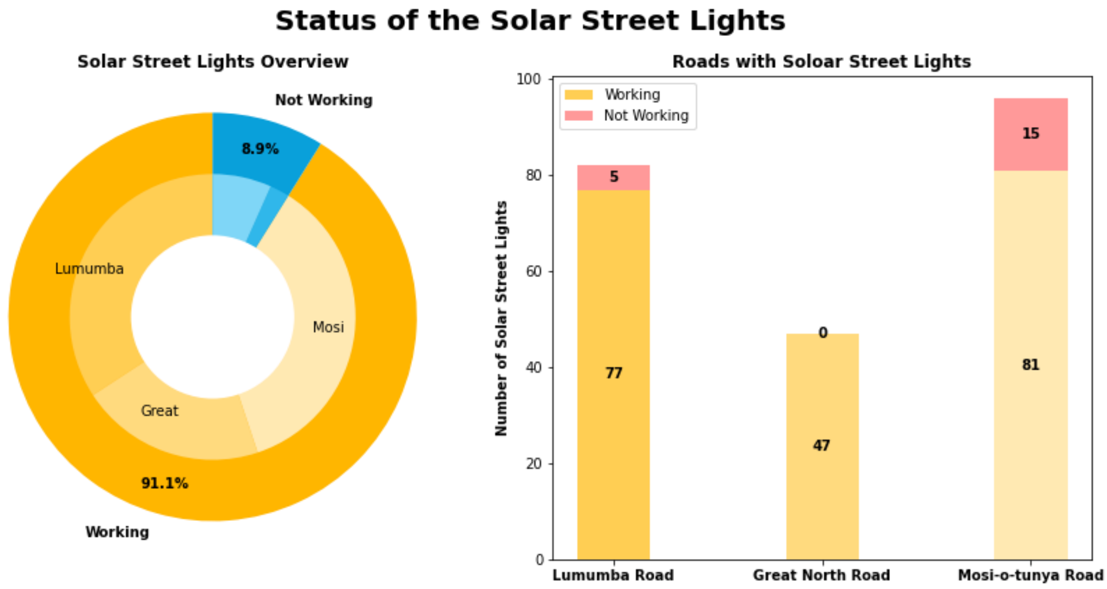


Figure 20: Status of the solar street lights

4.7 Challenges on security/vandalism and maintenance of solar street lights in Lusaka

4.7.1 Security/Vandalism

The survey on security and vandalism impact on solar street lights within selected streets of Lusaka revealed insightful responses from the participants.

Table 9: Vandalism on the solar street lights

Vandalism	Frequency	Percentage
Very low extent	5	25
Moderate extent	6	30
Very great extent	9	45
Total	20	100

The analysis highlighted that 30% of the respondents believed vandalism moderately affected the street lights' performance, 45% indicated a significant impact to a very great extent. Additionally, 25% of the respondents perceived a very low extent of influence by vandalism on performance. This data suggests a consensus among respondents that vandalism predominantly affected solar street lights, particularly those operating on flooded lead acid batteries, to a very great extent. Addressing this concern is crucial for enhancing the sustainability and effectiveness of solar street light installations in Lusa

Quantitatively, the researcher sought to identify and understand the challenges associated with security, vandalism and maintenance affecting solar street lights in Lusaka. The analysis of questionnaire responses revealed that most solar street lights installed within Lusaka face many of challenges that consistently hinder the seamless operation of these lighting systems.–A detailed exploration of specific concerns and their impact on the performance of solar street lights will be presented in the subsequent sections.

4.7.2 Security, vandalism, and maintenance

An alarming revelation emerged from the investigation into security, vandalism, and maintenance issues surrounding solar street lights in Lusaka. The findings underscore a critical gap in security measures, with a notable absence of proper safeguards to protect these installations. The vulnerability of these street lights becomes apparent as citizens, and even road users, engage in acts of vandalism, including theft of essential components like batteries, solar panels, and lighting fixtures.

Moreover, the frequent instances of motor vehicles colliding with street lights further contribute to the vandalism challenge. Reports indicate an average of 3-4 street lights being hit by vehicles every week. This continuous vandalism not only jeopardizes the integrity of the solar street lights but also hinders the Lusaka City Council (LCC) from effectively replacing or maintaining defective charge controllers, energy storage units, and other vital components due to the scarcity of resources.

The study indicates a higher incidence of vandalism affecting solar street lights operating on polycrystalline and flooded lead-acid batteries in the streets of Lusaka. The study found that there are three types of solar street lights in Lusaka. The first generation, installed by AVIC contractors, operated on lithium-ion batteries and ultra-capacitors, both used monocrystalline solar panels. The third generation, powered by flooded lead acid batteries, used polycrystalline solar panels. Among the three categories of generations, solar street lights using flooded lead acid batteries were found to be more vulnerable to theft, while those with lithium-ion batteries were frequently damaged by motorists. Solar street lights with ultra-capacitors faced challenges from both theft and motorist accidents.

Collaborative efforts between ZESCO Limited, the LCC Electrical Engineering Department, and the RDA in 2021 aimed at installing solar street lights as a strategy to lower crime rates underscored the importance of lighting infrastructure in enhancing security. In various African cities, increased crime rates have been linked to inadequate public services [7], emphasizing the potential of street lighting investments to improve safety, particularly for women and men. However, the situation in Lusaka depicts a contrasting reality, where crime rates are on the rise, and street light vandalism is becoming increasingly common.

Aligned with the findings of this study, the report highlights discrepancies in the claimed routine maintenance of solar street lights by LCC. Irregular maintenance practices were evident, contributing to multiple streets experiencing blackout conditions. Additionally, LCC acknowledged a lack of substantial electrical engineers' involvement during the installation process, posing challenges in subsequent maintenance efforts due to limited awareness about specific components of the solar street lighting system. Secondly, not enough equipment has been set aside for maintenance after the solar-powered street lights were installed. They thus find it extremely difficult to replace malfunctioning charge controllers, ESDs, solar panels, and lampposts as a result of the local government's unplanned maintenance, which results in dark streets leading to higher security risks and crime rates.

4.7.3 Measures of vandalism

The survey conducted with LCC electrical engineers shed light concerning the absence of effective measures against vandalism, particularly since 2013. Engineers revealed that despite implementing night-time patrols by state and council police, specifically targeting solar street lights, the lack of robust safety precautions has left many areas of the city vulnerable. This vulnerability has translated into recurring blackouts, impacting various neighbourhoods relying on solar street lights, especially those operating on flooded lead acid batteries.

The engineers' responses indicated a surge in component theft, which began in 2021 during the installation of AFCORN’s solar street lights in specific areas such as Nagwena road, Kamloops Road, parts of Alick Nkanta road in Mutendere and the Kasama roads. Highly populated areas like Kalingalinga, Mutendere, Matero, Chilenje and Chawama reported more theft incidents. Consequently, the growing component theft has led to reduced selling hours for men and women who sell during late hours and compromised safety for residents moving about due to poorly lit streets.

LCC claims to address the issue through community sensitization via social media platforms, television, and radio, educating citizens on caring for solar street lights and providing channels for reporting theft. In 2022, during AFCORN contractors’ tenure, an attempt to curb battery theft involved putting rivets to all of the city’s battery boxes. Despite these measures, the city grapples with persistent challenges related to theft, motorist accidents and maintenance issues, particularly concerning flooded lead acid batteries. Reasons why the city faces challenges of theft for the street lights that use FLA is because some citizens use them in applications like cars, and for power supply in homes.

The cost of maintenance must be considered while installing solar street lights. When solar street lights are not maintained properly, their predicted lifespan is shortened. Planned maintenance, while cost-effective, involves routine activities such as summertime panel cleaning and electrical component servicing. [71]. This proactive approach ensures the longevity and optimal performance of solar street lights, contributing to their overall efficiency and sustainability.

CHAPTER 5

5.0 Conclusion and Recommendations

5.1 Overview

This chapter presents the culmination of the extensive exploration and analysis presented in the preceding chapters. It serves as the platform for drawing conclusive insights and providing practical recommendations based on the study's outcomes. The subsequent sections not only synthesize the key findings but also extend into proposing valuable suggestions for future investigations, thereby contributing to the ongoing discourse on solar street light systems in Lusaka and beyond.

5.2 Conclusion

In this study, it has been shown that the optimal performance of solar street lights in Lusaka is intricately linked to proper solar panel orientation and tilt angle. These two factors are as pivotal determinants of efficiency within the studied context. Notably, solar panels facing northeast and northwest demonstrated superior power output. However, interestingly, solar panels along the Great North road and Lumumba road, despite their diverse orientations toward the North, northwest, and northwest, exhibited no statistically significant difference in power output. The minimal variance in energy loss among these groups implies that solar street lights deployed across these two roads functioned efficiently and optimally, thereby failing to reject the hypothesis as at present.

On Mosi-O-Tunya road, where solar panels were oriented towards the north, northwest, northeast, and southeast directions, the power output exhibited a statistically significant difference, as indicated by a calculated p-value of 0.042. This substantial difference among the groups led to the rejection of the hypothesis, suggesting that solar street lights along this particular road in Lusaka do not operate efficiently and optimally under the implemented orientation, particularly those oriented southeast. It was also observed after the analysis that from the total solar streetlights studied only 78.7% of the solar panels were aligned optimally.

The inclination of the solar panels studied within the streets of Lusaka varied within the range of 15^0 to 22^0. Those exhibiting optimal performance were inclined at 15^0, with inclinations in both the northeast and northwest directions.

The study identified three types of energy storage in solar street lights, highlighting that ultra-capacitors and lithium-ion batteries demonstrated superior performance compared to lead-acid batteries. This superiority was attributed to factors such as maintenance-free operation, long life cycle and increased resistance to vandalism to mean solar street lights components that operated on lithium-ion and ultra-capacitors were not easily accessible to the citizen hence vandalism through stealing was not common.

The study revealed that malfunctioning charge controllers posed a significant challenge, resulting in issues like battery swelling and bursting, particularly for lithium-ion batteries and ultra-capacitors. Additionally, vandalism emerged as a substantial threat to solar street lights in Lusaka, emphasizing the importance of enhancing security measures and implementing durable designs and uniform nighttime illumination to deter theft. Maintenance-related issues, including irregular maintenance practices and a lack of dedicated equipment, has also emerged as a threat especially on solar street lghts that operated on flooded lead acid batteries, highlighting their adverse impact on overall system reliability

5.3 Recommendations

The study was based on some factors affecting the performance of the solar street lights within selected streets of Lusaka, Zambia. several key recommendations based on the findings are presented.

Optimal solar panel orientation

- During the installation of solar panels in Lusaka, it is advisable to orient them in the North direction for optimal performance since Lusaka is in the southern hermispere however, if solar panels are deviating from the north this study has recommended that if in the northeast direction then they should be oriented at angles 11^0-16^0, while those facing northwest should be oriented at angles 1^0-5^0. Closer proximity to the north direction enhances system efficiency.

Consistent tilt at geographical latitude

- Municipal authorities should ensure that during installation, solar panels are inclined or tilted at the geographical latitude of the installation location. For the case of Lusaka, this would be 15.14^0.
- In other locations in Zambia, municipal councils should determine the specific latitude of the area for optimal performance and efficiency.

Optimal performance of energy storage devices

- Municipal authorities should utilize lithium-ion batteries and ultra-capacitors for their superior performance in the high energy densities for the lithium-ion batteries and power densities for the ultra-capacitors, durability, and low maintenance requirements.
- On the other hand, if utilizing lead-acid batteries for streetlights (Flooded), consider placing the battery boxes at elevated heights to prevent easy citizen access and this will minimize vandalism risks. Furthermore, Municipal authorities should ensure maintenance of the flooded lead acid is done every 6 months.

Planned maintenance budget

- A planned maintenance budget before the installation of solar street lights is necessary. This proactive approach ensures preparedness for unforeseen expenses and contributes to the long-term sustainability of the lighting systems.
- In order to maintain the continued best performance of solar street lights, routine maintenance should be carried out on a regular basis to prevent blackouts within Lusaka city.
- Furthermore, a strong monitoring team should be established that will be responsible of monitoring the performance of the solar street lights in order to establish and identify those which failed or about to fail and make replacement before they failed completely

Further research on shading effects

- Conduct further studies to explore how any form of shading on solar panels affects the performance of the entire solar street light system. This will contribute to a more comprehensive understanding of potential challenges and solutions.

These recommendations aim to guide municipal authorities in optimizing the performance, efficiency, and durability of solar street lights, ultimately contributing to sustainable and effective urban lighting solutions.

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Appendices

Appendix 1: Semi Structured Questionnaire for LCC Electrical Engineers

This questionnaire is to collect data for purely academic purposes. The study seeks to determine the technical specification and the factors affecting the performance of solar street lights within some selected streets of Lusaka. All information will be treated with strict confidence. Do not write your name on this questionnaire

Answer all questions as indicated by either filling in the blank or ticking the option that applies.

PART 1: GENERATION SIDE.

1.1. What types of solar panels are installed?

Polycrystalline [ ] monocrystalline [ ] Amorphous [ ]

1.2. Besides the listed types above, are there other types of solar panels installed? Yes [ ] no [ ]

If yes to 1.2 Specify ……………………………..

1.3. What are the numbers of solar panels installed?

3 [ ] 2 [ ] 1 [ ] 4 [ ]

1.4. What are the sizes of the solar panel installed?

………………………………………………………………………..

………………………………………………………………………..

1.5. Is the orientation and the inclination of the solar panels installed across Lusaka the same?

Yes [ ] no [ ]

If yes, what is the orientation?

What is the inclination?

Else, what are the orientations, inclination and how many are shaded of the panels installed in Lusaka:

Street	Orientation	Shaded	Inclination
Great east road			
Lumumba			
Ring road			

1.6. What are the types of batteries installed?

Lead acid battery [ ] Lithium ion battery [ ] Nickel Cadmium (NiCd) [ ]

1.7. Aside from the above mentioned are there any other types of batteries installed?

Yes [ ] or no [ ]

If Yes to 1.7. Specify……………………………………

1.8. What is the required battery capacity for each street light?

1.9. What is the nominal voltage of the battery?

If: Lead acid……..../..…... Lithium ion battery………/……….

Nickel cadmium (NiCd) ………/……..... other………..

1.10. Is there one battery installed for each street light? Yes [ ] or No [ ]

If no to 1.10 what is the capacity of each battery and how are the batteries connected?

Series [..] Parallel [..] Series and parallel [ ]

Capacity…………………………………………………..

PART 2: CHARGE CONTROLLERS.

2.1 What are the types of charge controllers installed?

Pulse width modulation (PMW) [ ] Maximum power point tracking (MPPT) [ ]

Others: …………………………………..

2.2 What is/are the current rating of the charge controllers?

PMW……………….…..MPPT….………… others: ………………….

PART 3: INVERTERS

3.1 What type of inverters are installed?

Modified sine wave ☐ pure sine wave ☐ others: ………………

3.2 What is the power rating of the invertors?

MSW……………………. PSW……………….others:………….

3.3 What are the input and output dc voltage of the inverters installed?

Inverter	dc input voltage	dc output voltage
Modified sine wave		
Pure sine wave		

PART 4: LOAD SIDE

4.1. What type of lamps are used for solar street light?

Light emitting diodes (LEDs) [ ]   High pressure sodium vapor (HPS) [ ]

4.2. What are the types of light emitting diodes (LEDs) installed?

Organic LEDs [ ]   High Brightness LEDs [ ]   Traditional inorganic LEDs [ ]

4.3. How long do they operate

……………………………………………………………………………………………..

4.4. What is the wattage of the (LEDs) lamps used?

30W [ ] 50W [ ] 5W [ ] 60W [ ] 40W [ ] 70W [ ] 10W [ ] 20W [ ]

Others: ………………………………………………………………………………

4.3. What is their life span?

……………………………………………………………………………………………….

PART 5: SWITCHING SYSTEM

1.1. How do solar street lights switch on and off?

…………………………………………………………………………………………….

……………………………………………………………………………………………

1.2. What sensors are used for the solar street lights used in Lusaka?

………………………………………………………………………………………………
………………………………………………………………………………………………

1.3. At what time do they go on and off?

………………………………………………………………………………………………

1.4. Do they use any Motion sensing?

Yes [ ] or No [ ]

If yes to 5.4;

How is the motion sensor integrated into the switching system?

………………………………………………………………………………………………
………………………………………………………………………………………………
…………………………………………………………………….

Does the motion sensor work independent of the on off switching system or it can only work at night when the light is on?

………………………………………………………………………………………………
………………………………………………………………………………………………
……………………………………………………………………………….

PART 6: MAINTENANCE

6.1. How is the monitoring done?

Physical [ ] Digitalized [ ]

Others: ………………………………………………………………………………………..

6.2. How often are solar street lights maintained/checked?

Not often [ ]

Often [ ] very often [ ]

6.3. How is the maintenance done and who are the people in charge?

………………………………………………………………………………………………
………………………………………………………………………………………..

6.4. Are there some people in charge of the security?

………………………………………………………………………………………………
……………………………………………………………………………………….

PART 7: VANDALISM

7.1. To what extent has vandalism affected the performance of solar street lights in Lusaka?

Very low extent [ ] low extent [ ]

Moderate extent [ ] Great extent [ ]

Very great extent [ ]

7.2. What measure has the council put in place to avoid vandalism in Lusaka?

…………………………………………………………………………………………………
…………………………………………………………………………………………………
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…………………………………………………………………………………………………
…………………………………………………………………………………………………
….

End of Questionnaire

Appendix 2: Raw Data collection

Technical Specifications of Solar streets Lights in Lusaka

1. Solar panels' electrical and physical parameters

a) Monocrystalline solar panels

Solar panels Electrical Parameters		Physical parameters	
Maximum power (Pmax)	120 W	Solar cell material	Monocrystalline
Tolerance of Pmax	±3%	Cell arrangement	4*9 in series
Voltage at Pmax (Vmp)	18 V	Module net weight	8.4Kg
Current at Pmax (Imp)	6.67 A	Module dimension	670*1130*35 mm
Open circuit voltage (Voc)	21.6V		
Short circuit Current (Isc)	7.57A		
Maximum series fuse	15 A		
Maximum system voltage	700 V DC		

At STC F=1000W/m2, Am=1.5, Tc=25^{o}C

Solar panels Electrical Parameters		Physical parameters	
Maximum power (Pmax)	80 W	Solar cell material	Monocrystalline
Tolerance of Pmax	±3%	Cell arrangement	4*9 in series
Voltage at Pmax (Vmp)	18 V	Module net weight	5.4Kg
Current at Pmax (Imp)	4.44 A	Module dimension	670*770*30 mm
Open circuit voltage (Voc)	21.6V		
Short circuit Current (Isc)	5.04 A		
Maximum series fuse	15 A		
Maximum system voltage	700 V DC		

At STC F=1000W/m2, Am=1.5, Tc=25^{o}C

b) polycrystalline solar panels

Solar panels electrical parameters		Solar panel physical parameters	
Maximum power (Pmax)	330.0 W	Application class	A
Open circuit voltage (Voc)	46.70 V	Dimension	1960*990 mm
Short circuit current (Isc)	9.26 A	Material	Polycrystalline
Maximum power voltage (Vmp)	37.95 V	Module net weight	22.50 Kg
Maximum power current (Imp)	8.70 A		
Maximum system voltage	1500 V DC		
Maximum series fuse rating	15 A		

At STC F=1000W/m2, Am=1.5, Tc=25^{o}C

2. Battery types and their capacities

Lithium-ion battery	12.8V	40Ah	Other Energy Storage	
Lead acid battery	12V	120Ah	ultracapacitors	2.7 V 300,000F

3. Charge controllers

Types of charge controllers

Supercapacitor PV Street light controller

MPPT Step-Up Constant Current Solar Controller

8A MPPT Step-Up Constant Current Solar Controller

4. Research Instruments

Magnetometer
Inclinometer
Luxmeter
Multimeter

(a)

(b)

(c)

(d)

FIELDWORK MEASUREMENTS OF ORIENTATION, INCLINATION, SHADING, MORNING AND EVENING VOLTAGES AND CURRENTS

Parameters to analyse

1. *Orientation*
2. *Inclination*
3. *Voltage and current*

This research involves a mixed-method type

Key:ssl = solar street lights

Great North Road Lusaka

ssl	Orientation (º)		Inclination (º)	lux	Nominal voltages (Volts)			Currents (Amps)	
	NW	NE			Morning For 1 battery	Morning for 4 batteries	Evening voltages	Morning currents	Evening Currents
1		9	17.8	7	2.51	10.10	8.87	6.97	5.56
2		30	14.9	7	2.54	10.17	8.76	13.90	13.50
3	5		18.5	6	2.6	10.33	9.45	12.90	12.20
4	26		18.5	7	2.52	10.10	8.83	13.90	13.52
5		30	18.9	7	2.40	10.29	9.54	12.70	11.98
6		11	19.7	6	2.62	10.44	9.55	13.50	12.58
7	3		20.5	6	2.45	10.21	9.20	11.60	10.25
8		18	18.9	7	2.58	10.51	9.61	9.50	8.67
9		30	17.3	6	2.7	10.80	9.70	10.05	9.33
10		15	19.5	6	2.58	10.40	9.51	13.0	11.67
11		6	16.6	6	2.6	10.30	9.26	10.45	9.45
12	25		18.3	7	2.61	10.45	9.40	9.87	8.39
13	10		17.5	7	2.64	10.56	9.33	10.64	9.87
14		11	17.9	7	2.6	10.40	9.35	10.39	9.69
15		30	105.1	6	2.51	10.04	8.65	10.45	9.48
16	5		18.7	6	2.58	10.23	8.98	10.62	9.73
17		24	18.2	6	2.53	10.19	8.89	10.23	9.65
18		21	19.0	6	2.40	10.31	9.35	10.66	9.75
19		16	16.3	7	2.69	10.76	9.69	9.98	9.23
20	8		15.8	7	2.65	10.60	9.56	11.06	10.55
21		30	17.6	6	2.90	10.30	9.26	11.50	10.92
22	5		16.6	0	2.53	10.10	9.42	13.43	12.85
23	5		16.5	11	2.93	11.70	9.79	13.74	13.35
24		27	15.7	9	2.71	10.84	9.91	13.80	13.40
25		16	16.5	10	2.65	10.60	9.54	13.91	13.50
26	10		20.2	9	2.77	11.08	10.06	8.90	7.44
27	25		18.4	10	2.81	11.24	10.28	12.40	11.01
28		20	17.3	10	2.78	11.12	10.14	5.50	4.87
29		29	18.5	11	2.54	10.16	8.98	8.45	7.64
30		15	16.2	11	2.75	11.0	10.04	9.10	8.52
31	15		15.9	9	2.78	11.12	10.72	6.60	4.81
32		12	16.3	10	2.73	10.92	10.52	12.50	11.30
33		2N	15.5	9	2.56	10.24	9.64	9.30	8.10
34	3		16.6	7	2.70	10.80	10.30	11.95	10.45
35	9		18.3	7	2.81	11.24	10.54	12.10	10.81
36	11		17.5	6	2.81	11.24	10.56	11.10	10.24
37		20	17.9	7	2.79	11.16	10.76	11.50	10.30

38		15	15.1	7	2.75	11.0	10.50	12.20	10.96
39		22	18.7	6	2.83	11.32	10.72	13.13	12.90
40		36	15.1	6	2.84	11.36	10.96	13.24	11.98
41	12		15.9	7	2.69	10.76	10.16	9.38	8.56
42	15		15.6	6	2.87	11.48	11.08	12.80	12.20
43	9	5	16.4	6	2.88	11.52	11.02	7.80	7.10
44		37	19.2	6	2.75	11.01	10.61	9.98	8.37
45	30		18.5	7	2.56	10.25	9.85	8.99	8.46
46	10		20.5	9	2.61	10.44	9.94	9.56	9.10
47		33	19.5	10	2.59	10.36	9.76	8.07	7.78

Lumumba Road Lusaka

SSL	**Orientation (º)**		**Inclination (º)**	**Lux**	**Nominal voltages (Volts)**			**Currents (Amps)**	
	NW	**NE**			**Morning For 1 battery**	**morning For 3 batteries**	**evening For 3 batteries**	**Morning**	**Evening**
1		25	20.1	5	2.52	7.79	7.03	12.10	10.90
2		16	19.2	4	2.60	7.80	7.05	12.0	10.70
3		40	18.5	6	2.60	7.90	7.41	13.80	13.20
4	10		17.4	5	2.56	7.78	7.20	13.90	11.20
5	37		16.5	6	2.55	7.80	7.30	8.90	7.50
6	35		17.5	5	2.62	7.76	7.06	13.70	13.10
7		40	16.7	5	2.54	7.60	7.10	13.80	13.40
8		28	19.9	6	2.59	7.81	6.98	13.70	12.80
9		30	20.0	5	2.61	7.85	7.21	9.60	9.10
10	10		20.5	6	2.51	7.53	6.91	12.50	11.30
11	20		20.3	6	2.30	7.70	6.80	11.30	10.10
12		5	18.5	5	2.39	7.6	7.39	11.95	10.45
13		9	19.3	5	2.45	7.8	7.29	12.10	10.81
14		35	21.1	4	2.7	7.98	7.18	10.10	9.24
15		29	21.3	6	2.61	7.8	7.13	11.50	10.30
16		8	20.9	6	2.56	7.84	7.13	12.20	10.96
17		10	22.6	5	2.61	7.85	7.35	13.13	12.90
18		12	20.1	5	2.59	7.83	7.56	13.24	11.98
19	25		20.8	6	2.54	7.69	7.19	8.40	7.87
20	Sos dampside	30	21.9	5	2.48	7.77	7.35	12.80	12.20
21	25		21	4	2.4	7.70	6.98	12.80	12.10

22	30	shdd	20.9	5	2.3	7.10	6.64	12.90	12.20
23		11	21.6	6	2.36	7.20	6.77	13.10	11.56
24		30	20.5	5	2.3	7.2	6.93	11.90	10.50
25		2	20.8	4	2.29	7.39	7.13	12.90	12.20
26		1	21.8	4	2.45	7.30	7.14	9.58	8.82
27		5	19.6	5	2.49	7.40	7.08	12.70	11.98
28		6	20.9	5	2.49	7.30	7.10	13.50	12.58
29		4	21.4	4	2.30	7.30	7.10	11.60	10.25
30		5	21.3	5	2.40	7.60	7.26	9.50	8.67
31		4	21.5	5	2.50	7.60	7.52	14.0	13.33
32		10	22.5	6	2.56	7.70	7.56	13.0	11.67
33		23	22.1	5	2.30	7.60	7.26	10.45	9.45
34	30		21.3	5	2.40	7.30	7.19	9.87	8.39
35		25	22.5	5	2.40	7.40	7.29	10.64	9.87
36		5N	21.2	4	2.50	7.20	6.60	10.39	9.69
37		5N	18.9	4	2.40	7.20	7.19	10.45	9.48
38		9	18.4	4	2.45	7.35	7.15	10.62	9.73
39	11		17.5	0	2.40	7.20	7.19	10.23	9.65
40		4	18.5	6	2.40	7.20	7.20	10.66	9.75
41		5N	18.6	6	2.60	7.90	7.55	9.98	9.23
42	24		18.8	7	2.70	8.00	7.40	11.06	10.55
43	9		16.8	7	2.81	8.43	7.39	6.55	5.92
44		7	18.6	4	2.81	8.43	8.21	13.43	12.85
45		26	20.6	7	2.79	8.36	8.10	9.74	9.35
46	13		17.7	7	2.75	8.24	8.01	13.80	13.40
47	10		16.8	6	2.83	8.41	8.25	13.91	13.50
48	10		17.7	6	2.84	8.50	7.58	12.96	11.85
49		3N	16.5	7	2.69	8.60	7.69	5.78	6.95
50		10	17.2	6	2.87	8.61	7.70	9.85	8.58
51	13		17.6	6	2.88	8.61	7.70	9.32	8.59
52		8	15.1	6	2.75	8.23	7.55	10.98	9.37
53	30		15.2	7	2.66	7.98	7.68	8.99	8.46
54		5	15.1	7	2.75	8.25	7.75	9.56	9.10
55		16	16.6	7	2.30	7.50	7.34	8.07	7.78
56	11		17.7	6	2.40	7.30	7.13	8.91	8.35
57	16		18.4	5	2.80	8.40	7.65	9.12	8.43
58	5		16.2	0	2.31	7.50	7.45	9.57	8.98
59	10		15.8	5	2.34	7.02	6.86	8.58	8.39
60	11		16.9	4	2.70	8.11	7.45	9.23	8.75
61	10		16.4	4	2.46	7.33	7.13	7.21	6.78
62		30	16.5	7	2.74	8.23	7.28	9.85	8.98
63		24	17.1	5	2.62	7.88	7.56	9.73	9.59
64	11		15.2	5	2.40	7.40	6.93	7.55	9.41
65		15	16.1	6	2.78	8.34	7.36	8.99	8.65
66		10	17.0	6	2.85	8.56	7.86	10.01	8.98
67		15	16.6	5	2.91	8.74	7.98	10.34	9.88
68		5	16.5	6	2.56	7.56	7.32	8.87	8.27
69	6		17.0	4	2.50	7.59	7.36	9.61	9.06

70		16	16.1	7	2.68	8.06	7.56	9.44	9.20
71	9		15.9	7	2.65	8.00	7.45	8.84	8.15
72		40	20.1	5	2.53	7.80	7.04	12.2	10.9
73		16	19.5	4	2.57	7.87	7.23	13.2	11.3
74		40	18.5	6	2.60	7.90	7.41	5.80	4.29
75	10		17.5	5	2.58	6.61	6.60	0.00	0.00
76		30	17.4	6	2.56	7.78	7.20	13.9	13.2
77		37	16.5	6	2.55	7.80	7.30	6.90	5.50
78		28	19.9	5	2.61	7.81	6.98	8.70	7.15
79	10		20.3	5	2.30	7.70	6.80	11.3	10.10
80		5	19.5	5	2.39	7.60	7.05	11.9	11.15
81		35	21.0	6	3.10	7.89	7.42	11.1	10.80
82		8	20.9	5	2.56	7.84	7.35	7.99	7.54

Mosi-O-Tunya Road Lusaka

Ssl	**Orientation (º)**		**Lux**	**Nominal voltages (Volts)**				**Currents (Amps)**
	WN	**EN**		**morning**	**morning**	**evening**	**evening**	**Morning**
1		15	12	12.98	12.98	12.3	12.30	3.16
2	20		16	13.2	13.1	12.2	12.20	3.40
3		50	19	12.9	13.0	12.1	12.20	2.75
4	48		17	13.0	13.0	12.32	12.24	2.85
5	35		12	13.0	13.0	12.0	12.0	3.85
6	12		12	13.0	13.0	12.0	12.0	3.98
7		53	15	13.38	13.46	12.25	12.27	4.94
8		25	15	12.90	13.0	12.19	12.22	4.72
9	24		17	13.0	13.0	12.28	12.22	5.12
10	23		16	13.0	13.0	12.15	12.13	5.20
11	23		16	13.75	13.82	12.37	12.26	5.21
12	39		17	13.47	13.53	12.43	12.38	4.56
13	39		16	14.2	14.3	12.32	12.28	4.71

14		8	12	12.10	3.59	12.09	3.60	0.02
15		25	13	12.5	12.5	12.23	12.19	4.87
16		30	14	13.71	13.72	12.76	12.86	5.02
17	28		19	13.11	13.10	12.22	12.30	3.25
18	27		19	13.14	13.18	12.40	12.40	4.23
19		5	18	2.0	0.0	2.0	0.0	0.0
20		1N	17	13.04	13.04	12.83	12.82	4.57
21		8N	18	13.26	13.36	13.01	12.98	3.04
22	15		17	13.36	13.41	13.10	13.20	5.0
23	15		15	13.31	13.26	12.45	12.56	4.17
24	46		17	12.95	12.94	12.87	12.86	6.07
25	43		16	12.94	12.97	12.45	12.48	4.85
26	28		16	13.10	13.05	12.87	12.85	5.95
27		2	17	13.06	13.20	12.65	12.65	6.14
28		5	16	12.01	12.10	11.89	11.87	6.25
29		18	16	13.60	13.50	13 20	13.22	6.19
30		15	18	13.62	13.56	12.76	12.86	6.39
31	25		18	14.31	14.27	13.43	13.36	6.72
32	20		19	14.98	14.95	13.75	13.68	6.98
33		2	18	13.26	13.17	13.0	12.98	4.14
34		8N	17	13.10	13.20	12.12	12.22	4.13
35		5	17	13.01	12.97	12.30	12.20	4.68
36	20		16	13.45	13.43	13.17	13.26	4.75
37	50SE		17	12.64	12.66	12.24	12.32	5.23
38		25	19	13.65	13.63	12.26	12.28	6.23
39	48SE		0	13.02	13.01	11.89	13.01	1.03
40	20		0	13.10	13.11	13.10	12.56	1.43
41	12		16	12.45	12.40	12.20	12.21	5.31
42	53SE		17	11.68	12.45	12.22	12.25	2.56
43	35		17	12.31	12.34	12.10	12.20	3.75
44	24		0	12.10	7.45	12.10	12.10	0.67
45	23		17	12.87	12.60	12.20	12.22	7.45
46		39	17	12.50	12.40	12.40	12.30	6.05
47		38	17	12.54	12.51	12.45	12.50	6.76
48	40SE		0	12.0	12.0	12.0	12.0	0.0
49	28		0	12.0	12.0	12.0	12.0	0.0
50	27		0	12.35	11.87	12.3	12.3	1.45
51	55SE		17	11.78	11.74	12.2	12.2	2.67
52	20		16	11.89	11.80	12.30	12.20	3.77
53	51SE		16	12.67	12.66	12.39	12.32	3.99
54	24		16	12.65	12.67	12.50	12.40	4.56
55		11	0	8.50	12.70	8.50	12.70	0.56
56		5	17	14.10	14.10	13.87	13.86	5.35
57	31		16	13.5	13.6	13.15	13.14	6.23
58	36		17	12.65	12.63	12.40	12.41	7.51
59		12	17	12.45	12.43	12.10	12.11	7.02
60		15	17	13.0	13.0	12.32	12.24	2.85
61		10	16	13.0	13.0	12.0	12.0	3.85

62	23		15	13.0	13.0	12.0	12.0	3.98
63	32		16	13.38	13.46	12.25	12.27	4.94
64		38	17	12.90	13.0	12.19	12.22	4.72
65		36	16	13.0	13.0	12.28	12.22	5.12
66		5	16	13.0	13.0	12.15	12.13	5.20
67	9		16	13.75	13.82	12.37	12.26	5.21
68		11	17	13.47	13.53	12.43	12.38	4.56
69		14	17	14.2	14.3	13.32	13.28	4.71
70		5	13	11.98	12.00	11.75	11.74	5.16
71		47	15	13.6	13.5	12.2	12.20	4.40
72	8		17	13.02	13.02	12.1	12.20	6.75
73		50SE	16	13.0	13.0	12.32	12.24	2.85
74	41		17	13.0	13.0	12.56	12.56	6.85
75		26	16	13.0	13.0	12.0	12.0	7.98
76		35	16	13.23	13.25	12.65	12.65	3.94
77	29		16	12.90	13.0	12.90	12.91	2.72
78	40		17	13.05	13.06	12.38	12.32	3.12
79		40	16	13.10	13.11	12.15	12.13	4.20
80		47SE	16	13.75	13.82	12.37	12.26	5.56
81		20	17	13.47	13.53	12.43	12.38	4.56
82	10		17	14.27	14.23	13.42	13.48	7.71
83	40SE		0	10.25	3.59	10.25	3.60	0.02
84		25SE	17	12.53	12.52	12.23	12.19	4.57
85		16	18	13.51	13.52	12.69	12.68	8.02
86	10		17	13.15	13.15	12.24	12.25	4.25
87	31		17	12.5	12.51	12.05	12.04	3.23
88		12	17	13.08	13.09	12.81	12.80	3.65
89		15S	0	3. 0	0.0	3.0	0.0	00
90		39	19	13.16	13.16	12.81	12.83	8.04
91	15		17	13.56	13.51	13.08	13.09	8.0
92	18		15	13.31	13.26	12.45	12.56	2.17
93	30SE		17	12.85	12.84	12.85	12.84	5.07
94		25	16	13.26	13.21	12.90	12.90	8.10
95	10		16	13.31	13.26	12.45	12.56	5.17
96	40		18	13.95	13.94	12.67	12.68	8.07

All-in-one solar panels in Ring Road

Specifications

Panel voltage = 21.6

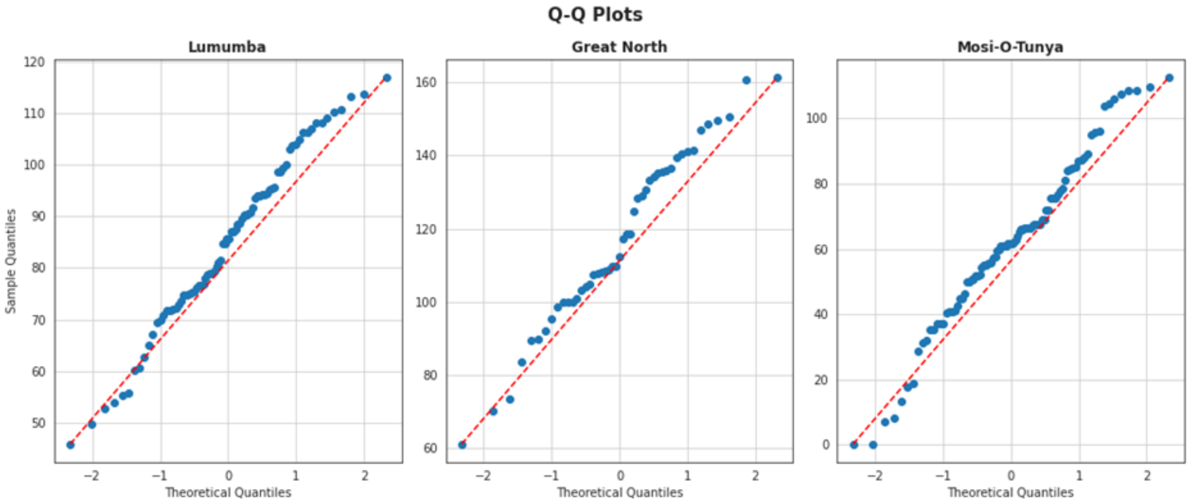
Panel current = 3.45

Ring Road Lusaka

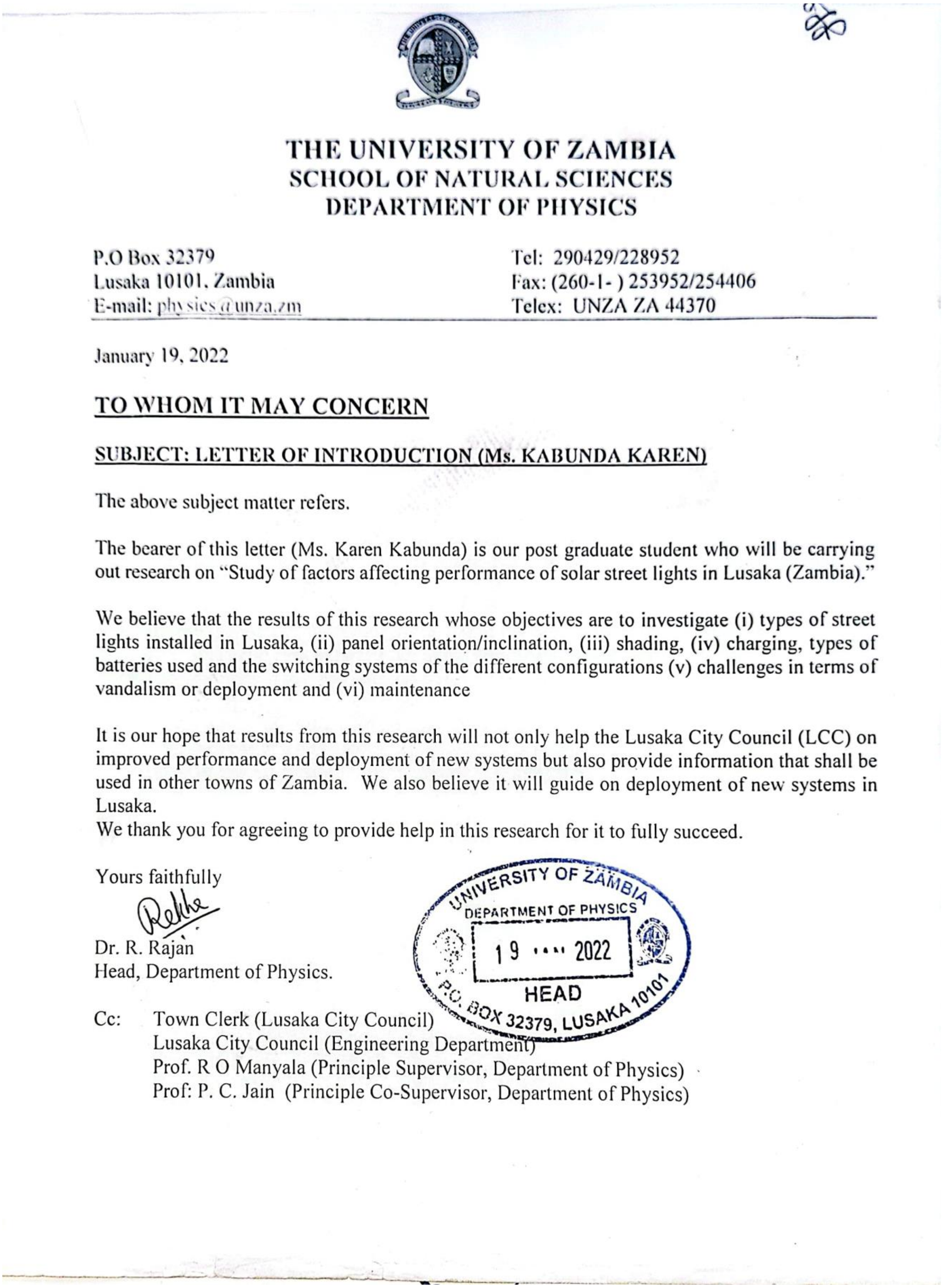
Ssl	**Orientation (º)**			**Inclination (º)**	**Lux**
	NW	NE	N		
1			4	9.5	5
2	51			9.6	4
3	24			7.5	4
4		11		7.6	5
5			13	7.8	5
6	31			8.7	5
7	36			9.6	2dim
8		12		6.8	6
9		15		7.7	5
10			2	8.7	5
11	23			8.7	5
12	32			8.1	4
13		38		8.3	5
14		36		8.9	7
15			1	10.7	7
16	9			11.6	5
17	11			10.4	6
18	14			10.1	5
19		5		9.2	7
20		47		9.5	7
21	8			10.5	4
22	not	Battery burst		working	0
23			1	9.5	5
24	41			10.2	5
25		26		9.7	5
26		35		10.3	5
27	29			10.4	6
28	40			12.2	5
29		40		8.7	5
30		47		8.9	7
31		20		10.5	6
32	not	Battery burst		Working	0
33	10			9.5	5
34	16			10.7	5
35		25		9.8	5
36			4	9.3	6
37	10			8.5	6
38	31			8.8	5
39		12		9.7	4
40		15		7.8	5
41		39		9.3	5
42	not	Battery burst		Working	6

43	15			11.6	6
44	18			9.6	6
45		30		7.8	4
46		25		9.7	4
47	10			10.3	5
48	40			6.9	5
49	not	working	2	11.5	0
50		12		9.4	6

Appendix 3: Q-Q plots to Test for Normalisation the Data Set



Appendix 4: Introduction Letter to LCC Electrical Engineering Department



THE UNIVERSITY OF ZAMBIA
SCHOOL OF NATURAL SCIENCES
DEPARTMENT OF PHYSICS

P.O Box 32379
Lusaka 10101, Zambia
E-mail: physics@unza.zm

Tel: 290429/228952
Fax: (260-1-) 253952/254406
Telex: UNZA ZA 44370

January 19, 2022

TO WHOM IT MAY CONCERN

SUBJECT: LETTER OF INTRODUCTION (Ms. KABUNDA KAREN)

The above subject matter refers.

The bearer of this letter (Ms. Karen Kabunda) is our post graduate student who will be carrying out research on "Study of factors affecting performance of solar street lights in Lusaka (Zambia)."

We believe that the results of this research whose objectives are to investigate (i) types of street lights installed in Lusaka, (ii) panel orientation/inclination, (iii) shading, (iv) charging, types of batteries used and the switching systems of the different configurations (v) challenges in terms of vandalism or deployment and (vi) maintenance

It is our hope that results from this research will not only help the Lusaka City Council (LCC) on improved performance and deployment of new systems but also provide information that shall be used in other towns of Zambia. We also believe it will guide on deployment of new systems in Lusaka.
We thank you for agreeing to provide help in this research for it to fully succeed.

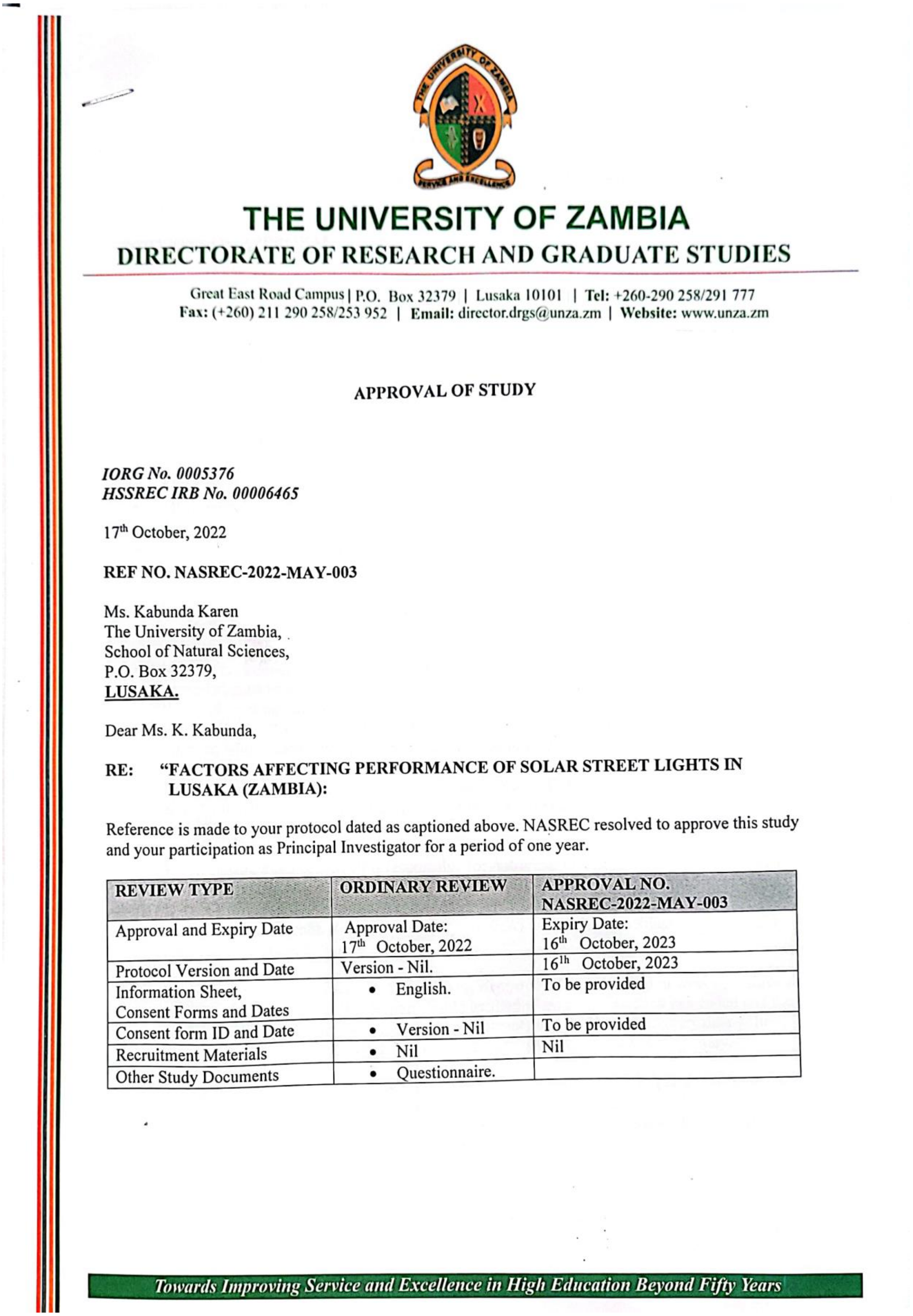
Yours faithfully

Dr. R. Rajan
Head, Department of Physics.

UNIVERSITY OF ZAMBIA
DEPARTMENT OF PHYSICS
19 •••• 2022
HEAD
P.O. BOX 32379, LUSAKA 10101

Cc: Town Clerk (Lusaka City Council)
Lusaka City Council (Engineering Department)
Prof. R O Manyala (Principle Supervisor, Department of Physics)
Prof: P. C. Jain (Principle Co-Supervisor, Department of Physics)

Appendix 5: Approval of Study for Ethical Clearance



THE UNIVERSITY OF ZAMBIA
DIRECTORATE OF RESEARCH AND GRADUATE STUDIES
Great East Road Campus | P.O. Box 32379 | Lusaka 10101 | **Tel:** +260-290 258/291 777
Fax: (+260) 211 290 258/253 952 | **Email:** director.drgs@unza.zm | **Website:** www.unza.zm

APPROVAL OF STUDY

IORG No. 0005376
HSSREC IRB No. 00006465

17th October, 2022

REF NO. NASREC-2022-MAY-003

Ms. Kabunda Karen
The University of Zambia,
School of Natural Sciences,
P.O. Box 32379,
LUSAKA.

Dear Ms. K. Kabunda,

RE: "FACTORS AFFECTING PERFORMANCE OF SOLAR STREET LIGHTS IN LUSAKA (ZAMBIA):

Reference is made to your protocol dated as captioned above. NASREC resolved to approve this study and your participation as Principal Investigator for a period of one year.

REVIEW TYPE	**ORDINARY REVIEW**	**APPROVAL NO.** **NASREC-2022-MAY-003**
Approval and Expiry Date	Approval Date: 17th October, 2022	Expiry Date: 16th October, 2023
Protocol Version and Date	Version - Nil.	16lh October, 2023
Information Sheet, Consent Forms and Dates	• English.	To be provided
Consent form ID and Date	• Version - Nil	To be provided
Recruitment Materials	• Nil	Nil
Other Study Documents	• Questionnaire.	

Towards Improving Service and Excellence in High Education Beyond Fifty Years