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ARTICLE

Evaluation of Factors Influencing the Operational Performance of Solar-Powered Street Lighting in Selected Areas

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ABSTRACT

Significant investments have been made in solar street lighting due to its cost-effectiveness compared to grid electricity. Some factors affect the performance of solar street lights. The research investigated battery types, switching systems, shading, inclination, and orientation effects on sampled solar street lights. Systematic sampling and selection of street lights were based on the Yamane Taro formula. Data was collected through fieldwork measurements and observations in addition to the use of questionnaires. The Statistical Package for Social Science (SPSS) and Python were used to analyze the data. Results showed that switching mechanisms, charging systems, and battery type significantly influenced the performance of the studied solar street lights. Lithium-ion (Li-ion) and ultra-capacitors (UCs) outperformed lead-acid batteries, keeping the lights on longer by up to 3 hours compared to flooded lead-acid batteries. Some charge controller components, such as regulating capacitors, were faulty and affected the lithium-ion batteries and ultra-capacitors. The failures caused the batteries to overcharge, resulting in swelling and bursting. The majority of the solar street lights were found to be 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 an average power output of 84 W.

Keywords: Solar Street Lights; Factors Affecting; Performance; Case Study; Lusaka

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1. Introduction

1.1. 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, others have embraced renewable energy sources and nuclear energy [1]. Solar energy, which is an abundant resource has captured the attention of researchers worldwide. The growing interest in adopting solar energy has led to an impetus in research efforts towards other renewable energy sources. Studies are aimed not only in providing better understanding of the potential of solar power but also at highlighting 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 resource potentials [1,3,4]. However, in most developing countries like Zambia, the availability of solar energy resource information is limited due to lack of widespread metrological stations for collecting weather data across the country [1]. The lack of data not only limits research opportunities but also poses substantial lack of understanding of solar energy capabilities in Zambia. Zambian is abundantly endowed with diverse resources and the potential of solar energy stands out as a promising alternative for energy production. Zambia receives about 2100 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) [5].

Several of energy technologies have been developed to take advantage of solar energy. These technologies include passive solar heating and daylighting, photovoltaic systems, solar hot water, solar air conditioning systems and refrigeration. Solar energy can be used in large-scale applications as well as in small-scale systems such as homes, traffic lights, and street lighting, water pumping for agriculture or home use, food drying, and many others.

Well-lit streets bring confidence to residents in cities and towns, enhancing security, which 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 at night emerges as a critical factor in mitigating accident risks, particularly for pedestrians who rely heavily on walking as their primary mode of transportation. Insufficient funds for public services such as paying for the use of hydroelectricity to power street lights has resulted in many challenges, such as rising crime rates, underscoring the urgent need for urban interventions [7]. Therefore, investing in solar street lighting can reduce costs spent on grid electricity bills. It can also improve 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 which is allowed elsewhere but illegal in Zambia. Poor lighting conditions limit their trading activities to daylight hours, imposing constraints on their income potential [10].

Beyond immediate gains, there are substantial reciprocating benefits for social cohesion and community empowerment by adopting solar street lights. 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 the way for joint financing initiatives and also improve revenue collection from taxpayers [11].

Environmental and system factors are important to consider when planning for the installation of solar street lights. These factors include temperature, energy conversion efficiency, shading, orientation, and inclination of the solar panel, to mention a few. Zambia is in the southern hemisphere, so it is important to ensure that panels are 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 panels. This will ensure maximum exposure of the panel to solar radiation. The street lighting systems should not be exposed to excessive temperature, otherwise their efficiency will reduce hence perform poorly. 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.

By examining the determinants of their performance, this study aimed to find out potential challenges, propose recommendations, and contribute to the advancement of effective street lighting in Zambia.

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

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 residence. In Lusaka, a significant step has been made with the deployment and installation of approximately 4000 solar street lights since 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 aimed to find out potential challenges, propose recommendations, and contribute to the advancement of effective street lighting in Zambia.

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

1.2. Limitations of the Study

The study was confined to looking at performance of solar street light in some selected streets of Lusaka. The study was carried out only on four major roads (streets) with installed lights due to time constraints. Other factors such as dust, age of panels, wiring losses, or ambient weather were not considered due to time and financial constraints. However, it is known that these factors affect photovoltaic systems to a certain extent. These are good topics for future research. Secondly, the focus on four roads was because the machinery used for the measurements of the orientations and inclinations was also being used by the Lusaka City Council engineers. New rules implemented by the police to protect the solar street lights from vandalism were already in effect. The rules restricted the study from being carried out at night, when it was necessary to take some measurements like voltage and current. The researchers were given access to solar street lights that operated on flooded lead-acid batteries on a single road to ensure the components' safety, as several had sealed battery boxes. Only two solar street lights installed at Lusaka City Council yard, along Ring road, were made available for the study due to their unique design which included battery, LED fitting, charge controller, and solar panels mounted in a single sealed fitting. As a result, dismantling the lights in the field was not allowed to avoid damage to the systems. However, orientations and inclinations were measured during the day.

1.3. Solar Panel Orientation, Inclination, and Shading Effects

The efficiency of a solar power system is determined by two pivotal factors, namely, orientation and location. To achieve maximum power output, it is crucial to ensure that solar panels are oriented optimally. 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 during installation to expose the panels to maximum radiation for long periods [12]. In the southern hemisphere, solar panels should be oriented north, otherwise south for northern hemisphere installations. 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 proven to considerably enhance energy production. However, it should be noted that in Zambia, solar street light systems have fixed panel orientation. Solar tracking systems are not used for solar street lights by the Lusaka 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 Lusaka.

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. The fine-tuning enables solar panels to generate more electricity during peak hours of demand by aligning energy production more effectively with consumption patterns [13].

1.4. The Angle of Tilt/Inclination

The angle of tilt or inclination of a solar panel also plays important 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. Studies have reported that the tilt or inclination of solar panels is relative to the location, period, and duration. Gevorkian advocates a general guideline where the optimal tilt angle aligns with the geographical latitude, ensuring an efficient annual energy output [14]. Dave emphasizes that solar panels located closer to the equator benefit from a more vertical inclination to either the north or south [12], while those nearer the poles should tilt towards the equator for increased efficiency.

1.5. 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 reduction for the overall power output of the system. In a study conducted in Germany on improving photovoltaic power output, Strache et al. revealed that shading has the potential to compromise a PV system's output by up to 20% [15]. Kumari et al. further highlighted that even if just one cell is shaded, it can compromise the power output of the entire set of interconnected cells [16]. 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.

2. Components of a Solar Street Light

Frering et al. 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 [5]. In a study on solar street lighting systems, Liu identified key components to include solar cell panels, LED lights, lamp posts, charge controllers and batteries [17].

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) which plays a crucial role in monitoring the charging and discharging of the battery by checking the status of each cell individually [18]. It employs a transistor switch and a properly sized discharge resistor placed 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.

Advantages and Disadvantages of Solar Street Lights

As highlighted by Ambhore et al*.,* solar street lights offer several notable advantages [19]. Firstly, solar energy, being sourced from the Sun, is a sustainable power supply. The sunshine available during the day, most of the year can lead to substantial reductions in electricity bills for street lighting. 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 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. Because, they do not have grid connection, they have operational 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 due to grid power interruptions.

While solar-powered street lights offer remarkable benefits, it is crucial to acknowledge certain drawbacks such as poor operation and performance 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 drawback is the heightened risk of theft, attributed to the comparatively higher equipment costs associated with solar street lights [20]. Putting security measures in place becomes imperative to mitigate theft risk.

The dependency on direct sunlight underscores a limitation of solar street lights as it is essential to guarantee unobstructed access to sunlight, ensuring that the solar panels are not shaded by shadows or obstructed by taller structures.

3. Research Methodology and Materials

3.1. Research Approach

A mixed-method approach to comprehensively investigate some factors influencing the performance of solar street lights within selected streets of Lusaka was employed in the study. Teddlie et al*.* define 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, analysis procedures, and inferences [21]. 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. It was therefore necessary to adopt the mixed-method approach for the study.

The qualitative aspect of the study used a descriptive approach, focusing on meaning and understanding. It involved collecting information from electrical engineers at the Lusaka City Council. The process focused on gathering information on their opinions regarding the technical specifications and models of the installed solar street lights. Conversely, the quantitative approach was applied to the technical part of the research, facilitating the quantification of the problem. This involved generating numerical data to derive usable statistics that could contribute to a more comprehensive analysis of the factors affecting the performance of solar street lights. The mixed-method strategy was aimed at providing a complete and detailed understanding of the research topic.

3.2. Research Design

The research employed non-experimental research design which is used to conduct quantitative research in which no manipulation is done to any variable in the study. In this design, variables are measured as they occur naturally, without interference of any kind by the researcher. Mertler points out that manipulation may exist because the variables may be naturally "manipulated" before the study was undertaken [22]. It is also possible that the researcher can manipulate a particular variable. Out of the types of non-experimental research design, the study used both descriptive and observational study designs. Kerlinger 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 [23].

3.3. Study Location

Lusaka is a district situated in the Lusaka province of Zambia. It is located in the south-central region at a latitude of −15.4°S and longitude of 28.3°E. Lusaka district shares boundaries with other districts, namely Chongwe in the East, Chibombo and Chisamba in the North, and Chilanga in the South.

Lusaka City Council (LCC) currently spends over K150,000 monthly on paying electricity bills to Zambia Electricity Supply Cooperation (ZESCO) for 17,000 conventional street lights. The Council (LCC) seeks a transition to solar-powered alternatives for cost-effectiveness. The council has deployed over 4,000 solar street lights in some selected streets/roads in Lusaka and has a plan to deploy more within the coming years. Not only does the transformative project underscore the commitment of LCC to innovation but it also sets a precedent for embracing renewable energy solutions. Proper guidelines and accurate information are therefore necessary for the expansion, and that is where the study comes in. **Figure 2** 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 2** shows study area and its location.

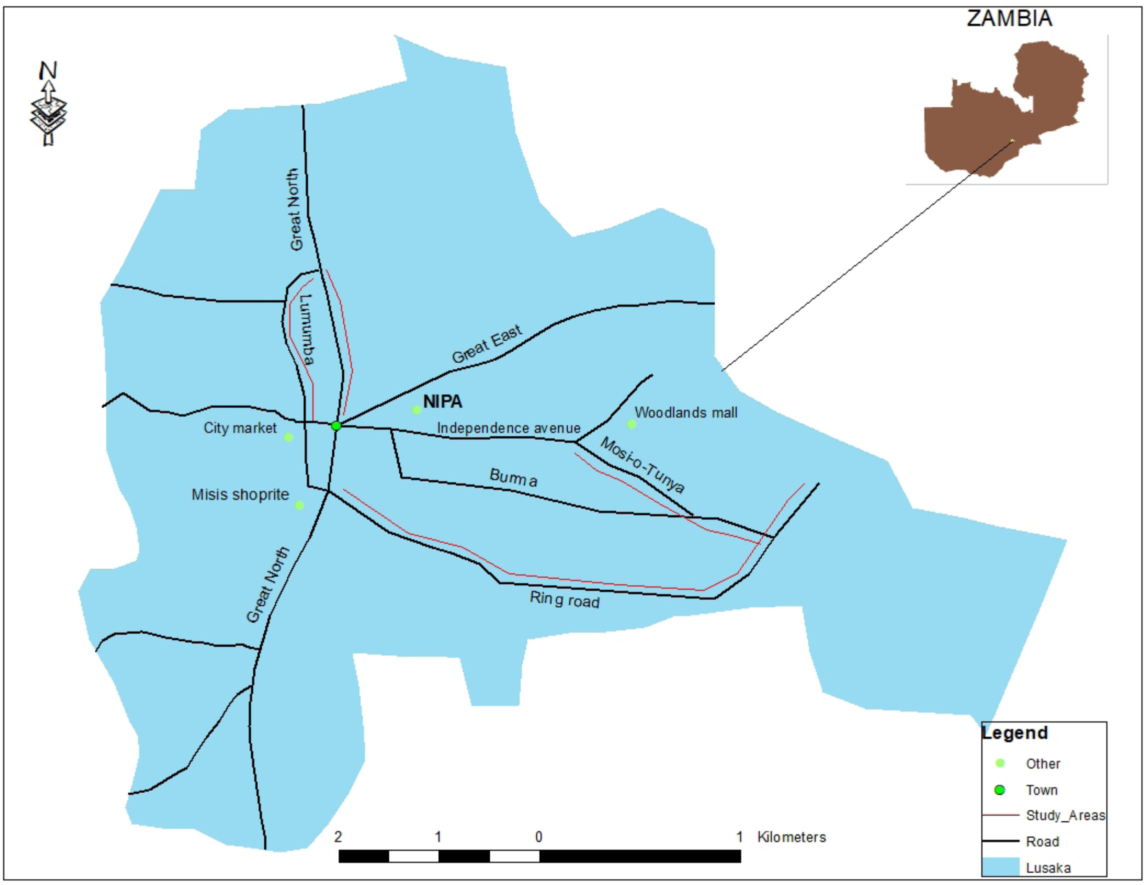

Figure 2. Location of the Study Area.

3.4. Sample Population Size and Sampling Technique

Out of a population of 4,000 installed street solar lights, a sample size of 321 solar street lights was arrived at using the Yamane Taro formula [24].

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

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

Employing a 90% confidence limit for each road under study, specific sample sizes were calculated for the selected streets/roads. A systematic sampling technique was then employed for each solar street light under observation. The systematic sampling technique was necessitated by the fact that different streets had street lights of non-identical capacities. Lauren 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 [25]. For example, if the population order is random or random-like (such as in alphabetical order), then this method will give a representative sample that can be used to conclude population of interest.

Originally, we intended to use the standard significance level of 0.05, but trying it returned fairly big sample sizes for the study. For example, using 0.05 for n_1 returned a value of 232 solar street lights. Since the study had both financial restrictions, 0.01 was a more appropriate choice.

Lumumba road 80 W solar panels

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

$$n = \frac{464}{1+464(0.01)} \quad (3)$$

$$n_1 = 93 \text{ solar street lights} \quad (4)$$

The sample size was then obtained by using

$$n = \sum_i^4 n_i \quad (5)$$

Use of equation (5) resulted in a sample size of 321 street lights studied, where n_1 is for Lumumba road (80 W solar panels), n_2 is for Great North road (120 W solar panels), n_3 is for Ring road (100 W solar panels) and n_4 is for Mosi O. Tunya road (330 W solar panels). The calculations were done by ignoring fractions in the denominator and rounding the values upwards if the decimal point was greater than 0.5.

3.5. Data Collection Method

During the data collection process, various research instruments were utilized for each required data set. The instruments included a magnetometer, digital multimeter, and an inclinometer (**Figure A1a–c**) presented in the appendix. First, a semi-structured questionnaire was administered to the electrical engineering department of LCC. The questionnaire method was chosen for its ease in obtaining responses 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 used for energy storage in the solar street light systems, 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 from the batteries and tabulated to assess their impact on performance. An inclinometer was used to measure the inclination or tilt angle of solar panels, while a magnetometer was used to measure the orientation of the solar panels.

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 super capacitors, exhibiting significant versatility across various applications and offering flexibility in terms of capacity. In a comprehensive study by Townsend et al., three types of Energy Storage Devices (ESD) were scrutinized: lead-acid batteries (LA), lithium-ion batteries (Li), and ultra-capacitors (UC) [26]. A comparative analysis of these energy storage device technologies, particularly focusing on their degradation over time is presented in **Table 1** [26]. Raw data for other parameters are provided in the appendix (**Tables A1–A4**).

Table 1. Lead Acid, Lithium-Ion, and Ultra-Capacitor Comparison.

	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

Note: **, *Adapted from the work by Townsend et al. [26].

4. Data Analysis

Ibrahim defines data analysis as the systematic process of performing specific computations and assessments to draw out pertinent information from data [27]. Since it is a process, several steps may be involved before certain conclusions and suggestions are reached. In this work, most of the data was analysed qualitatively. Before data analysis took place, the data had to be edited ("cleaned") to identify and correct any irregularities. Since the solar street lights were already erected at fixed inclinations at Lusaka's latitude the, angles could not be adjusted, nothing was done to correct the abnormalities in their inclination that were discovered. Secondly, further irregularities were subsequently detected in the voltage and current readings of solar street lights situated along some streets, 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 Statistical Package for Social Sciences (SPSS).

5. Results and Discussion

5.1. Technical Specifications and Models of the Components of the Solar Street Lights

5.1.1. Types of Solar Panels Installed

Lusaka's solar street lighting infrastructure incorporates two distinct types of solar panels classified as monocrystalline silicon and polycrystalline silicon. The data collected revealed that 197 street lights installed used monocrystalline solar panels which constituted the majority at 65.09% of all solar panels studied. In contrast, polycrystalline solar panels, amounting to 96 made up the remaining 34.91% of the sample in the study.

5.1.2. The Orientation on Performance of Solar Panels

Data was collected from 275 solar street lights for; Great North road, Ringroad, Mosi-O-Tunya road, and Lumumba road. However, due to insufficient information on voltage and current measurements for the street lights on Ring road, information for 50 was filtered out bringing the number to 225 for analysis. **Figures 3–5** display the data analysis results.

The data obtained for these roads included the orientation, inclination, morning and evening voltages, and currents. Shading details were not captured since most of the solar street lights studied were strategically installed without any building or tree covering on the roads used for the study.

The box plots in **Figure 3** illustrate the distribution of solar street lights' orientation and its effect on performance in different directions. The analysis focused on the three roads namely, Lumumba road, Great North road, and Mosi-O-Tunya road. Ring road was not part of the analysis because of limited data 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 used for the plot was calculated using the measured voltages and the currents through

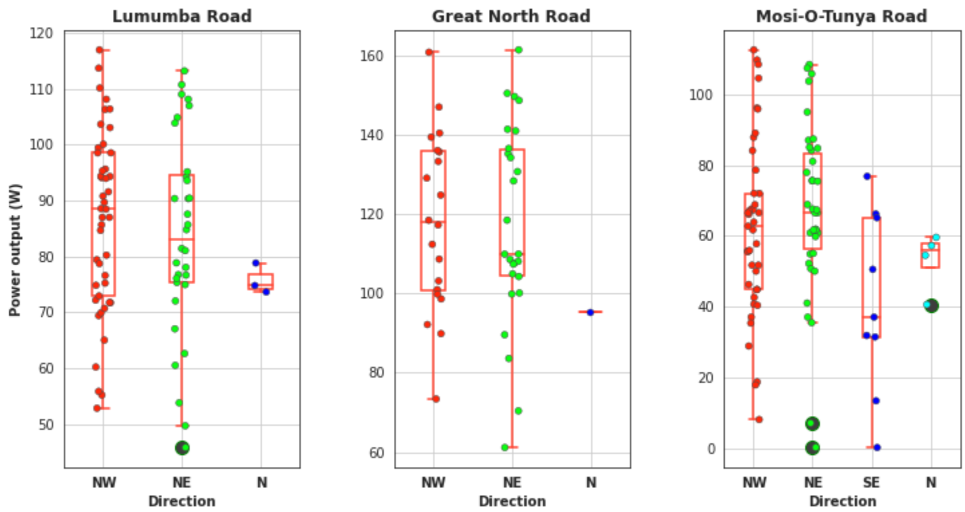

Figure 3. Box Plot of the Power Output Against the Orientation for Three Roads.

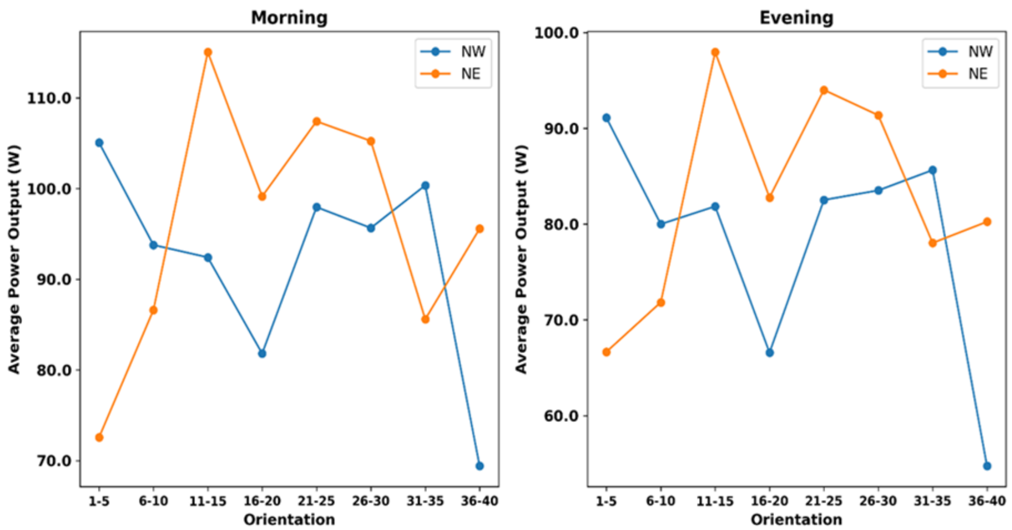

Figure 4. Average Power Output Against the Angle of Orientation.

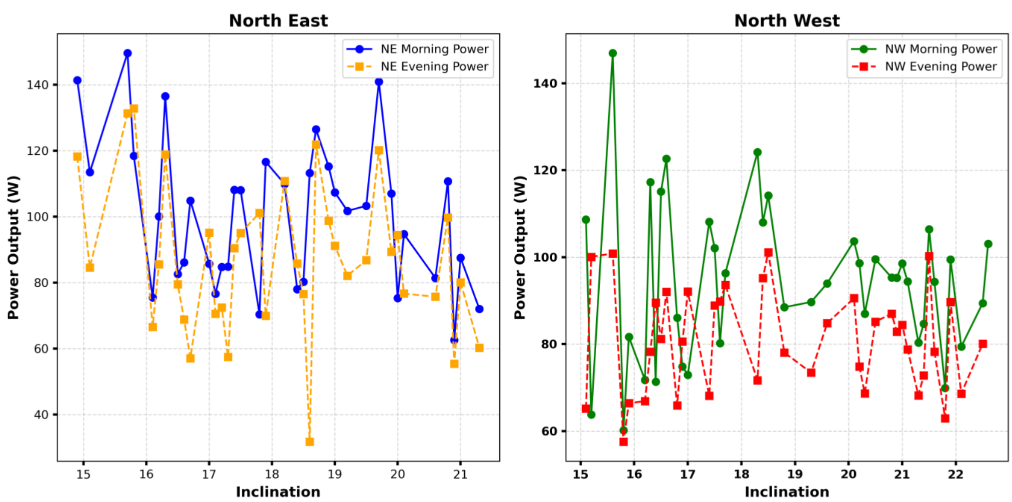

Figure 5. Effects of Inclination/Tilt Angle on the Power Output.

$$P = V \times I \tag{6}$$

where P is the electrical power, I is the current, and V is the voltage.

The study found that the majority of solar street lights studied are orientated in the northeast, with some facing northwest direction on Lumumba road, Great North road and Mosi-O-Tunyaroad. A limited number panels of solar street lights were oriented towards the north (N) 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 89W, while those oriented in the northeast showed an average power output of 84W. These findings suggest that solar panels facing northwest generally outperformed those facing northeast.

The results highlight the significance of orientation in influencing the performance of solar street lights in Lusaka. A one-way Analysis of Variance (ANOVA) test was performed for each direction on the three roads to assess the significant difference in power outputs. The F-statistics (F-value), a statistical measure to test the null hypothesis (H0) and the associated P-value indicating the level of significance in the F-statistic test, were employed. Panels on Lumumba Road showed an F-statistic of 0.661 with a P-value of 0.519, and those on Great North Road showed an F-statistic of 0.426 with an associated P-value of 0.656. Both roads exhibited high p-values, suggesting no significant difference was observed in power output, based on the orientations found within the two streets.

Solar panels along Mosi-O-Tunya road on the other hand exhibited a different trend 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. In the northeast, the median was 68W compared to 64W for the northwest orientation. Interestingly, some solar panels on Mosi-O-Tunya road were oriented southeast, yielding an average power of 38W, indicating poor performance compared to the other panels. In contrast to the other two roads, Mosi-O-Tunya road had a distinct scenario where solar panels oriented in the northeast direction performed better than those oriented in the northwest direction. Panels oriented in the southeast direction yielded lower power output, demonstrating a significant difference in power production. However, in Mosi-O-Tunya road, the one-way ANOVA test returned an F-statistics of 2.851 and an associated P-value of 0.042. Since the P-value 0.042 is less than the level of significance 0.05, the hypothesis that orientation affects power production was confirmed. A shift towards the southwest or the northwest results in a minor decrease in energy output and turning towards the west leads to a moderate drop in energy output. On the other hand, 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 4** represents the average power output in the morning and evening as a function of the angle of orientation of solar panels of the street lights studied.

Angles of orientation were measured with respect to the North direction. The impact of the angle of orientation on power output is shown graphically in **Figure 4**. 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 oriented 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 4**.

A number of studies have demonstrated that a solar panel's orientation angle won't significantly affect power generation as long as it is within ±20 degrees to the north or south. The other studies agree with the finding of this study that solar panels oriented at between 1^{o} and 5^{o} northwest and between 11^{o} and 16^{o} generated optimal power. 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 oriented optimally, in Lumumba road 58.9% and Mosi-O-Tunya road had 87.5% panels properly oriented.

The performance of the solar panels was found to be influenced by the type of solar panels used. Monocrystalline solar panels found on both Lumumba and Great North roads, while polycrystalline solar panels were used on Mosi-O-Tunya Road. The findings of the study align with previous research, such as Hidayanti's which highlights the superior efficiency of monocrystalline solar panels compared to their polycrystalline counterparts [28]. Hidayanti reported efficiency rates of 9.22% for monocrystalline panels and 7.94% for polycrystalline panels. In this study, results agree well with Hadayanti's work.

Energy loss during the evening was observed to be primarily attributed to voltage drops that occurred when the load engaged, 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.

5.1.3. Inclination/Tilt Angle of Solar Panel

Figure 5 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 5**, it is evident that within the range of 15°, 16°, 17°, and 20° the solar panels in the northeast demonstrated higher power output, and northwest inclination at 15° and 16°. 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.

Gevorkian's study contributes valuable insights by proposing a fundamental guideline for maximizing annual energy production through solar panels [14]. 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°, the recommended tilt angle would be 50°. Applying this principle to Lusaka, with a geographical latitude of 15° 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. 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 efficient performance.

5.1.4. The Effects of Orientation and Inclination on the Performance of Solar Street Lights

It was observed that misaligned angle of orientations and inclinations negatively affected solar street light performance. Reduced power generation, insufficient night-time illumination and decreased charging efficiency were some of the effected parameters [28,29]. 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. Compromised performance of solar street lights, as they were unable to illuminate adequately due to the restricted energy supply was also observed.

6. Conclusions

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 major 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 having panels oriented in many directions exhibited no statistically significant difference in power output. The minimal variance in energy loss among these group of street lights implies efficient and optimal operation.

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 found by a calculated p-value of 0.042. This substantial difference among the groups of solar panels 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 conditions, specifically the orientation. It was also observed from the analysis that from all the solar street lights studied; only 78.7% of the solar panels were optimally aligned.

The inclination of the solar panels studied on 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 gave better 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. Street lights that operated on lithium-ion batteries and ultra-capacitors were well protected and not easily accessible; hence vandalism through stealing was not common.

The study revealed that malfunctioning charge controllers posed a significant challenge, resulting in issues like batteries 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 in addition to implementing durable designs. Maintenance-related issues, challenges such as irregular topping of distilled water, terminal cleaning and a lack of dedicated equipment, also emerged as a threat especially on solar street lights that operated on flooded lead acid batteries, highlighting their adverse impact on overall system reliability.

6.1. Ethics

The study was carried out at the University of Zambia in collaboration with the Lusaka City council who gave permission to use their yard and also provided assistance in accessing all the street lights that were studied. An official letter allowing the research to be carried out was written through the mayor's office to the supervisor of the researcher and a copy given to the researcher.

6.2. Recommendations

The study was based on determining and analyzing 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 [30].

6.2.1. 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 being in the southern hemisphere, solar panels in general if to be installed deviating from the north, this study recommends that they should be oriented at angles 11^0–16^0 East of North. Those facing northwest should be oriented at angles between 1^0–5^0 North of West. Closer proximity to the north direction was found to enhance system efficiency.

6.2.2. 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 15^0.

In other locations in Zambia, municipal councils should determine the specific latitude of the area for optimal performance and efficiency.

6.2.3. 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 access to minimize vandalism risks. Furthermore, Municipal authorities should ensure maintenance of the flooded lead acid is done every 6 months.

6.2.4. 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.

A strong monitoring team should be established responsible for 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 fail completely. The team should develop a tracking log mechanism for possible scenarios to do with failure of the street light.

6.2.5. 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 not only in Lusaka but also in other towns in optimizing the performance, efficiency, and durability of solar street lights, ultimately contributing to sustainable and effective urban lighting solutions.

Author Contributions

The research project was visualized conceptualized by R.M. and discussed with P.J. and R.R. The study methodology was then developed by K.K. who went to the field to collect data which she later analyzed. K.K. decided on the software to be used and ran the data through the software she had picked. K.K.did the formal analysis and the results were discussed by R.R., P.J. and R.M. who validated the results by making sure that the results made sense. Three of the authors namely R.M., P.J. and R.R. supervised the research. The writing and review and editing of the work was done by all the four authors. The funding acquisition was done by K.K. who obtained the funds for student research project. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data collected and used in this research is provided in the Appendix of this paper **(Table A1–A4)**.

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Conflicts of Interest

The authors declare no conflict of interest.

Appendix A

(a) (b) (c)

Figure A1. Research Instruments. **(a)** Magnetometer. **(b)** Digital Multimeter. **(c)** Inclinometer.

Fieldwork Measurements of Orientation, Inclination, Shading, Morning and Evening Voltages and Currents

Parameters to analyse

i. Orientation

ii. Inclination

iii. Voltage and current

This research involved a mixed-method type.

Table A1. Great North Road Lusaka.

ssl	Orientation (°)		Inclination (°)	lux	Nominal voltages (Volts)			Currents (Amps)	
	WN	EN			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

Table A1. *Cont.*

ssl	Orientation (°)		Inclination (°)	lux	Nominal voltages (Volts)			Currents (Amps)	
	WN	**EN**			**Morning For 1 battery**	**Morning for 4 batteries**	**Evening voltages**	**Morning currents**	**Evening Currents**
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

Table A2. Lumumba Road Lusaka.

SSL	Orientation (°)		Inclination (°)	Lux	Nominal voltages (Volts)			Currents (Amps)	
	WN	**EN**			**Morning 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	Sosdampside	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

Table A2. *Cont.*

SSL	Orientation (°)		Inclination (°)	Lux	Nominal voltages (Volts)			Currents (Amps)	
	WN	EN			Morning 1 battery	Morning For 3 batteries	Evening for 3 batteries	Morning	Evening
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

Table A2. Cont.

SSL	Orientation (°)		Inclination (°)	Lux	Nominal voltages (Volts)			Currents (Amps)	
	WN	EN			Morning 1 battery	Morning For 3 batteries	Evening for 3 batteries	Morning	Evening
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

Table A3. Mosi-O-Tunya Road Lusaka.

Ssl	Orientation (°)		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

Table A3. *Cont.*

Ssl	Orientation (°)		Lux	Nominal voltages (Volts)				Currents (Amps)
	WN	EN		Morning	Morning	Evening	Evening	Morning
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

Table A3. *Cont.*

Ssl	Orientation (°)		Lux	Nominal voltages (Volts)				Currents (Amps)
	WN	EN		Morning	Morning	Evening	Evening	Morning
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

Table A4. Ring Road Lusaka.

Ssl	Orientation (°)			Inclination (°)	Lux
	WN	EN	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

Table A4. *Cont.*

Ssl	Orientation (º)			Inclination (º)	Lux
	WN	EN	N		
7	36			9.6	2_{dim}
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

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