Techno-economic assessment of solar-powered lighting: A case study of the Cape Town Metropolitan Area

by

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DECLARATION

By

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“I hereby declare that this research dissertation submitted for the degree (MASTER OF ENGINEERING IN ENGINEERING MANAGEMENT) at the Cape Peninsula University of Technology, is my own original unaided work and has not previously been submitted for any other institution of higher education. I further declare that all sources cited or quoted indicated or acknowledged by means of a comprehensive list of references”.

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ABSTRACT

This research addresses the critical need for sustainable and cost-effective public lighting solutions in the Cape Town Metropolitan Area, where previous literature has overlooked a comprehensive evaluation of solar lighting systems in urban settings. This has led to uncertainties in optimal system architecture, cost-effectiveness compared to traditional grid-powered lighting, energy consumption patterns, and technical feasibility under specific meteorological conditions. The primary research question driving this study is the feasibility and economic viability of solar-powered street lighting in Cape Town. To bridge these gaps, the research employs a thorough analysis that includes system architecture exploration, cost-effectiveness comparisons, energy consumption pattern analysis, and technical feasibility assessment under Cape Town's unique meteorological conditions, utilising quantitative data collection and analysis methods. The research aims to determine the feasibility, cost-effectiveness, and potential benefits of solar-powered lighting systems for urban sustainability, with anticipated outcomes that include insights into system architecture optimisation, cost comparisons, energy consumption patterns, and technical feasibility to guide decision-making in urban lighting infrastructure planning. This study fills the gap in understanding the economic feasibility, technical viability, and societal impact of scaling up solar-powered lighting in urban settings like Cape Town. The findings are expected to inform policymakers, lighting suppliers, and residents, potentially reducing reliance on conventional energy sources, cutting electricity costs, and promoting renewable energy and sustainable development. Ultimately, this research contributes valuable insights to the broader discourse on integrating solar energy solutions in urban environments.

Keywords: solar-powered, lighting, cost-effectiveness, techno-economic assessment, renewable energy, feasibility.

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LIST OF ABBREVIATIONS

AC	Alternating Current
CCT	Correlated Colour Temperature
CFL	Compact Fluorescent Lamp
CoCT	City of Cape Town
COGTA	Cooperative Governance and Traditional Affairs
CRI	Colour rendering index
DC	Direct Current
DMRE	Department of Mineral Resources and Energy
DoE	Department of Energy
DPBP	Discounted Payback Period
HPS	High-Pressure Sodium
IRR	Internal Rate of Return
LED	Light Emitting Diode
MH	Metal Halide
MPPT	Maximum Power Point Tracking
MV	Mercury Vapour
NPV	Net Present Value
PV	Photovoltaic
PWM	Pulse Width Modulation
SANS	South African National Standards
SARB	South African Reserve Bank
SOLAR PV	Solar Photovoltaic
USD	United States Dollar
USDAFAS	United States Department of Agriculture Foreign Agriculture Services
WCG	Western Cape Government

CHAPTER ONE

INTRODUCTION AND MOTIVATION

1.0 Introduction

South Africans rely on electricity in their lives, just like the rest of the world. Energy usage influences communities and is fundamentally critical for sustaining people's livelihoods (Halkos and Gkampoura, 2021; Hussein and Filho, 2012). South Africa has old electricity generation equipment which is frequently failing and usually offline for maintenance repairs (Akinbami et. al, 2021).

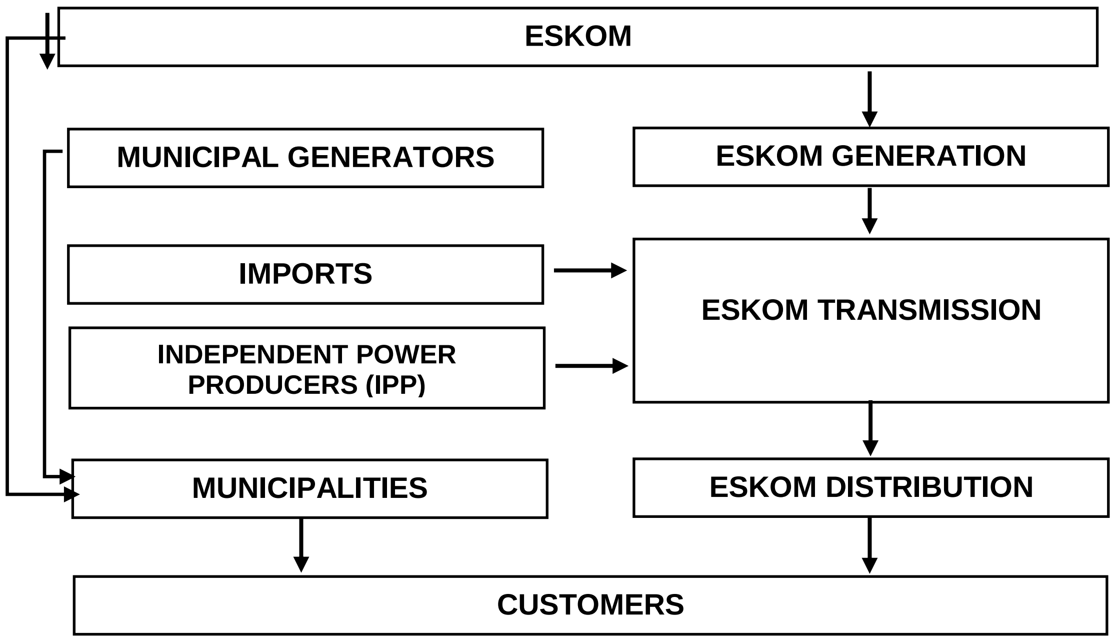

Figure 1.1 Flow chart of the South African electricity generation, transmission and distribution (DMRE, 2021).

Figure 1.1 summarises South Africa's electricity generation, transmission, and distribution model. Baker and Phillips (2018) note that the monopolistic national utility, Eskom, accounts for 95% of power generation.

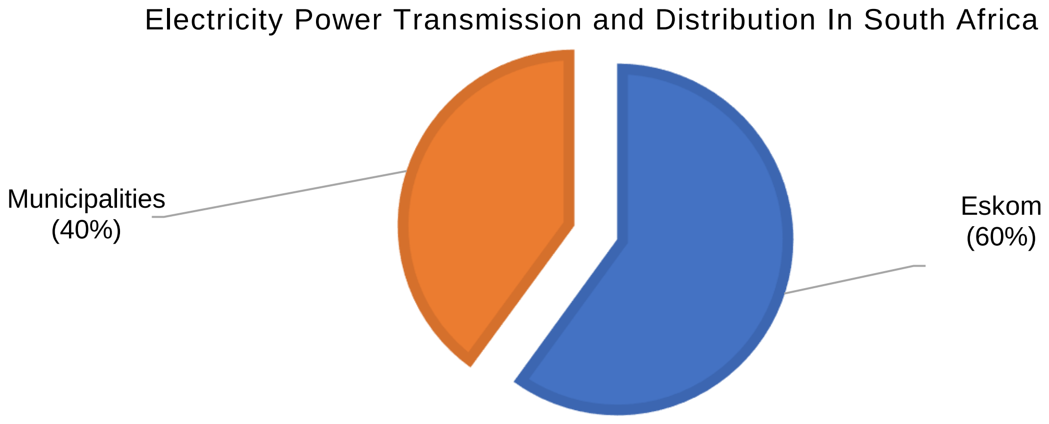

Figure 1.2 Electricity transmission and distribution in South Africa. (Baker and Phillips, 2018).

Eskom accounts for sixty percent (60%) of the power transmission to the various users while the municipalities distributed the remaining 40% as shown in Figure 1.2 (Baker and Phillips, 2018). Akinbami et al. (2021) suggested South Africa is the world's seventh-largest coal producer. Coal accounts for the bulk of South Africa's electricity supply, with an approximate contribution of close to 90% (Baker and Phillips, 2018). Voumik et al. (2023) pointed out that the use of coal for energy generation has adverse impacts on the environment owing to the effects of greenhouse gas emissions on the environment through climate change. Owing to its reliance on coal for electricity generation, South Africa is rated among the world's top ten greenhouse gas emitters (Akinbami et al., 2021). This status quo is unlikely to change significantly over the next 20 years, despite the adoption of other cleaner energy sources (Department of Energy, 2021).

In the past several months, electricity demand has outstretched the power supply in South Africa. This phenomenon has resulted in Eskom implementing power cuts, which are widely termed as "load shedding." These load-shedding events are usually classified into numbered stages from stage 1 to stage 8 by the government-owned monopolistic electricity supplier Eskom. Recently, load shedding has also coincided with the increase in liquid fuel prices in the country. This was attributed mainly to global forces, such as foreign exchange rates and the ongoing Russia-Ukraine impasse (South African Reserve Bank, 2022). The economic outlook suggests that load shedding has had detrimental effects, such as delays in investments and job losses (South Africa Treasury, 2021).

The post-Covid-19 economic recovery has faced additional turmoil due to power outages. Lenoke (2017) highlighted that energy shortages are detrimental and adversely affect the economy. United States Department of Agriculture Foreign Agriculture Services (2022) projected that the cost of these negative impacts from load shedding could reach billions of U.S. dollars. For instance, Business Tech (2022) reported that during the stage 6 load-shedding schedule, the economy experienced a daily loss of approximately R4 billion.

Gordic et al. (2021) suggested that energy usage in public lighting systems constitutes a substantial portion of the energy profiles of municipalities and cities. George (2020) noted that using outdated and inefficient lighting technologies leads to energy wastage. High electricity consumption results from the use of inefficient lighting equipment and the poor management of public lighting systems (Gordic et al., 2021). Subsequently, as electricity tariffs continue to rise, municipalities face higher expenses for maintaining public lighting. Such increased costs are typically transferred to consumers, leading to a reduction in disposable income. The fourth industrial revolution has steered towards the development of smart cities, with Cape Town emerging as a leading example in Africa. Sustainable Energy Africa (2015) pointed out that

Cape Town took an early initiative among African cities by formulating a climate change and energy strategy.

Gordic et al. (2021) predicted an annual 3,6% increase in the public lighting energy demand based on current global trends. The public lighting sector is very attractive presenting abounding opportunities for improvement. Various sector-specific demand-side management techniques can be implemented to achieve energy efficiency. Demand-side management initiatives may be energy reduction or load-management measures (GreenCape, 2022). Demand-side management techniques help reduce energy costs, ease pressure on overburdened supply quicker and, in some cases, reduce greenhouse gas emissions (DoE, 2019). Energy efficiency is achievable through the adoption of alternative technologies and/or energy usage behavioural change without compromising desired outputs (GreenCape, 2022). However, accurate and reliable information on the cost-effectiveness of possible interventions that may be implemented is critical for decision-makers.

Cape Town has experienced the impacts of climate change, evident in recent occurrences of extreme weather events like floods, storms, and rising sea levels. The climatology data specific to Cape Town differs significantly from other regions, emphasizing the inadvisability of adopting a one-size-fits-all product selection approach.

In summary, energy is critical for socio-economic development. South Africa's energy situation requires sustainable solutions amidst prevalent climate change and utility supply unreliability. There is a need to transition from fossil-based fuel power supply to more sustainable energy technologies such as solar energy. Demand-side management initiatives such as substituting conventional lighting with more efficient LED lighting technology result in energy cost savings. The next section will explore the background context of Cape Town, as the area of focus.

1.1 Background

Cape Town is South Africa's major port city whose coordinates are -33.88565671003413°, 18.52876621967593° i.e. (33.89°S, 18.53°E). It holds the legislative seat of the South African Government. Cape Town is both South Africa's second-largest economic hub and second-most populous city (Cooperative Governance and Traditional Affairs, 2020). It is the Western Cape's provincial capital. The Western Cape province is broken down into thirty municipalities consisting of one metropolis, five rural districts, and twenty-four other local municipalities. Cape Town is the Western Cape province's sole metropolitan municipality.

The Western Cape Government (2018) points out that Cape Town municipality accounted for approximately sixty percent of the energy used in the province making it the primary CO_2 emission contributor. As shown in Figure 1.3, the City of Cape Town supplies electricity to 75%

of consumers whilst Eskom supplies to the rest (Western Cape Government, 2018). The prevalent load-shedding as well as theft and vandalism of distribution infrastructure affects the delivery of services for the city’s residents. Prevalent load-shedding diminishes the municipality’s revenue base.

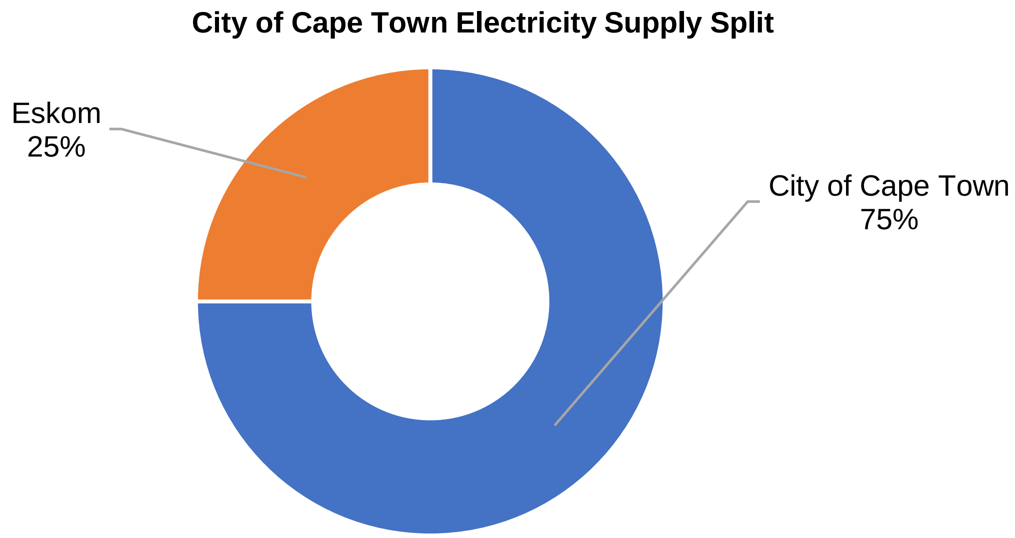

Figure 1.3 City of Cape Town electricity supply split (Western Cape Government, 2018).

The city’s population growth since 2001 is attributed to urbanisation as shown in Figure 1.4 below. The city recorded a 29.31% increase between 2011 and 2001 and a further increase of 27.23% from 2011 to 2021. The projected 7.88% increase from 2021 to 2025 is recorded (Western Cape Government, 2021).

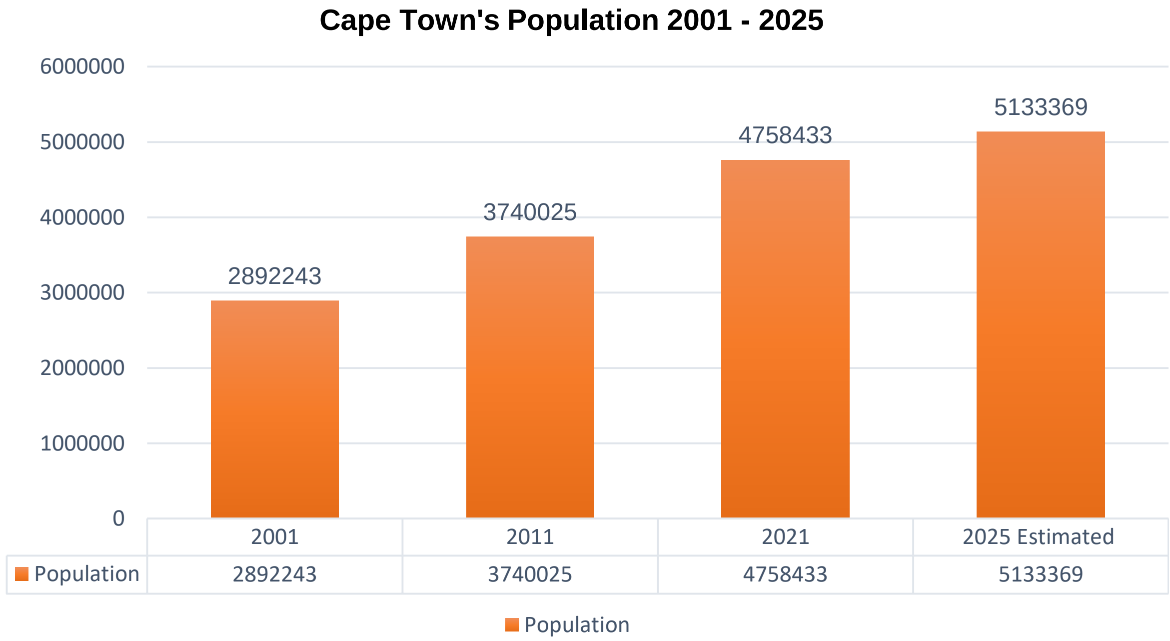

Figure 1.4 Cape Town population between 2001 – 2025 (COGTA, 2020; Western Cape Government, 2021).

The city has a population density of 1955 people per square kilometre (people/km2) which is very high compared to other districts and the provincial average population density of 55 people per square kilometre (Western Cape Government, 2021). The Western Cape province contributed R658 billion from South Africa's gross domestic product (GDP) of R4.6 trillion (City of Cape Town, 2023). Cape Town contributes the bulk of the Western Cape province's annual gross domestic product at an estimated 73% (City of Cape Town, 2023). The province recorded a GDP growth of around 0.5% mirroring the country's GDP growth of 0.6%. As of mid-2023, the province recorded a 1.5% decrease in comparison with the preceding quarter (City of Cape Town, 2023). The city's gross value added (GVA) by sector is shown below in Figure 1.5.

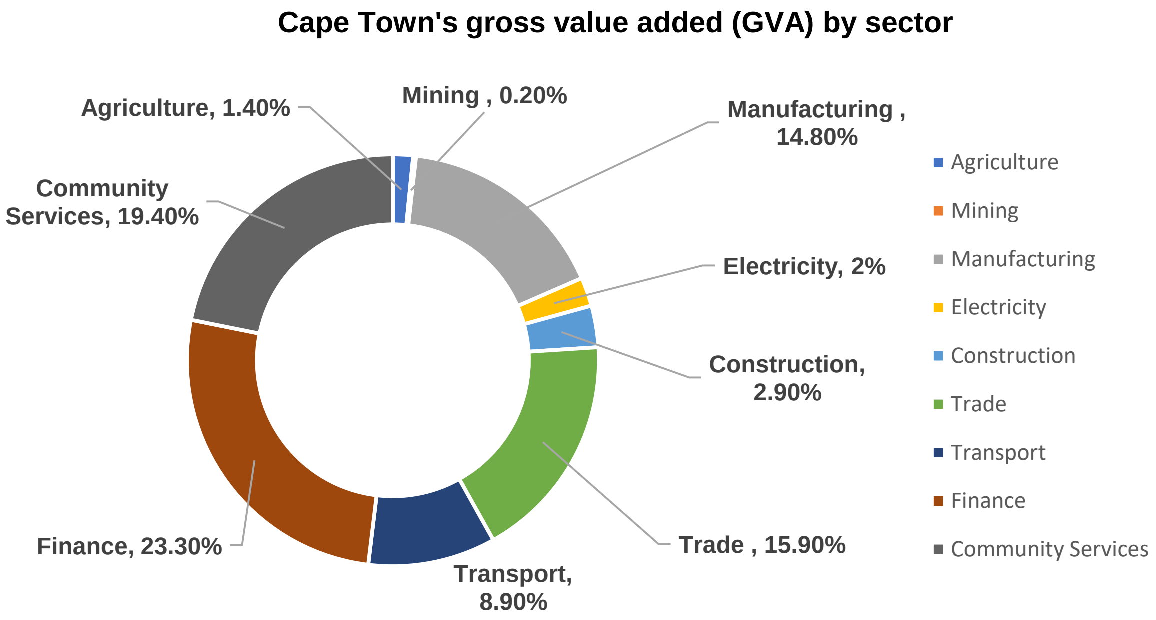

Figure 1.5 Cape Town's gross value added by sector (City of Cape Town, 2023).

Cape Town has a Mediterranean-type climate with the rainfall being received during winter and experiencing dry summers (World Bank Group, 2021). The city has experienced climate change impacts evident in the recent occurrences of reduced rainfall, and extreme weather events like floods and storms just to mention a few. Cape Town, just like other coastal cities, is experiencing rising sea levels (World Bank Group, 2021). This phenomenon subsequently causes adverse effects on key economic activities like tourism and fisheries. Cape Town is more at risk of rising sea levels than Durban which has better elevation (Davis-Reddy and Vincent, 2017). The city is also experiencing substantial temperature increases which can potentially result in human health risks such as heat stress (World Bank Group, 2021). The World Bank Group (2021) further adds that temperature rises will result in regular and severe heatwaves and more high heat days.

During the last census in 2022, it was observed that Cape Town's population comprised 51.7% female and 48.3% male (Statistics South Africa, 2022). Approximately 19.3% of the metropolitan's population resides in informal structures such as shacks (City of Cape Town, 2021). The crime levels in Cape Town are higher than the national statistics (City of Cape Town, 2023). For instance, the crime, partly due to poor external lighting, is of major concern to the city and its stakeholders (Urban Power, 2023). For example, there have been many reports of violent crime incidents such as murder, and robberies along the N2 road towards informal settlements such as Langa affecting the residents, tourists, and visitors who contribute to the growth of the city's economy. The City of Cape Town is also reportedly interested in the evaluation of solar-powered lighting as an alternative (Urban Power, 2023). Solar-powered lighting enhances the residents' sense of safety and security however there is a threat of vandalism of public lighting infrastructure such as high mast lighting, particularly near informal settlements (Urban Power, 2023).

The city's energy consumption is split by sector as shown in Figure 1.6. The public lighting infrastructure serves a critical service delivery function with the city's streetlights contributing 14% of its energy consumption as shown in Figure 1.6 below (City of Cape Town, 2024).

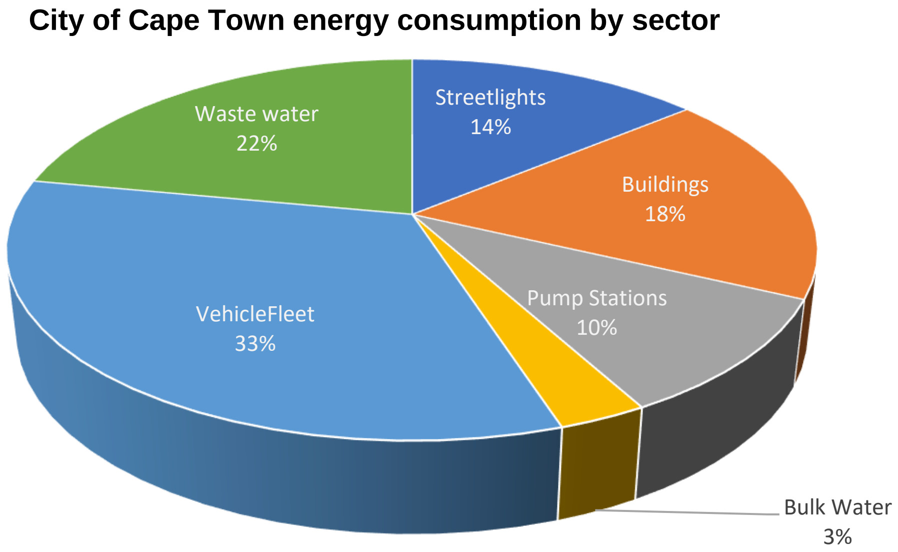

Figure 1.6 Energy consumption is split by sector (City of Cape Town, 2024).

Public lighting is a very critical segment of service delivery for local authorities (Noel et al., 2020). Smidt-Hart (2019:1) highlighted that adequate public lighting is synonymous with safety and security, leading to extended hours of socio-economic activity for communities. The local municipality, the City of Cape Town (CoCT), currently operates and maintains all the streetlight infrastructure which comprises different lighting technologies. These range from High-Pressure sodium (HPS), mercury vapour (MV), metal halide (MH), compact fluorescent lamps (CFL), and light-emitting diodes (LED) all powered by conventional grid electricity. These lamps are termed alternate current (AC) luminaires. The breakdown is summarised in Figure 1.7 below.

The luminaires must comply with local standards such as SANS 60598-1, SANS 60598-2-3, and/or SABS 1277. The City's local authority has, in the past, retrofitted traditional street lighting with LED luminaires spanning over 1200km (South Africa News Gazette, 2020). According to the City of Cape Town's five-year integrated plan (July 2022 to June 2027), the city's expansion is ongoing with various projects on plan and prioritised to improve safety and quality of life for the residents.

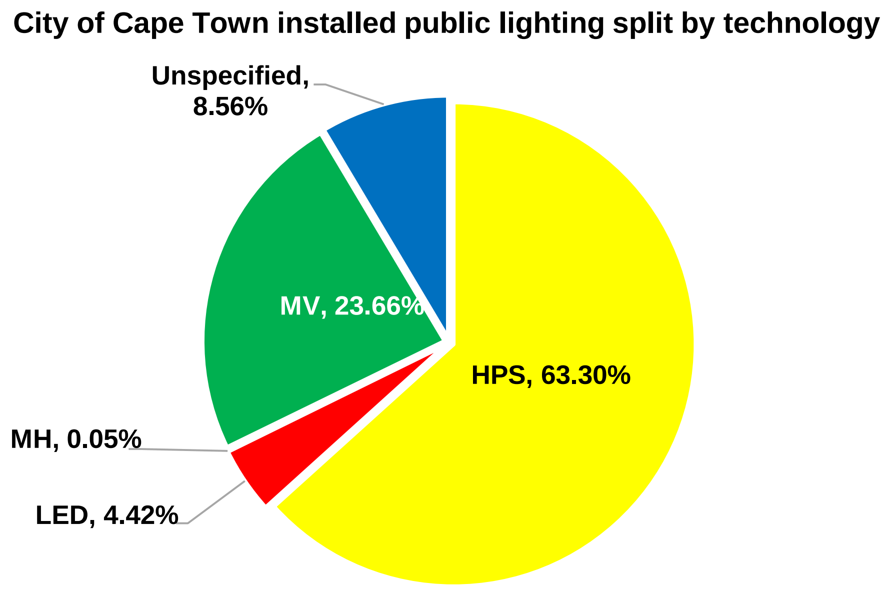

Figure 1.7 The City of Cape Town installed public lighting split by technology (City of Cape Town Open Data Portal, 2023).

Major routes connecting various areas to the central business are currently being explored. This presents opportunities to assess the best possible solutions for public lighting. For consideration, the lighting solutions need to meet functional technical requirements whilst demonstrating cost-effectiveness.

Liu et al. (2017) suggest that over the past twenty years, the cost of LED lamps has decreased by a factor of 20 while the luminous flux has increased by a factor of 40. Khalil et al. (2017) pointed out that the remarkable performance improvement coupled with their typical lifespan exceeding ten years and a continuous decline in their prices over the years has established them as the standard for efficient lighting technology. There is an increase in the use of renewable energy resources as an alternative to conventional AC luminaires. Over the years, the sub-Saharan African market has been exposed to a wide variety of products and solutions from all over the world (Lighting Africa, 2010).

Business Tech (2021) noted that faulty load control mechanisms could be the reason why the city's streetlights are unnecessarily on during daytime. Kuamthab and Mustafa (2021) in a Malaysian study noted that the conventional streetlights switched on during daytime and lit up at full intensity during less active hours such as midnight. In their opinion, this resulted in energy wastage hence they recommended a solar-powered LED streetlight with automatic intensity control. Rajeev and Nair (2012) however noted higher installation costs for solar-powered LED streetlighting in comparison with conventional streetlighting. However, they noted that the lifetime costs of solar-powered LED streetlighting are lower than those of conventional streetlighting.

Baladi and Shah (2018) suggested the use of solar-powered LED streetlights as ideal due to their installation ease, reliability, flexibility, and minimal maintenance costs. Ibrahim et al. (2021) propose that the declining PV costs, alongside rising electric tariffs, render solar-powered street lighting a financially attractive alternative. Rajeev and Nair (2012) proposed various system configurations for solar-powered LED streetlighting namely grid-connected, standalone (autonomous), and PV-hybrid. In a grid-connected configuration, grid electricity powers the lamps during cloudy conditions and at night, while surplus energy is exported to the grid during sunny periods. Conversely, in a standalone system, an alternative energy source such as solar PV and energy storage powers the lamp instead of grid power.

Velaga and Kumar (2012) emphasised that a typical autonomous solar-powered LED lighting system includes a solar PV panel for energy generation, a battery for storage, a controller for charging and load management, and a light fitting. Sutopo et al. (2020) additionally noted that solar-powered street lighting operating autonomously as a standalone system is more energy-efficient, contributing to reduced operational costs. However, Nyemba et al. (2019) suggested that combining solar energy with another source, like wind energy, enhances the performance and reliability of standalone streetlight systems, especially during periods of limited solar resource availability. Their study determined that this design reduces the required energy storage capacity by half and decreases the solar panel array size by 15% achieving over 98% reliability.

Velaga and Kumar (2012) recommended the comparison of the total life cycle costs of two different technologies to ascertain the more cost-effective option. Archibong et al. (2020) in their life cycle cost analysis, noted the associated costs including the operational and maintenance costs, initial capital investments, and design and production costs. Katyara et al. 2018, estimated the annual operation and maintenance cost to be 2% of the system's initial capital cost. In contrast, Mardikaningsih et al. (2016) proposed that the annual operation and maintenance cost be 1% of the system's initial capital cost.

Wu et al. (2009) concluded that the payback for solar-powered LED streetlighting was 3.3 years whilst 2.2 years for grid-powered LED streetlighting. In a similar study, Ibrahim et al. (2021) determined that the payback for a grid-powered LED luminaire system is just over two years, and over 3 years for a solar-powered LED. Allwyn et al. (2021) in a similar study made an economic analysis for replacing HPS lamps with more efficient LED streetlights. The study concluded that the discounted payback period was approximately one year. Orejon-Sanchez et al. (2021) noted the outcomes of various projects of a similar nature that have been executed. Initially, in Angola, an installation project involving 1365 units of 50W solar-powered streetlights proved to be 35% more cost-effective than conventional street lighting. Secondly, a similar project in Jordan conducted by Al-Kurdia et al. (2015) determined that 50% savings were achieved by switching from conventional streetlights to solar-powered streetlights. Al-Kurdia et al. (2015) observed a payback period of 3.15 years for solar-powered streetlights in comparison to 7.20 years for conventional grid-powered streetlights.

Katyara et al. (2018) in a feasibility study concluded that the payback for their proposed solar-powered LED system was approximately 5.384years which is comparable to the 5.9 years reported by Rajeev and Nair (2012) when they used CFL technology with lead acid battery technology. Pipattanasomporn et al. (2014) reported a payback period of about 6 years. They reported that for LED streetlights the net present value (NPV) after the period of assessment was lower than that for the HPS streetlights. Karmiathi et al. (2018) noted in a study that the NPV for solar-powered LED streetlights was negative implying that it was not feasible to replace them with traditional lighting. The diverse feedback from comparable projects in different locations motivates the researcher to ascertain the specific outcomes for Cape Town, South Africa.

1.2 Research problem statement

South Africa, particularly Cape Town, has been plagued by a persistent issue of load shedding, resulting in frequent disruptions to the electricity supply. The City of Cape Town, like many cities in South Africa as well as globally, faces pressing challenges in ensuring sustainable and cost-effective energy solutions for public lighting. Conventional grid-powered lighting infrastructure not only contributes to the city's carbon footprint but also poses economic challenges due to rising energy costs and grid reliability issues. There is a need to have sustainable ways of powering our daily requirements. To address these concerns, there is a need for a comprehensive techno-economic assessment of solar-powered lighting solutions tailored to the specific context of the City of Cape Town. Despite the growing recognition of solar energy as a viable alternative, a gap exists in understanding the economic feasibility, technical viability, and potential societal impact of integrating solar-powered lighting at scale in an urban setting like Cape Town.

1.3 Associated research questions

1.3.1 Research question

Is solar-powered lighting technically feasible and economically viable for street lighting in the City of Cape Town?

1.3.2 Research investigative sub-questions

- What is the optimal solar lighting system architecture that can provide equivalent functionality to the tailor-made conventional grid-powered lighting in Cape Town?
- How does the cost- of solar lighting compare to conventional grid-powered lighting when considering factors such as initial investment, ongoing expenses, and long-term financial benefits?
- What are the actual energy consumption patterns in Cape Town related to solar-powered lighting, and what potential savings can be identified through its implementation?
- What are the differences in the efficiency, durability, maintainability, and other technical factors of the different lighting systems?
- Is solar-powered public lighting technically feasible for deployment in Cape Town, considering the city's specific meteorological conditions?

1.4 Primary research aim & objectives

The project aims to conduct a comprehensive techno-economic assessment of solar-powered lighting systems in the context of the City of Cape Town, with a focus on evaluating their feasibility, cost-effectiveness, and potential benefits for urban sustainability.

To achieve the primary research aim, sub-research objectives as explored in the research methodology in Chapter 3.1 were formulated. These objectives are as below: -

- To determine the optimal solar lighting system architecture of equivalent functionality to the conventional grid-powered lighting tailor-made for Cape Town.
- To determine cost-effectiveness by comparing initial investment, ongoing expenses, and long-term financial benefits of solar-powered streetlighting.
- To determine the energy consumption and potential savings from solar-powered lighting in Cape Town.
- To evaluate solar-powered streetlighting’s technical suitability in replacing conventional streetlighting under Cape Town meteorological conditions using simulation tools.

1.4.1 Assumptions

The research study assumptions are listed below.

- The researcher assumes that the data collected from primary and secondary sources are accurate and a correct representative of the actual situation in the Cape Town metropolitan area.
- This study assumes that the solar lighting systems used in Cape Town operate efficiently and consistently.
- The study also assumes that solar technology and components (solar panels, batteries, LED drivers, etc.) used in the study will perform as per the manufacturers' specifications throughout their expected lifespan.
- It is assumed that quantitative data related to Cape Town's solar lighting systems, energy consumption, and meteorological conditions are available.
- The study assumes that Cape Town's economic conditions and regulatory environment remain relatively stable over the study's duration. Changes in economic policy, tax structures, and regulations may affect the economic analysis.
- The study assumes that there are no major technological breakthroughs or disruptive innovations in solar technology during the study period, which could significantly alter the cost-effectiveness and technical feasibility of solar lighting systems.

1.4.2 Delimitations

- The study's geographical scope is limited to the Cape Town metropolitan area.
- The research's specific focus is on solar-powered streetlighting systems and excludes other solar energy applications or technologies.
- The analysis is limited to a twenty-year projection timeframe which may not capture long-term technological advancements or market dynamics changes beyond this period.

1.4.3 Hypothesis

The research hypothesises that solar-powered lighting systems are more cost-effective and sustainable alternatives to conventional high-pressure sodium (HPS) street lighting systems in the Cape Town metropolitan area. This hypothesis was meticulously tested by conducting a comprehensive techno-economic analysis, considering meteorological data, initial investment costs, operational expenses, and a sensitivity analysis of key variables' impact on the project's economic viability over time.

1.5 Research methodology

The research methodology was carried out following a well-defined plan of action, which was segmented into distinct tasks. Each task with different durations held equal significance in ensuring the successful completion of the project. The outlined tasks are as follows:

- Problem Identification
- Review of Literature
- Problem Clarification and Setting of Research Questions
- Selection of research design
- Data collection and processing
- Quantitative data analysis
- Summary of findings and drawing of conclusions and
- Peer review and final report compilation.

Figure 1.8 shows a concise structure diagram for the adopted methodology. The research was conducted using an approach comprising quantitative data collection and analysis methods. The research process involved the following steps:

- Review of existing literature to identify the key concepts, and research gaps and establish the theoretical framework of the research topic.
- Collection of quantitative data on solar-powered streetlighting, including capital and operational costs and energy savings.
- Evaluation of the suitability of solar-powered streetlighting to replace conventional streetlighting using the DIALux simulation tool.

1.6 Dissertation Chapter Breakdown

This dissertation is divided into distinctive chapters, orderly numbered from 1 to 5. Each chapter addresses specific aspects of the research objectives and contributes to the achievement of the study’s aim.

- Chapter 1: Introduction
  Serving as the dissertation’s foundation, this chapter provides context for the research topic. In this chapter, the problem statement and the research’s aim are outlined. The research objectives, assumptions, delimitations and hypothesis are presented.

- Chapter 2: Literature Review
  The existing literature on solar lighting systems, including their components, configurations, and economic and technical performance is reviewed in Chapter 2. In

this chapter, current research gaps are identified, and the study’s theoretical framework is established.

- Chapter 3: Methodology
  This chapter focuses on the research design and methodology employed to evaluate the techno-economic viability of solar-powered lighting systems. In Chapter 3, distinct steps taken to achieve the research objectives are outlined.

- Chapter 4: Results and Discussion
  The research findings, including data analysis and comparisons between solar-powered and conventional lighting systems, are presented in Chapter 4. The implications of the research findings are discussed therein.

- Chapter 5: Conclusion and Recommendations
  The final chapter summarises the research’s key outcomes discussing their significance. Future recommendations are discussed for various stakeholders regarding the implementation of solar-powered lighting solutions in Cape Town.

In conclusion, Chapter 1, has established the research’s foundation outlining the primary objectives, assumptions, delimitations, and hypotheses. Chapter 2, which follows, explores a comprehensive literature review on solar-powered streetlighting systems identifying research gaps that this study aims to address. The literature review provides the requisite context and theoretical framework for understanding the techno-economic assessment of solar lighting solutions in Cape Town.

Adopted methodology structure diagram

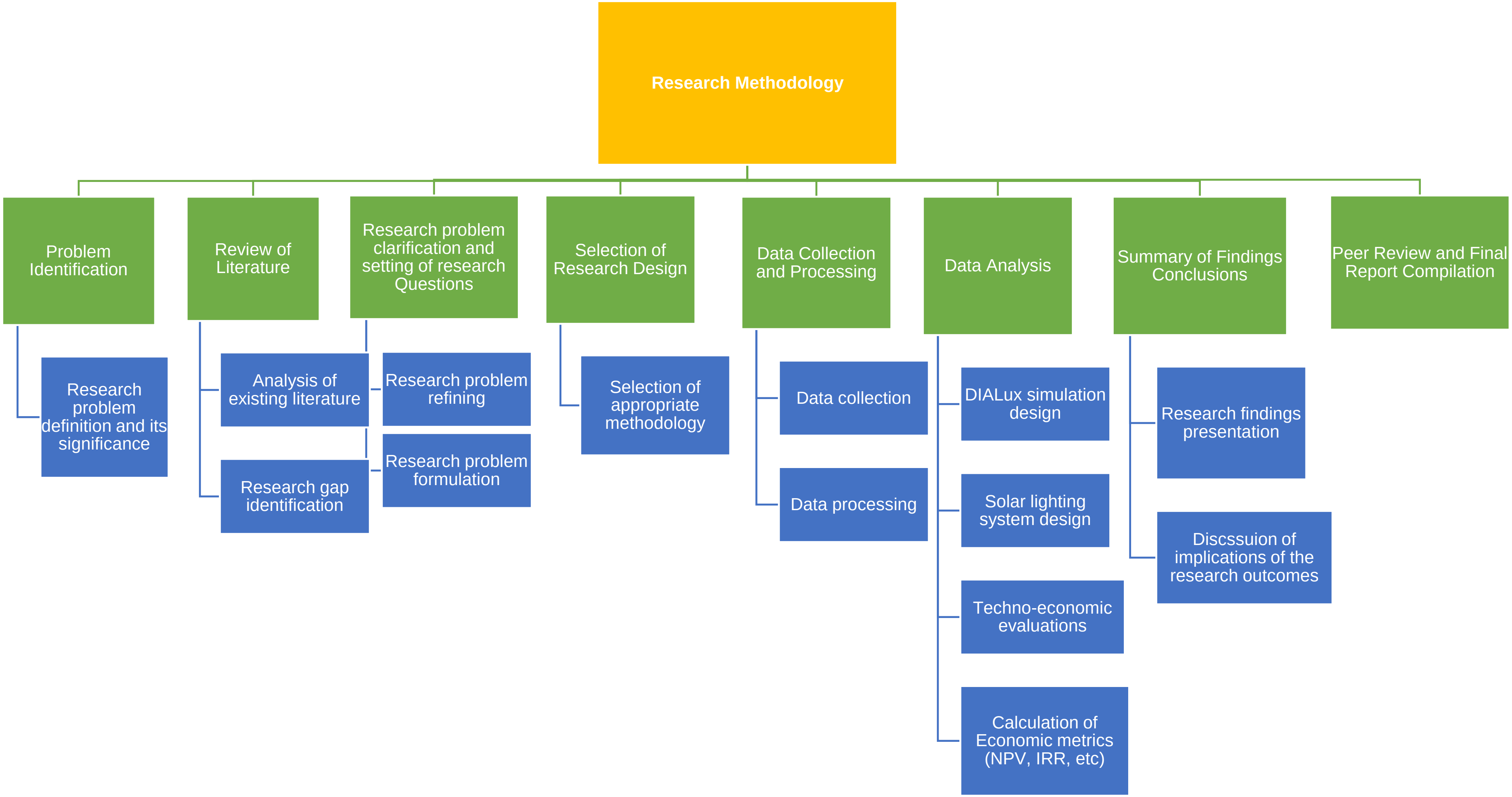

Figure 1.8 Adopted methodology structure diagram.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

This section is a crucial part of this research document. This literature review delves into various relevant to solar-powered lighting systems. It will include an in-depth study of the various solar-powered lighting system components and their interrelations within the system. Every system component plays a role in the overall technical and economic assessment of that system. This section starts by exploring the various solar module or panel types. There is further addressing of the several factors affecting the photovoltaic energy output, such as environmental conditions and material efficiency. From there, the next subsection focuses on energy storage solutions. The battery energy storage types applicable for solar-powered street lighting, as well as their role within the system's working, are explored.

Subsequently, there is a transition into the analysis of the charge controller and its functional role within the system as far as managing the flow of energy and protecting the system components. The exploration of the LED driver and its role in maintaining consistent lighting and its contribution to the overall system follows thereafter. A dedicated subsection ensues focusing on the luminaire where the different types of lamps are compared, and key performance criteria parameters are discussed. Further, a subsection on the lighting design, various street lighting arrangements, and road classification to understand the application of these systems in real-life scenarios.

Solar-powered lighting configurations and classifications are then explored to highlight the versatility and adaptability of solar lighting solutions. Finally, an economic and technical performance analysis would provide a critical assessment of the cost-effectiveness and operational efficiency of solar lighting systems. This structured approach yielded a comprehensive understanding of the solar-powered lighting system. In conclusion, the literature review provides a summary review and discussion for the whole section.

The research study's literature review diagram is shown in Figure 2.1 below

Literature Review structure diagram

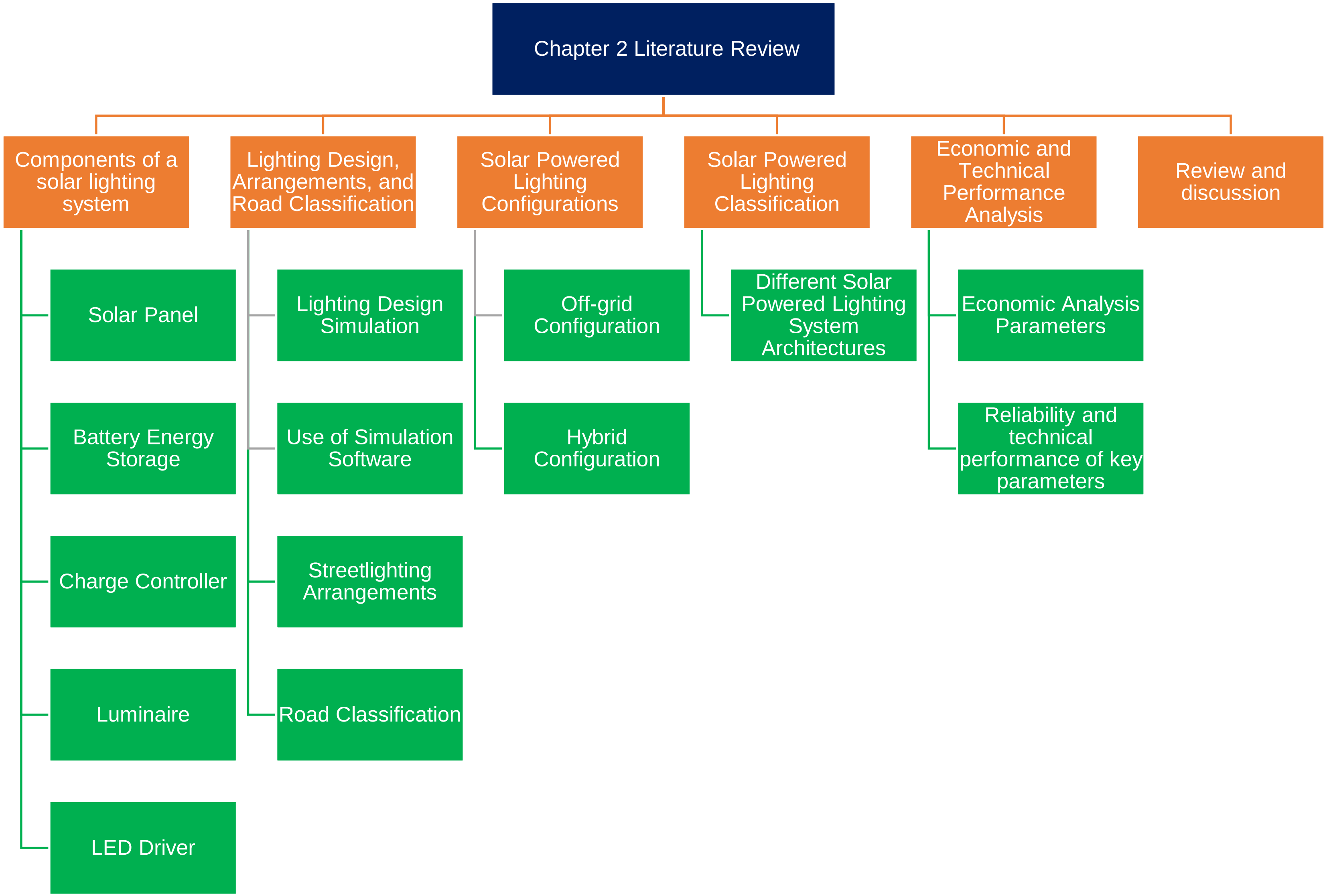

Figure 2.1 Literature review structure diagram.

2.1 Components of a solar lighting system

A solar-powered lighting system consists of various components also referred to as subsystems. These components are the building blocks interconnected to achieve overall system functionality. The major components include: -

- Solar PV module/panel
- Battery/energy storage
- Charge controller
- LED driver
- Luminaire

2.1.1 Solar module/panel

A photovoltaic (PV) panel is also known as a solar module or more commonly a solar panel. It consists of various cells that are connected in series and/or parallel to achieve the desired electrical rating such as voltages and/or currents (University of Central Florida, n.d.). Shetty et al. (2012) noted that solar panels convert incident sunlight to direct current electricity. Accordingly, Katyara et al. (2018) describe the solar panel as an integral part of a solar lighting system. According to Alami et al. (2022), the most common solar panel types are both silicon-based. These are: -

- Monocrystalline and
- Polycrystalline.

Asrori et al. (2020) estimated that these solar panel types constitute over 95% of the current total installed capacity. The monocrystalline panels have a black appearance whilst the polycrystalline panels have a blue appearance (Nsasak et al. 2021). Alami et al. (2022) noted the current market solar panel efficiencies range from 15% to 23% whilst Asrori et al. (2020) noted that solar panel efficiencies to between 14%–24%.

Singh (2016) conducted a study on solar radiation in South Africa and its split by province for the period spanning close to three decades from 1980-2009. The surface incident solar radiation flux, described as the amount of solar radiation incident per unit area, was a very important index for their study. This metric influences the system's technical performance. Singh (2016) concluded that solar radiation differs from one place to another depending on various factors. Table 2.1 below shows that the Western Cape province where Cape Town, our project area, has a mean solar flux in W/m^2 was estimated to be 244.34 $\pm$ 3.10 W/m^2. Areas with higher mean surface incident solar radiation flux receive more solar radiation on average. For example, the Northern Cape and North-West provinces with higher mean values of 262.38 and 263.32 respectively will receive more solar radiation on average than Kwazulu-Natal and

Eastern Cape whose mean values are 232.99 and 236.06, respectively. A higher surface incident solar radiation flux corresponds to a better solar PV system performance. The standard deviation values shown in Table 2.1 below indicate the solar radiation flux values variability around the mean in each province. In general, higher standard deviation values suggest that the amount of solar radiation received in those areas generally fluctuates more over time. On the other hand, lower standard deviation values suggest reduced solar radiation flux variability, implying more consistency over time. In essence, areas with higher mean surface incident solar radiation flux values and lower variability, are more suitable for solar PV applications.

Table 2.1 South Africa's surface incident solar radiation flux by province (Singh, J., 2016).

Province	1980 - 2009 (Mean ± SD) Surface Incident Solar Radiation Flux
Free State	259.20 ± 02.66
Northern Cape	262.38 ± 04.32
Western Cape	244.34 ± 03.10
Gauteng	252.28 ± 02.46
Mpumalanga	242.49 ± 06.46
North-West	263.32 ± 02.13
Limpopo	252.95 ± 06.16
Kwazulu-Natal	232.99 ± 02.02
Eastern Cape	236.06 ± 05.98

Benghanem et al. (2023) carried out a study to investigate how different solar panels behave at various solar flux intensities. They concluded that monocrystalline solar panels are best suited for low-temperature areas with low solar radiation with typical solar flux values below 500W/m^2. Conversely, Benghanem et al. (2023) concluded that polycrystalline solar panels were more suitable for areas with higher solar radiation (typically above 500W/m^2) and high temperatures. Consequently, it can be concluded that the monocrystalline solar panels are more suitable for deployment in the Cape Town area. El-din et al. (2014) made a comparative study on the different solar PV types namely monocrystalline, polycrystalline as well as amorphous. In their cost comparison, they concluded that the monocrystalline panels had a higher price per watt than the polycrystalline panels. However, in their PV panel technical performance assessment, El-din et al. (2014) concurred with Kuamthab and Mustafa (2021) that the monocrystalline panels are most preferred due to their superior efficiency.

In conclusion, solar panel type selection in consideration of the site-specific conditions is crucial for the overall efficiency and performance of a solar PV system. The next sub-section will provide an in-depth deeper into the factors affecting solar PV energy output. The effects of the various factors are later explored in a dedicated section.

2.1.2 Battery / energy storage

Dwipayana et al. (2021) noted the intermittence of solar energy as a key driver of battery energy technology research and development. Sobamowo et al. (2024) suggested that the battery cost represents the biggest share of a typical solar PV system's cost. Katyara et al. (2018) emphasized that batteries store daytime-generated energy for nighttime use, charging during the day and discharging at night. Yoomak and Ngaopitakkul (2019) suggested that the utilisation of battery energy storage improves power quality, and the system's energy efficiency as well as reduces overall system costs. The current technologies in the market have distinctive characteristics owing to their chemical composition and design.

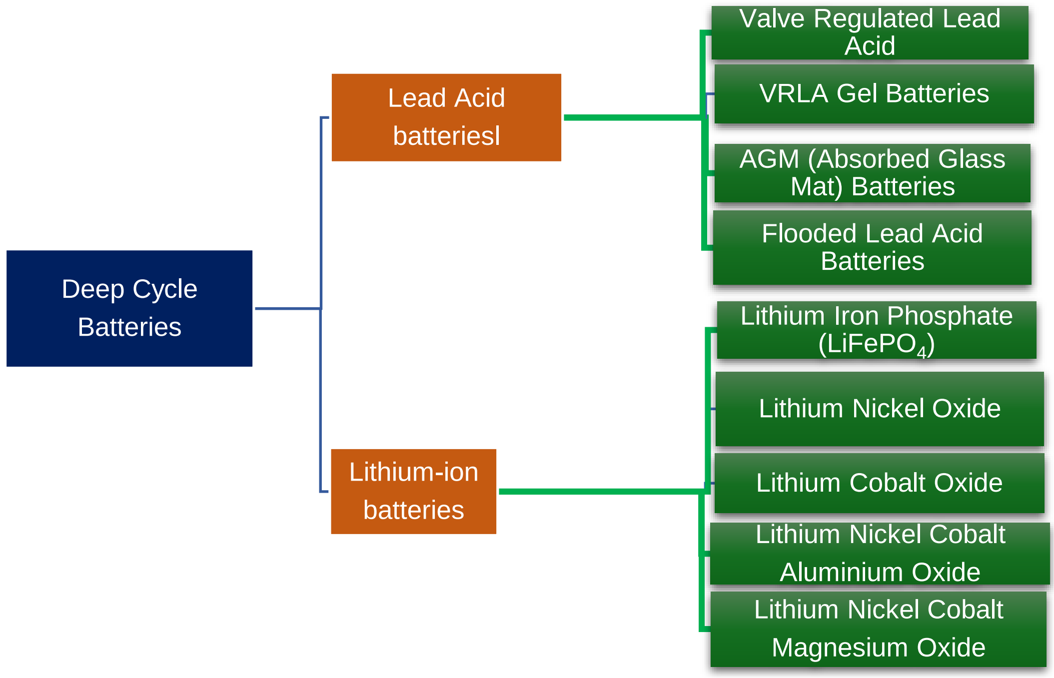

Figure 2.2 Deep cycle battery types (Sobamowo et al., 2024).

Solar street lighting systems commonly use deep-cycle batteries as shown in Figure 2.2 such as lithium-ion and lead-acid batteries, although lead-acid is the more prevalent option (Yoomak and Ngaopitakkul, 2019). Sobamowo et al. (2024) suggest that lithium iron phosphate batteries are the dominant, safest, and most developed variant of lithium-ion technologies possessing desirable thermal and chemical characteristics. Dwipayana et al. (2021) suggested that there are critical technical parameters that must be considered for battery selection. The lead-acid and lithium-ion battery types were compared in depth by Dhundhara et al. (2018) and (Yoomak and Ngaopitakkul, 2019). Their summaries included power density, energy density, capital cost, cycle efficiency, and cycle life as characteristics of comparison. Energy density indicates the amount of energy that can be stored per unit volume. Sobamowo et al. (2024) noted the high energy density of $LiFePO_4$ batteries as compared to lead acid batteries allowing more energy to be stored per unit volume.

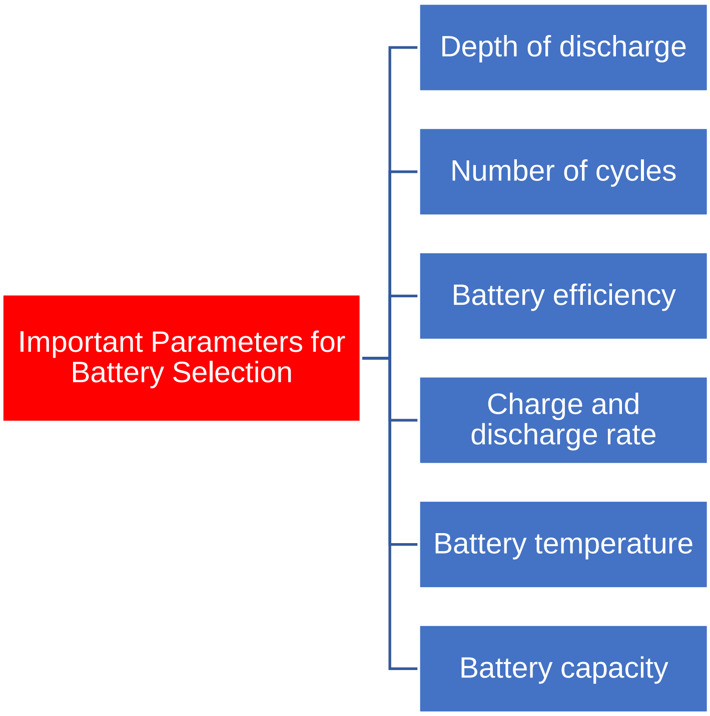

Figure 2.3 Important parameters for battery selection (Dwipayana et al., 2021).

The cycle efficiency indicates the performance of a battery, and it is a product of the discharge efficiency and the charging efficiency. The charging efficiency, η_{charging} is the ratio of the energy stored by the battery and the energy supplied, in this case from the solar PV panel. This is shown in equation [2.1] below.

$$\eta_{\text{charging}} = \frac{E_{\text{stored}}}{E_{\text{supplied}}} \qquad [2.1]$$

The discharging efficiency, $\eta_{\text{discharging}}$ is the ratio of the energy delivered by the battery to the load to the energy stored by the battery. This is shown in equation [2.2] below.

$$\eta_{\text{discharging}} = \frac{E_{\text{delivered}}}{E_{\text{stored}}} \qquad [2.2]$$

The cycle efficiency, η_{cycle} is shown in the equation [2.3] below.

$$\eta_{\text{cycle}} = \eta_{\text{charging}} \times \eta_{\text{discharging}} \qquad [2.3]$$

Table 2.2 Comparison of typical lead acid and lithium-ion battery technologies (Adapted from Dhundhara et al. 2018; Yoomak and Ngaopitakkul, 2019).

	Energy Storage Technologies/Types	
Characteristics	**Lead Acid**	**Lithium Ion**
Power density (W/kg)	180	1800
Energy Density (Wh/kg)	30-40	150-250
Capital Cost ($/kWh)	24-222	500-1400
Cycle efficiency	20-90%	80-90%
Cycle life	500-800	1200-3200

There are energy losses during the battery's charging and discharging. In that regard, batteries with higher cycle efficiency are desirable. Lithium batteries generally have better cycle efficiency than lead acid as shown in Table 2.2 above.

A 'cycle' is defined as discharging from full charge to a point of discharge and then being charged again to full capacity. The cycle life indicates the lifespan of the battery showing the number of cycles that a battery can achieve without performance loss. The number of cycles is dependent on the battery chemistry. Yoomak and Ngaopitakkul (2019) and Dhundhara et al. (2018) showed that the lifetime of lithium-ion batteries can quadruple that of lead-acid batteries. They concurred that lithium-ion batteries were more expensive than lead acid batteries which ordinarily have lower capital costs.

However, despite their higher capital cost, Jamaluddin et al. (2012) and Sobamowo et al. (2024) concurred that lithium-ion batteries have superior characteristics such as longer lifespan, and high energy density as compared to lead acid batteries and recommended them for solar standalone streetlighting systems. Sobamowo et al. (2024) suggest that $LiFePO_4$ batteries are sensitive to temperature changes and noted poor performance at low temperatures as well as reduced efficiency at high temperatures. They further pointed out that $LiFePO_4$ batteries are prone to excessive charging and undercharging as well as overheating. Sobamowo et al. (2024) have a charging temperature range of between 0°C to 45°C and a discharging temperature range of -20°C to 60°C. The uptake of lithium-ion batteries is however set to improve due to the continuous decline of the global price as shown in Figure 2.4 below.

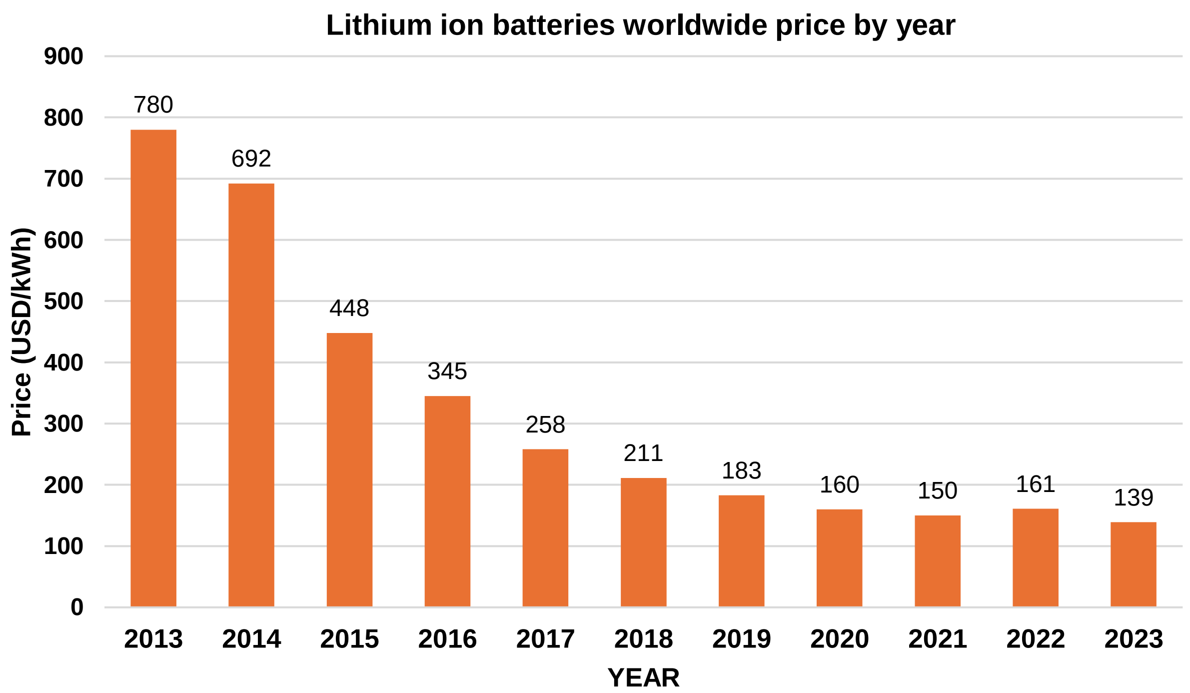

Figure 2.4 Lithium-ion battery prices worldwide from 2013 to 2023 (Statista, 2023).

In summary, there are key technical parameters that need to be considered in the design and subsequent battery choice as energy storage is particularly important in the overall system performance. The lithium-ion batteries generally outperform the lead acid batteries. However, there is a need to understand the charging and discharging processes to determine the overall technical system performance. The energy yield, and subsequent supply to the battery during charging, and the energy delivered to the load during discharge influence the battery lifespan. The battery’s compatibility with a charge controller is also a key consideration in the system design. The following sub-section below is thus important for the investigation of the charge controller’s function within a solar-powered lighting system.

2.1.3 Charge controller

A charge controller has other names that can be used interchangeably such as charge regulator or solar charge controller. Asrori et al. (2020) observed that the market offers several types of charge controllers, notably Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT). Khera et al. (2015) suggest that the charge controller regulates both the charging and discharging of a battery. Sobamowo et al. (2024) noted that the use of compatible charge controllers for some battery types prolongs the battery’s life, prevents premature damage, and also ensures sufficient charging and discharging. Majaw et al. (2018) note that the charge controller is vital in ensuring the proper management and maintenance of batteries. Acharya and Aithal (2020) concurred and added that the proper working of a charge controller improves battery durability. Further elaboration on these charge controller types is provided in the following section.

2.1.3.1 PWM (Pulse Width Modulation) charge controller

Singh et al. (2012) noted that the PWM charge controller operates differently from MPPT variants. They describe the PWM charge controller as a switch connecting the battery and solar panel such that when closed, the two are at the same voltage. PWM charge controllers control the battery charging process by rapidly switching the power supplied to the battery on and off. By varying the width of these pulses, they regulate the battery's charge rate. Majaw et al. (2018) propose that the PWM charge controller maintains a steady voltage for battery charging. As the battery's state of charge rises, its voltage increases. When the battery nears full charge, the controller decreases pulse width resulting in a trickle charge (Majaw et al., 2018). Singh et al. (2012) note that this reduction prevents potential battery gassing and heating up. This charge control method is simple and cost-effective but less efficient than MPPT which will be described in detail in the sections below. The flowchart of a typical PWM Charge controller operation is Figure 2.5 below.

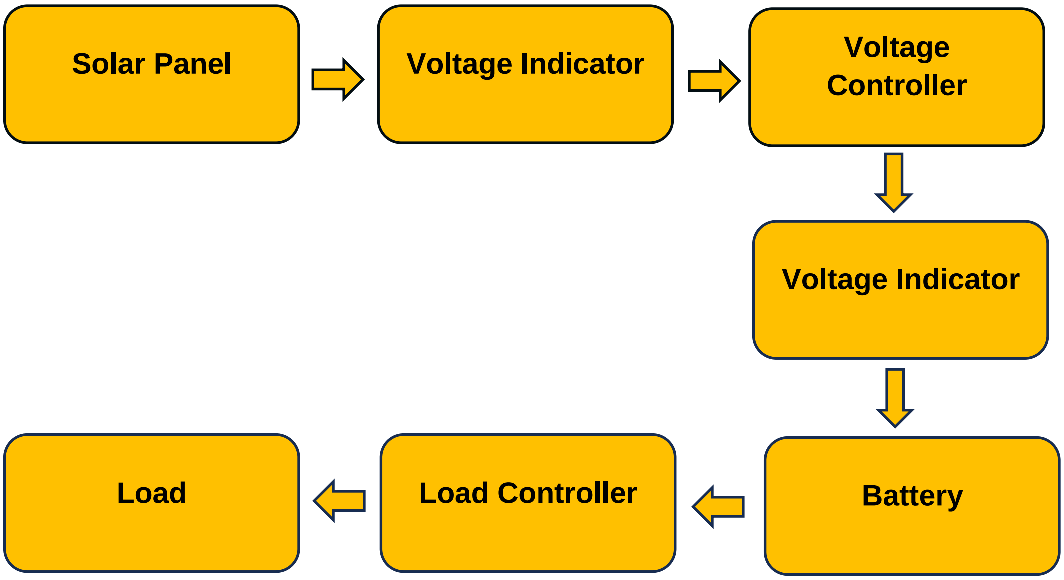

Figure 2.5 Pulse width modulation charge controller flowchart (Adapted from Majaw et al., 2018).

2.1.3.2 MPPT (Maximum Power Point Tracking) charge controller

Asrori et al. (2020) describe an MPPT charge controller as an input converter from the solar panel to different values of direct current (DC) and voltage to suit the instantaneous battery requirements. They further add that its modus operandi results in higher battery charging efficiency as the MPPT quickly compares the solar PV output to the battery's voltage and then prescribes the battery's instantaneous charge current requirements. Parthasarathy and Vijayaraj (2020) noted that solar panels are non-linear power sources and that their output is variable. An example of a typical solar panel's current-voltage curve is shown in Figure 2.6 below.

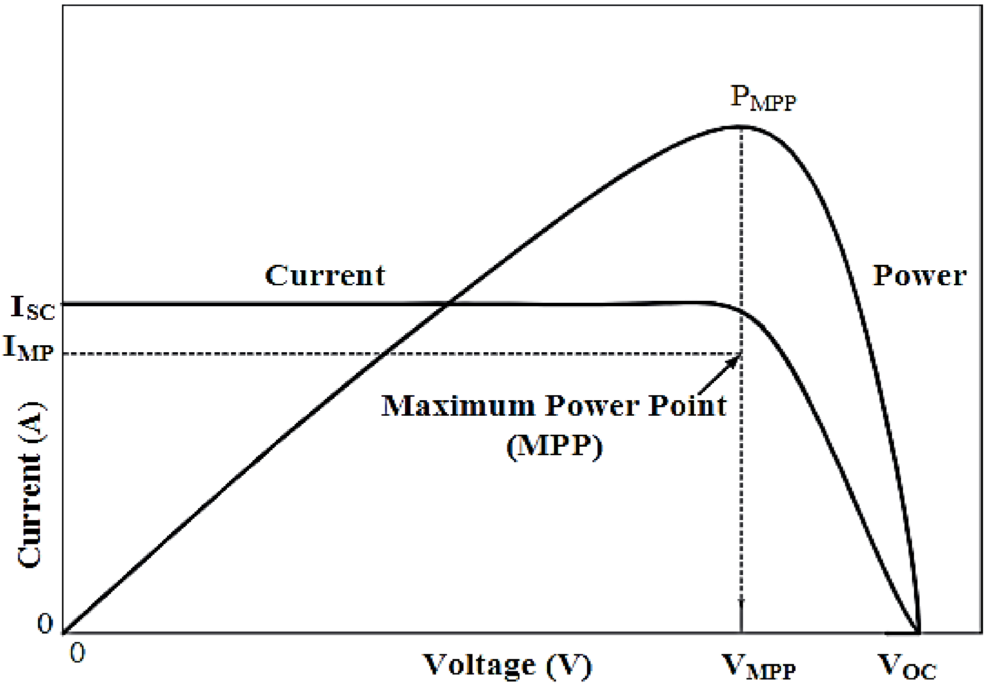

Figure 2.6 A typical current-voltage (I-V) curve for a solar panel (Pathak and Yadav, 2019).

Parthasarathy and Vijayaraj (2020) suggested that the solar panel output is influenced by temperature and light intensity incident on the solar panel. The solar power output is shown in equation [2.4].

$$P_O = V_m \times I_m \qquad [2.4]$$

where P_O is the instantaneous maximum power output from the solar panel.

V_m is the instantaneous maximum voltage output from the solar panel.

I_m is the instantaneous maximum current output from the solar panel.

Table 2.3 Comparison of MPPT and PWM charge controllers adapted from (Majaw et al., 2018).

	Charge Controller	
Aspect	**MPPT**	**PWM**
Efficiency	Higher efficiency (typically 93% to 98%)	Lower efficiency
Energy Harvesting	Energy yield is maximised by dynamic tracking of the maximum power point (MPP) of the solar panels even in variable weather conditions.	Provides a fixed charge rate and has poor adaptation to variable solar conditions
Cost	Usually more expensive due to superior electronics and design features	Typically, less expensive owing to a simpler design
Complexity	More complex design with advanced electronics and algorithms.	Simpler design with basic voltage regulation.
Battery Compatibility	Most in the market have compatibility with various battery types, including lithium-ion.	Limited compatibility with other battery types.
Suitability for Large Systems	Ideal for larger solar power systems due to higher efficiency and energy harvest.	Suitable for smaller systems with lower power requirements.
Temperature Compensation	They typically have temperature compensation features for improved battery charging at varying temperature levels.	Typically, low or no temperature compensation features.
Applications	Suitable in grid-tied and off-grid solar systems.	Recommended for smaller and simpler off-grid systems.
Performance in Low-Light Conditions	Exceptional performance in low-light conditions through dynamic adjustments to maximize available power.	Performance in low-light conditions is low since its working principle depends on fixed voltage regulation.
Maintenance Requirements	Requires minimal maintenance due to automatic tracking and optimisation.	Requires periodic manual adjustments for optimal performance.
Overall System Efficiency	Higher overall system efficiency and energy yield.	Typically, lower overall system efficiency is due to energy losses.
Cost of Ownership	Usually, higher capital cost with a good overall return on investment (ROI) through increased energy production and prolonged battery life.	Lower initial outlay cost but potentially higher long-term costs due to lower energy harvest and accelerated battery wear.

Parthasarathy and Vijayaraj (2020) emphasised the MPPT charge controller's ability to continuously track the maximum power point (MPP) of the solar panels by dynamically adjusting the voltage and current to match the MPP. This dynamic adjustment allows MPPT controllers to extract the maximum available energy from the solar panels, especially in varying weather conditions. Majaw et al. (2018), that MPPT controllers are at least 30% more efficient than the PWM leading to better energy harvest. Using an MPPT charge controller allows a solar panel of higher voltage output compared to the system battery voltage to be used together (Majaw et al. 2018). This leads to more flexibility in system design.

In summary, the charge controller types were compared and investigated. The technical performance of MPPT charge controllers surpasses that of PWM charge controller variants. The consideration of the technical performance of the charge controller is important in the overall system performance. Though the cost of the charge controller may be high, it must not solely deter its purchase, rather the propensity should be on the technical performance metrics such as efficiency, etc. The next section will explore the LED driver's function and its different types and forms.

2.1.4 Luminaire

Luminaires are very important components in solar-powered lighting systems, and their performance is evaluated based on several key parameters. There are different lamp types that are commonly used for streetlighting purposes. These include:

- Mercury vapour (MV) lamps
- Metal halide (MH) lamps
- High pressure sodium (HPS) lamps
- LED (light emitting diode) lamps

2.1.4.1 Key performance criteria parameters

a) Luminous flux and efficacy

In lighting, optical luminous efficacy is a key performance metric for lighting technology comparison. Luminous efficacy is an appropriate metric for the assessment or comparison of different lighting technologies measuring the luminaire's efficiency in converting electrical power input into usable light. The luminous efficacy is defined as the ratio of the usable light output per unit of electrical input power and is measured in lumens/watt (lm/W) (Narula et. al, 2012). Lighting products with higher efficacy are desirable as they consume less energy whilst conforming to the luminous intensity requirements. To achieve the required luminous flux, it is beneficial and cost-effective to use more efficient luminaires to help reduce power consumption.

Wu et al. (2009) noted various efficacies for HPS, LED, and MV lighting. At the time, these values were 72lm/W for LED, 120lm/W for HPS, and lastly 65lm/W for MV. Tahkamo and Halonen (2015) in their research noted an efficacy of approximately 100lm/W for LED and about 25lm/W for HPS which falls in their prescribed 50-150lm/W range. Balsky and Bayer (2011) in Figure 2.7 below confirm the continuous improvement in the efficacy of LED lighting over the years surpassing all the other technologies. The luminous efficacy is continuous improvement cements the LEDs as the current dominant lighting technology. This research will provide more insights into the current efficacies of various products on the market.

Luminous flux is the total luminous output of a luminaire, and it is quantified in lumens. The luminous flux differs from one product to another. The required illuminance in compliance with set standards such as SANS10098-1 and user satisfaction influences the selection of appropriate luminaires for different lighting applications.

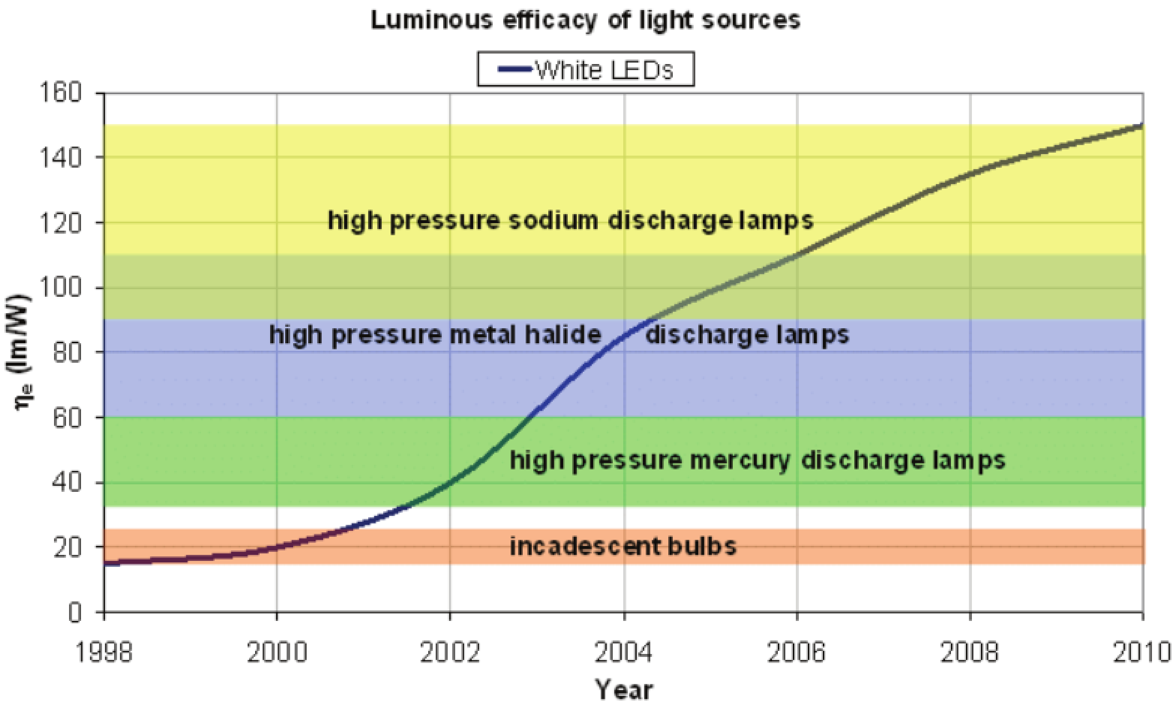

Figure 2.7 Progression of luminous efficacy for different lighting technologies over the years (Balsky and Bayer, 2011).

b) Operational life and lumen maintenance

The lifetime of a lamp is measured in operational hours and the lamp will provide usable light output typically when it reaches 20% of its original output (DFI, 2014). The lifetime values for LED are between 50 000 – 100 000hrs (Pipattanasomporn et al., 2014). The industry prescribes that all LEDs be tested and have LM80 reporting which ensures that say after 50000hrs of operation, the light will be providing 80% of its original luminance. Pipattanasomporn et al. (2014) noted a significant edge in the LED's lifetime in comparison with other conventional lighting technologies. They estimated that the LED's lifetime is over four times more than typical conventional lighting.

c) Power consumption

The power consumption of the luminaire also known as the wattage is measured in Watts. Luminaires with lower wattage are desirable as they consume less electricity resulting in reduced energy costs and carbon emissions. The LEDs are suitable for solar PV lighting applications because of their low energy consumption (DFI, 2014).

d) Illuminance (lm/m^2 or lux) and lighting power density

Illuminance is measured in lux or lumens per square metre indicating the amount of light incident (luminous flux) on a surface per area. Lighting power density is a key metric that is a measure of the amount of electrical power needed to light up an area in compliance with the required lighting requirements for that function (DFI, 2014).

e) Correlated colour temperature (CCT) and colour rendering index (CRI)

Correlated colour temperature indicates the colour appearance of the light produced by a luminaire measured in Kelvins. There is a scale with various CCTs suitable for various applications and these are broken down below and shown in Figure 2.8.

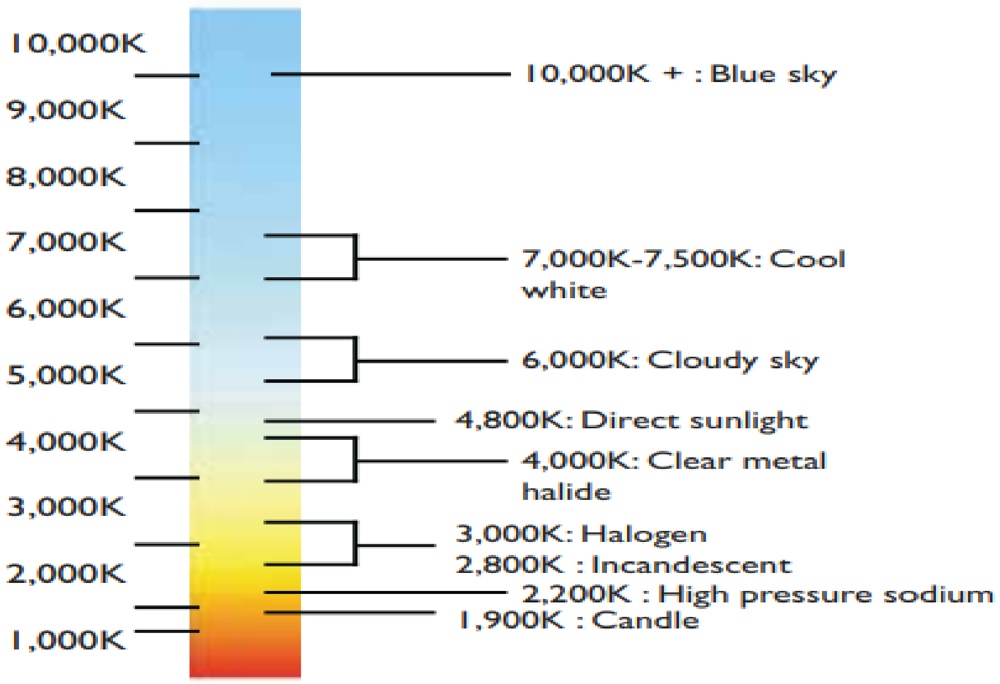

Figure 2.8 Correlated colour temperature scale (Genlux Lighting, 2019).

- Warm White is usually between 2200K – 3000K and the light has a yellowish and softer appearance suitable for a relaxing ambience.
- Cool White is usually between 3300K - 5300K Provides neutral, task-oriented lighting ideal for offices and commercial spaces.
- Snow White (e.g., 6000K): Provides bright lighting levels typically used where visual clarity is most required.

- Daylight (e.g., 6500K): The light emitted resembles natural daylight and usually best suited for industrial and outdoor applications.

The selection of lighting products with the appropriate CCT ratings will depend on the application or use case. LED lighting will CCT values ranging from 3000K to 5500K is suitable for road lighting use (DFI, 2014). The colour rendering index (CRI) measured on a scale of 0 to 100, indicates the luminaire's colour-rendering ability on objects as compared to natural light. For instance, the higher CRI values (typically 80 or above) are desirable and indicate more vivid colours which are true to life. The CRI is used to compare different luminaires of similar equivalent colour temperatures. LED lighting has superior CRI than conventional HPS lighting (Khalil et al. 2017). The white light output from LEDs improves visibility, and light penetration, and reduces glare (DFI, 2014). Visual differences in the lighting output are shown in Figure 2.9 below showing LEDs' superior performance over HPS lighting. Chiradeja et al. (2020) discovered that adequate lighting can reduce road accidents by over 30%.

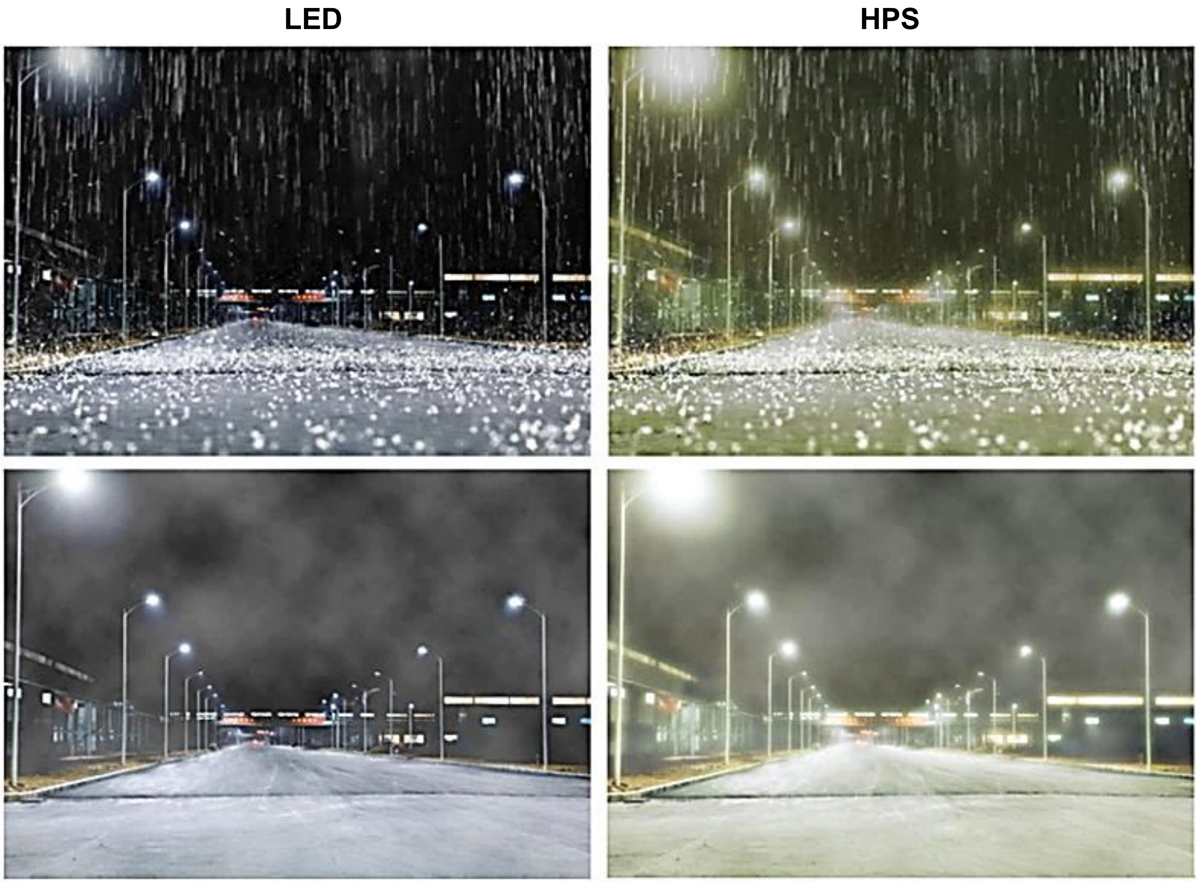

Figure 2.9 Light output comparison of LED and HPS under rainy and foggy settings (DFI, 2014).

f) Light uniformity and luminous intensity distribution

Lighting levels may vary along a carriageway and the contrast must be minimised to improve the user experience of motorists and road users alike. There are two uniformity parameters to consider. These are:

a) Overall luminance uniformity (U_O) is the ratio of the minimum luminance on the carriageway to the average luminance calculated within a specified area of the roadway. (Genlux Lighting, 2019).
b) Longitudinal luminance uniformity (U_L) is the ratio between the least and greatest luminance levels observed along a line of sight across a section of roadway (Genlux Lighting, 2019).

Zima and Ciepłucha (2023) suggested that LED light output uniformity and distribution efficiency outperformed conventional lighting. Luminous intensity distribution describes a luminaire's light output dispersal across various angles. The distribution patterns determine the uniformity of the luminaire's lighting performance, and its suitability fit for the selected use case.

g) Beam and tilt angle

The beam angle defines the spread of the light emitted from the luminaire. A smaller beam angle e.g. 30° means the light spread horizontally is very small but a longer range also known as forward distance in a specific direction. This is suitable for spotlighting. On the contrary, a wider beam angle like 120° will have more horizontal distance coverage and less range. Luminaires can be installed at a tilt angle allowing lighting system designers and contractors alike more flexibility to focus the light output to desired areas as well as have a better design output. In summary, understanding these performance criteria is essential when selecting the right luminaires for different applications. They affect energy efficiency, visual comfort, and the overall effectiveness of the lighting solution, ensuring it meets the specific needs of the environment and its users.

h) Light directionality

LED lighting output is directional resulting in minimal light wastage since the lighting optics focus the output onto the desired areas (DFI, 2014). Conventional lighting technologies do not provide directional light resulting in energy wastage and light pollution (Prommee and Phuangpornpitak, 2016). The superior efficacy coupled with light directionality makes LED lighting an attractive solution for lighting energy efficiency (DFI, 2014).

i) Dimmability

Pipattanasomporn et al. (2014) mentioned that LED’s dimmability sets it apart from other lighting technologies. Dimming allows the adjustment of the lighting intensity of a lamp to reduce energy consumption. They added that the dimming extends the LED's life and doesn't affect the colour output whilst, in contrast, it shortens the life of conventional lighting technologies.

Table 2.4 Summary comparison of different lighting technologies (Pipattanasomporn et al., 2014).

	Lighting Technology			
Characteristics	**LED**	**HPS**	**Metal Halide**	**Mercury Vapour**
Efficacy (lm/W)	20 – 150	50 – 130	65 – 115	24 – 60
CRI (%)	85 – 95	20 – 25	65 – 90	40 -50
Lifetime (hrs)	50 000 – 100 000	2 500 – 24 000^{+}	5 000 – 20 000	12 000 – 24000^{+}
Warm-up time	0 (instant)	3 – 4mins	2 – 5 min	5 – 2mins
Re-strike time	0 (instant)	0.5 – 1min	10 – 20mins	3 – 6mins
Mercury (mg)	0 (instant)	10 – 50mg	10 – 1000mg	10 -1000mg

Chiradeja et al. (2020) and Balsky and Bayer (2011) postulated that LEDs outperformed conventional lighting sources in various aspects such as light distribution and quality, energy efficiency, and lifetime just to mention a few. The HPS lighting has lower efficacy than LED though higher than both metal halide and mercury vapour variants. Khalil et al. (2017) suggested that LED replacement of conventional lighting leads to operating cost reduction. For the CRI comparison, the HPS had lower CRI scores as compared to Metal Halide. The downside of High-Intensity Discharge (HID) lamps is that they time lag to produce lighting output once switched on. These are also known as warm-up time and re-strike time.

The life of the luminaire is dependent on the proper working of the LED driver as the power supply source. The next section will explore the luminaire which is the light source and how the different characteristics tie into the overall system considerations.

2.1.5 LED driver

The function of LED drivers is to regulate the current and voltage supplied to the luminaire ensuring the LED's efficiency and safe operation (Beliakova et al., 2023). Esteki et al. (2023) noted that the LED driver is a power supply device. They add that the LED drivers can either be internal and built-in the luminaire itself or external where the LED driver will be connected separately. Esteki et al. (2023) categorised LED drivers into two types namely Constant Voltage and Constant Current. Constant current LED drivers have a fixed current output within a specific voltage range, and they are typically used in applications where consistent brightness level maintenance is critical, such as commercial lighting, outdoor lighting, and automotive headlights. On the other hand, constant voltage LED drivers are typically used in applications where the number of LEDs in a series or parallel configuration is variable, such as LED strips and electronic signage.

Ismeil et al. (2023) suggested that different categories of LED drivers depend on the input power source. The LED driver types can be AC-DC or DC-DC (Ismeil et al., 2023). DC-DC converters are most suitable for solar-powered streetlighting as the LEDs are DC electrical loads and the solar panel is a DC power source. Ismeil et al. (2023) noted that this makes the system more efficient as there is no conversion unlike in AC-DC variants. Lamar (2020) suggested that LED driver efficiency, durability, and compliance with regulations are critical for the lighting system’s performance. Arias (2012) noted that considering the streetlight's daily energy consumption, the LED driver's technical performance is more important than its cost. Dasohari et al. (2024) recommended that a solar-powered streetlight system have a high-quality LED driver to ensure efficient dimming, output regulation, and increased efficiency. The section below summarises diverse types, their applications, and potential causes of failure.

2.1.5.1 Combination of Charge Controller and LED Driver

In practice, various manufacturers have developed specialised products that combine the functionality of a charge controller and the LED driver. Integration of these functions results in optimized battery charging and LED lighting load output, ensuring efficiency and reliability.

Figure 2.10 Example of solar charge control with LED driver (SRNE, 2023).

The typical combined charge controller-LED driver unit, shown in Figure 2.10, allows the streetlight to run in off-grid mode. The charging and light output control parameters can be loaded using a remote-control unit.

2.1.5.2 Hybrid Control Unit

In recent times, manufacturers have brought innovative products onto the market such as hybrid control units which are designed to accept both solar PV power and mains supply units.

These combine the functionality of a charge controller, LED driver, and mains supply unit. The main supply unit enables the integration of utility supply for on-grid operation in a hybrid system.

The mains supply unit allows for 220V AC input thereby facilitating battery charging from the grid power supply or other AC power sources and load supply. The mains supply unit converts the grid power supply to DC power to provide the correct charge/discharge current and load output control. Including the hybrid control units allows for source input priority selection i.e. either DC or AC as priority. AC priority will allow for "on-grid mode" to preserve the battery charge and DC priority will allow for "off-grid mode".

The LED driver’s role in the overall technical performance of a lighting system cannot be ignored. The integration of solar charge controller functionality and load operation into one component results in easier installation reducing the number of system components. A typical hybrid control unit for solar streetlighting system is shown in Figure 2.11.

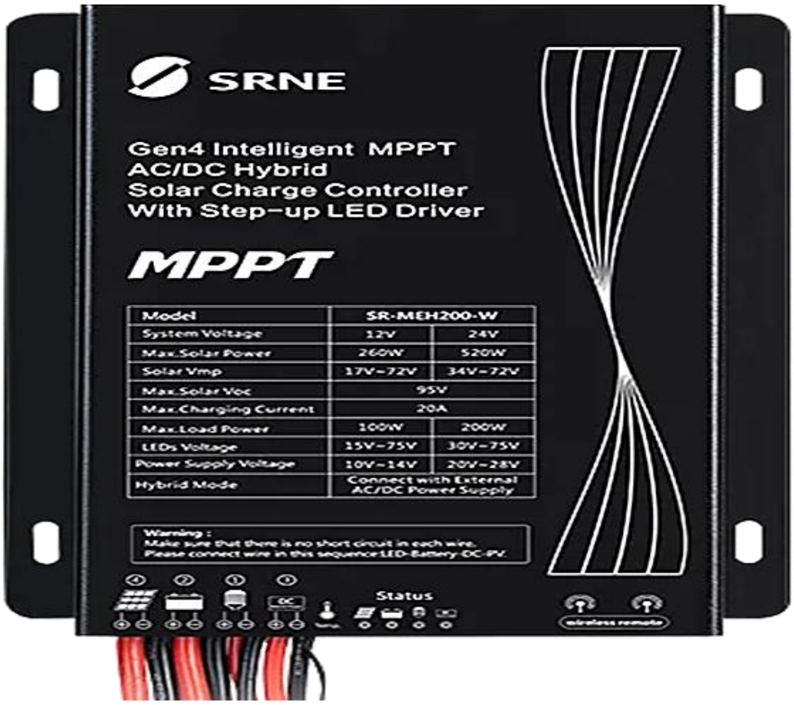

Figure 2.11 Example of a hybrid control unit for solar streetlights (SRNE, 2023).

A typical hybrid control unit system layout is shown in Figure 2.12.

where 1 is the lamp, 2 is the battery 3 is the Solar PV panel and 4 is the AC/DC power switch.

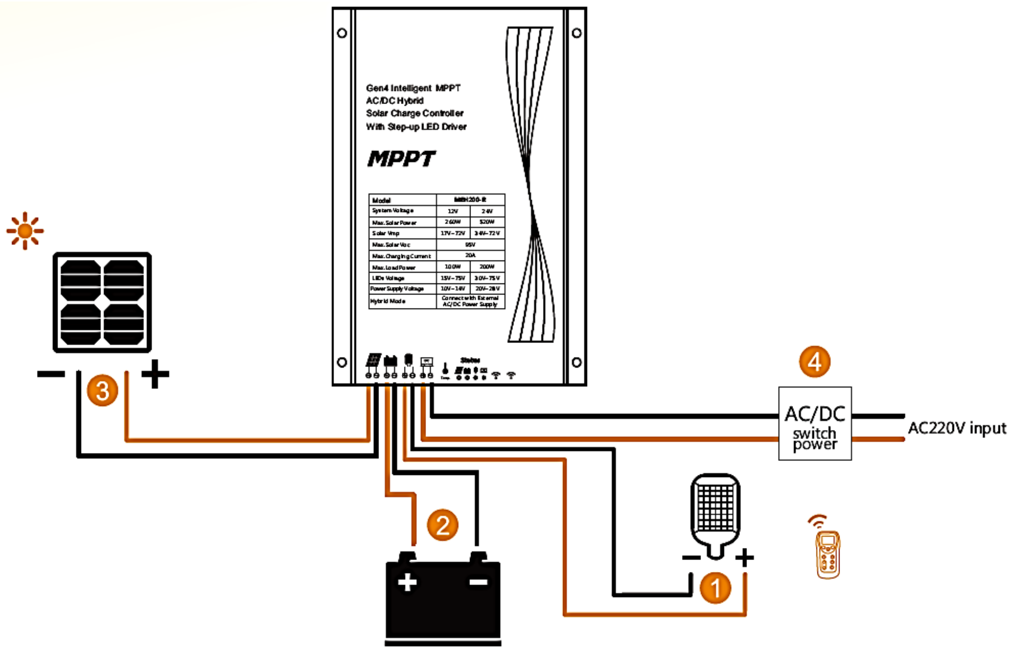

Figure 2.12 System layout of a typical hybrid control unit (HCU) (SRNE, 2023).

The selection of the lighting technology should be based on accurate data and consideration of the application and an overall analysis of each option available. LED lighting is the best lighting technology that is commercially available. The next section explores the lighting design considerations based on the various lighting arrangements as per the road lighting applications.

2.1.6 Review on solar PV performance

2.1.6.1 Effect of meteorological conditions on solar PV energy output

Kimathi et al. (2018) and Mardikaningsih et al. (2016) both had assessment sites in Indonesia. The sites had different potential solar energy generation yields despite being in the same country. Mardikaningsih et al. (2016) reported that the solar energy generation potential would reach 4,8kWh/m^2 per day in their study site whilst it was 5,33 kWh/m2/day for Karmi Athi et al. (2018). Yousif et al. (2019) considered solar energy as a dependable and environmentally friendly energy source and touted it as a solution for climate change and pollution mitigation. However, the authors bemoaned the energy output fluctuations mainly due to solar radiation changes and that it is highly dependent on environmental factors.

Mahmood and Majeed (2022) observed that the peak solar panel output is specified at 25˚C, such that any temperature deviations will lead to an output reduction as prescribed in the manufacturer's datasheet. Benghanem et al. (2023) pointed out the effect of temperature coefficient of the solar PV panel concluding that the PV panel current output decreases when the temperature increases. In addition, they postulated that cell temperature increases correspond to reduced solar PV panel efficiency. El-din et al. (2014) noted that an increase in temperature resulted in a decrease in the solar PV panel open circuit voltage output whilst the short circuit current slightly increased. Karki (2015) added that a temperature increase in an electric circuit leads to increased resistance.

Satsangi et al. (2018) noted the linear relationship between ambient and cell temperatures. The ambient temperature is the temperature of the surroundings whilst the cell temperature is the temperature on the solar PV surface. Gray et al. (2003) derived an equation to model the cell temperature if the ambient temperature of a site is known. Equation 2.5 is as follows:

$$\mathbf{T}_{\text{cell}} = \mathbf{T}_{\text{amb}} + [G \times \frac{(\text{NOCT}-25)}{800}] \qquad [2.5]$$

where

- $\mathbf{T}_{\mathbf{cell}}$ is the cell temperature.
- $\mathbf{T}_{\mathbf{amb}}$ is the site location's ambient temperature.
- **G** represented the solar irradiance measured in W/m^2.
- NOCT is the nominal operating cell temperature as provided by the solar PV panel manufacturer.

Patt et al. (2013) noted significant solar PV panel output reduction during periods of prolonged cloudiness. Satsangi et al. (2018) suggested that the solar PV panels' efficiency was highest during the rainy season which they attributed to the natural cleaning occurring when the rain falls onto the solar PV panels.

The effect of environmental factors on solar PV system performance was explored in this section. Every area has different meteorological conditions hence the need to select the right solar PV equipment applicable to the area in question. The next section delves into the effects of dust and soiling on solar PV system energy output.

2.1.6.2 Effects of dust and soiling on solar PV energy output

According to Salamah et al. (2022), despite Africa's solar energy resource abundance, dusty environments and air pollution are common. Salamah et al. (2022) categorised dust as material or particles of substances available in that site's atmosphere. They described dust deposition or 'soiling' as a critical factor affecting solar PV efficiency behind temperature and solar irradiance. Each site has its dust effect which is site-specific and dependent on the site's location and other prevalent conditions (Salamah et al., 2022). García et al. (2011) suggested there is greater soiling on horizontally mounted panels than in tilted solar PV panels. Benghanem et al. (2023) from their study concluded that under low solar radiation conditions, as shown in the section above, the dust effect was greater in polycrystalline than in monocrystalline solar PV panels. Salamah et al. (2022) pointed out that dust accumulation or soiling of solar PV panels affects their technical performance and solar PV technology feasibility due to limited sunlight penetration.

Maghami et al. (2016) highlighted the causes of the accumulation of different dust types and the factors that influence it as shown in Figure 2.13. They noted that the soiling effect is exacerbated by the progressive dust accumulation.

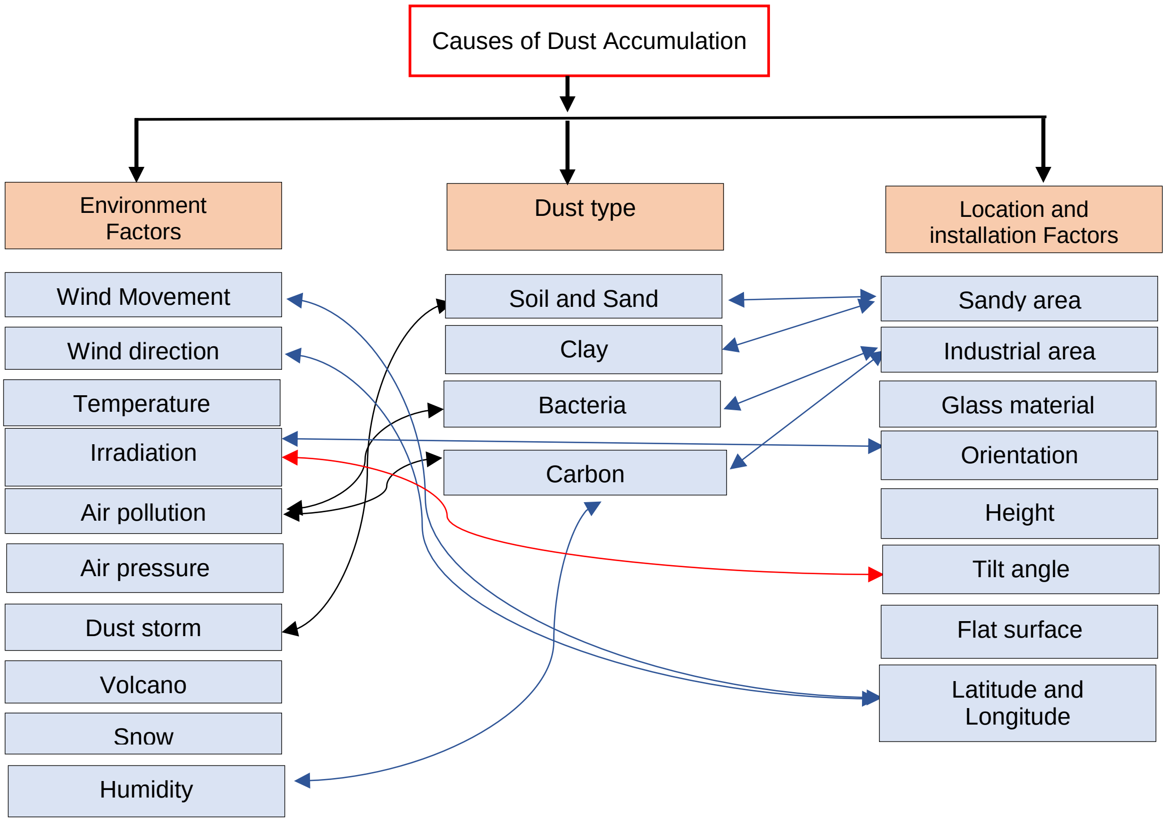

Figure 2.13 Dust accumulation causes of solar PV module surfaces, factors involved, and the dust types (Maghami et al., 2016).

In that same vein, Mahmood and Majeed (2022) concurred that dust and dirt accumulation on the solar panel surface leads to the solar PV panel's energy output reduction. This energy output reduction in turn adversely affects the overall technical performance of the solar PV system such as its efficiency and potentially its economic metrics.

Olorunfemi et al. (2022) concluded that a mere 1% decline in the overall performance of a solar PV system has a negative impact on financial metrics, such as the internal rate of return. To counter this, Kalam et al. (2020) recommended regular solar panel cleaning to ensure improved and more reliable energy generation. The cleaning of the solar panel is important in ensuring good technical performance. In wrapping up this section, it is noted that the effects of dust and soiling cannot be overlooked thus understanding and managing its impact is crucial for optimizing solar PV output. This leads us to the subsequent subsection, where we will shift focus and explore the effect of tilt and latitude on solar PV output. The effect of tilt and latitude will be investigated as another key factor in maximizing the efficiency and effectiveness of solar energy systems.

2.1.6.3 Effect of tilt and latitude on solar PV output

The tilt angle is shown in Figure 2.14. Taşçıoğlu et al. (2016) discovered that the solar panel tilt angle and latitude affect their energy output. They also noted that the maximum output from a solar panel is achieved when the solar panel is perpendicular to the incident sun rays. However, since their study was conducted in Turkey, located in the northern hemisphere, Taşçıoğlu et al. (2016) noted that the solar panel should be facing due south. This is a stark contrast to the norm in South Africa, where the solar panel should be facing due north as it is located in the southern hemisphere. García et al. (2011) suggested that the energy output reduction is greater in horizontally fixed than in tilted angles. They approximated energy reduction margins of between 8-22% for horizontal tilt (0°) whilst it was between 1-8% on 45° tilt angle.

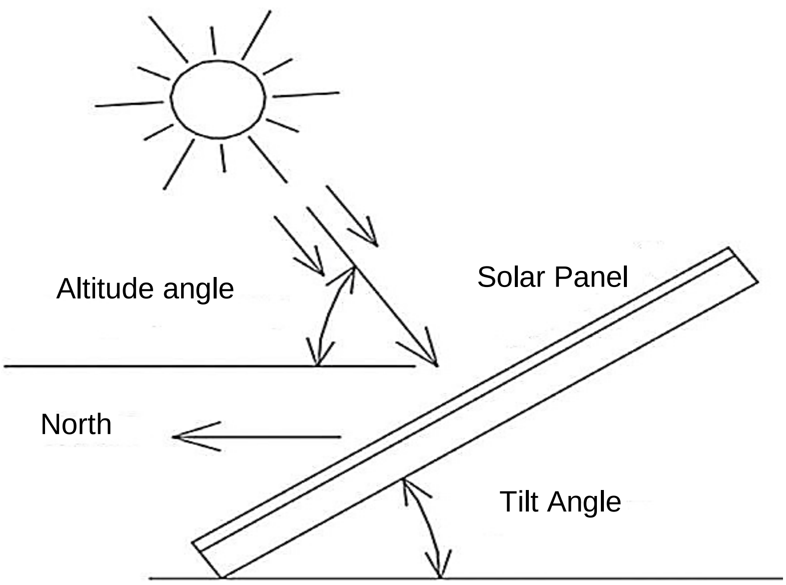

Figure 2.14 Diagram showing solar PV module facing due north at optimum tilt angle (Adapted from Mohammed et al., 2018).

Hertzog and Swart (2015) in their South Africa study recommended the tilt angle should equal the specific site's latitude and or a positive or negative tolerance of 10° to the site's latitude. They attributed this to the seasonality which particularly affects the solar radiation availability and fluctuations over the year as well as sun ray's inclination on the solar PV surface. This section investigated the effect of tilt and latitude on solar PV performance. In summary, the tilt angle is a key parameter that should be considered in the solar PV system's design and performance. The solar panel as the energy generation device within the system plays an important role in the overall system performance. The solar PV panel's positioning and angle of inclination and the subsequent effects have been explained in this sub-section. The energy from the solar PV panel needs to be optimized and its storage will need to be explored in the dedicated sub-section ahead.

2.2 Lighting design, arrangements, and road classification

2.2.1 Lighting design simulation

For accurate streetlight design, some parameters need to be input within the simulation program. These include: -

- Pole's distance from roadway
- Light centre height
- Boom tilt angle and
- Light overhang

These parameters differ from one area to another and as such they must conform to the prevalent stipulated specifications. For instance, Thailand has adopted the following on most main roads as shown in Table 2.5. (Yoomak and Ngaopitakkul, 2019). In South Africa, SANS 10098-1 is the dedicated public lighting standard set by the national standards body, the South Africa Bureau of Standards (SABS). The standard is the basis for the public lighting guidelines dealing with different road types.

Table 2.5 Road-lighting design specifications for simulation in Thailand by Yoomak and Ngaopitakkul (2018).

Parameter	Value
Mounting Height	9m
Boom Tilt Angle	15°
Light Overhang	1.5m
Boom Length	2.5m

For South Africa, the road surfaces comply with CIE R3 and are adopted as the standard for use during lighting design simulation (SABS, 2014). in South Africa, the road width is usually 3.7m. The mounting height, as shown in Table 2.6, will depend on the road type and the specifications of the road (SABS, 2007). The SANS 10098-1 standard suggests that the light overhang is usually between 0 to 3 metres and is typically a quarter of the luminaire mounting height (SABS, 2014).

Table 2.6 Mounting height for different road classification (SABS, 2014).

Road Classification	Mounting Height
A1	12 – 20m
A2	10 – 12m
A3	9 – 10m
A4	8 – 9m

The parameters necessary for streetlighting design are shown in Figure 2.15.

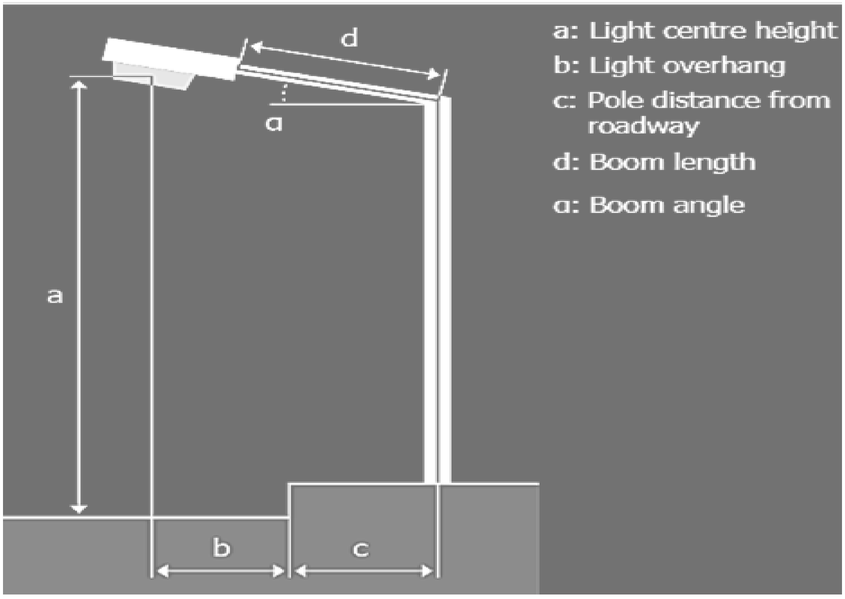

Figure 2.15 Schematic showing the parameters for lighting simulation from DIALux Evo (DIALux, 2024).

2.2.2 Use of simulation software in similar previous studies

The use of simulation software enhances the quality of the research output. By using the simulation software tools, accuracy is improved as well as saving money and time reducing the need for physical experimental work. There are various studies where simulation software tools have been used as shown in Table 2.7.

Table 2.7 Examples of studies where simulation software has been used.

Study	Study Location	Aim	Simulation Software Used
Katyara et al. (2018)	Pakistan	Techno-economic evaluation of solar streetlights	HOMER
Ali and Ammari (2022)	Jordan	Design of a wind-solar hybrid LED streetlight	HOMER
Dizon and Pranggono (2020)	England	Smart streetlighting assessment.	StreetlightSim
Zima and Cieplucha (2023)	Poland	Efficiency analysis for streetlighting retrofitting	DIALux
Karmiathi et al. (2018)	Indonesia	Techno-economic analysis of solar-powered lighting	DIALux
Hasan et al. (2019)	Bangladesh	Design and feasibility analysis of solar PV streetlighting	RETScreen

The benchmarking of the simulation software shown in Table 2.8 enabled the researcher to select the most suitable tool for accurate and flexible system design. The section that follows will focus on the streetlight arrangements, road classification, and the different solar streetlighting architectures. These areas will be considered during the system design and the inputs into the simulation software will produce a guideline on the overall project layout.

Table 2.8 Benchmarking of simulation tools.

Criteria	DIALux	PVSyst	HOMER	Helioscope
Scope	Primarily designed for indoor and outdoor lighting design.	Primarily used for solar PV system simulations.	Allows comprehensive microgrid system modelling and optimisation.	Primarily used in solar PV system design and performance analysis.
Lighting Design	Users can produce an end-to-end lighting design solution. System capabilities provide visualisation and technical analysis.	Limited or no capabilities for lighting design; focuses on solar energy system simulation.	There are no built-in capabilities for lighting design. It is primarily focused on energy system optimisation.	It is designed for solar PV project design and shading analysis and not lighting design.
Solar Resource Analysis	The software primarily focuses on lighting design. There is no solar PV analysis.	Provides advanced solar PV resource simulation, and scenario modelling considering various technical parameters like tilt, azimuth, shading, and more.	Provides site-specific solar resource assessment and shading analysis.	The software is suitable for shading analysis and solar project design with a wide database.
PV System design	It is not designed for photovoltaic system design.	Comprehensive design and simulation of solar PV systems, and site assessments.	Incorporates PV system design and sizing as part of microgrid optimisation.	Designed for solar PV system design and optimisation.
Energy Yield Calculation	There is no provision for detailed solar system energy yield calculations.	Provides detailed energy yield calculations, factoring in site-specific meteorological data.	Provides detailed energy production analysis for optimized microgrid configurations.	Calculates energy production considering shading, tilt, and system losses.
Financial Analysis	There are no built-in financial analysis tools for solar PV projects.	In-built financial modelling tools, allowing economic viability assessment of solar PV projects.	Includes economic analysis tools for evaluating the economics of microgrid solutions.	Limited financial analysis tools compared to comprehensive project design.
User interface	User-friendly interface for lighting design; allowing intuitive for system users.	Not user-friendly, especially for those without a background in solar energy.	Relatively user-friendly interface for microgrid design; though it can be challenging for new users.	Intuitive interface for solar PV project design and shading analysis
Integration with Other Tools	Limited integration with other tools; mainly focused on lighting-related software.	Integration capabilities with various tools and meteorological data databases, make it suitable for comprehensive solar system analysis.	May have limited integration options compared to more specialised software tools.	Integrates with various PV equipment databases which are regularly updated and support import/export functionalities.
Cost	Typically, more cost-effective for lighting design purposes.	Relatively expensive due to its specialized features and capabilities for solar energy systems.	Variable license costs are based on the edition and usage.	License costs are relatively high, and variable based on the software version and usage scenario.
Support & Updates	Regular updates and support for lighting-related queries.	Continuous updates and support for solar-related functionalities, reflecting industry trends.	Offers on-demand support and regular updates for microgrid modelling and optimisation.	Offers support and regular updates for solar project design and analysis.

2.2.3 Review of streetlighting arrangements

Figure 2.16 shows a roadway outline for a dual carriageway comprising two lanes per side with a median separating the left-hand and right-hand sides. For this research, a similar dual carriageway is considered. Each lane is 3.7 metres wide whilst the median **Z** is 1.5 meters wide separating the two sides. Each side is denoted by **Y** and will thus be 7.4 metres wide. **X** depicts the pole-to-pole spacing length which is a key metric that affects the lighting quality on the surface as well as the financial outlay for the project.

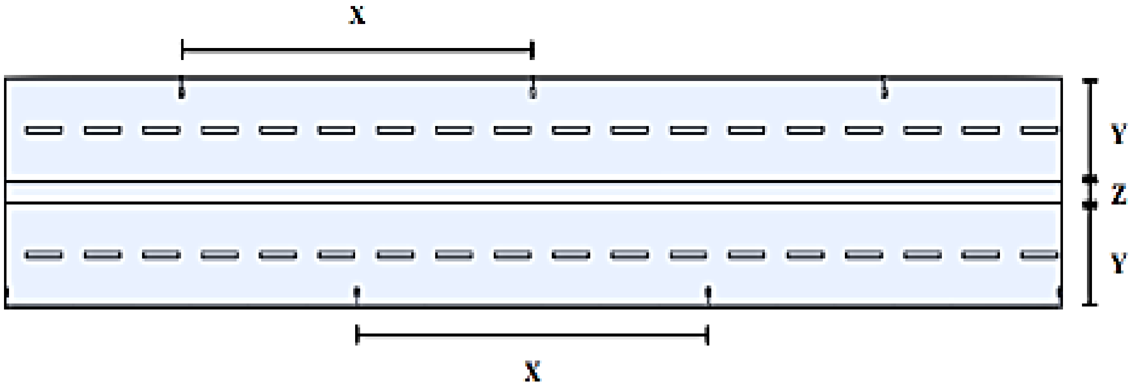

Figure 2.16 Dual carriageway road outline (Yoomak and Ngaopitakkul, 2019).

Mardikaningsih et al. (2016) suggested that the lighting arrangement will depend on the site. Various lighting arrangements will be considered for the streetlighting simulation. These include:

- Two-sided arrangement
- Two-sided arrangement offset/staggered arrangement
- Twin central arrangement.

The luminaire arrangements are shown below in the sub-section that follows showing their differences.

2.2.3.1 Two-sided streetlighting arrangement

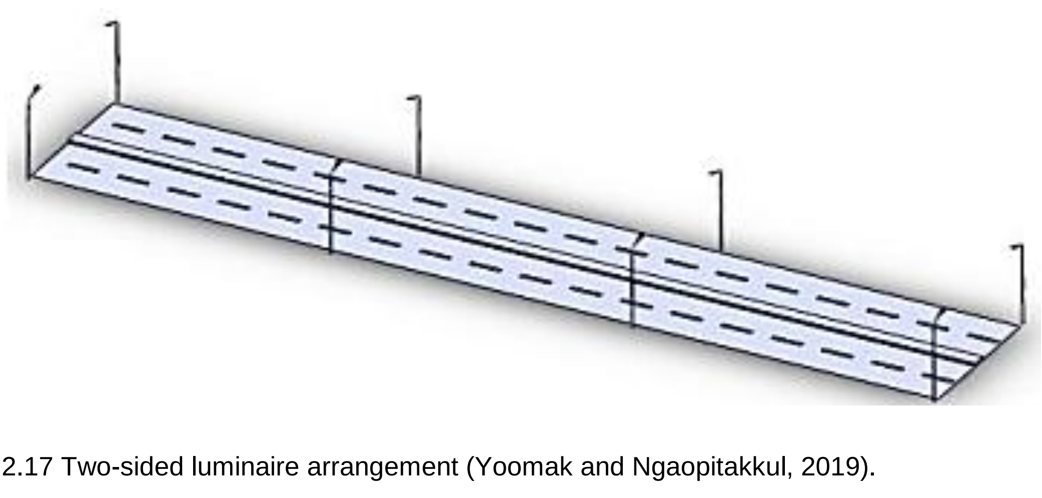

Figure 2.17 Two-sided luminaire arrangement (Yoomak and Ngaopitakkul, 2019).

In the two-sided configuration, luminaires are installed on both extremes of the road as depicted in Figure 2.17. Both ends of the road will have streetlight poles and the poles will be facing each other from one side to the other to another.

2.2.3.2 Staggered streetlighting (Two-sided arrangement offset)

In this arrangement, the luminaires are placed on both extremes of the sides forming a zig-zag pattern as shown in Figure 2.18. This arrangement also helps achieve lighting uniformity and avoid shadowing.

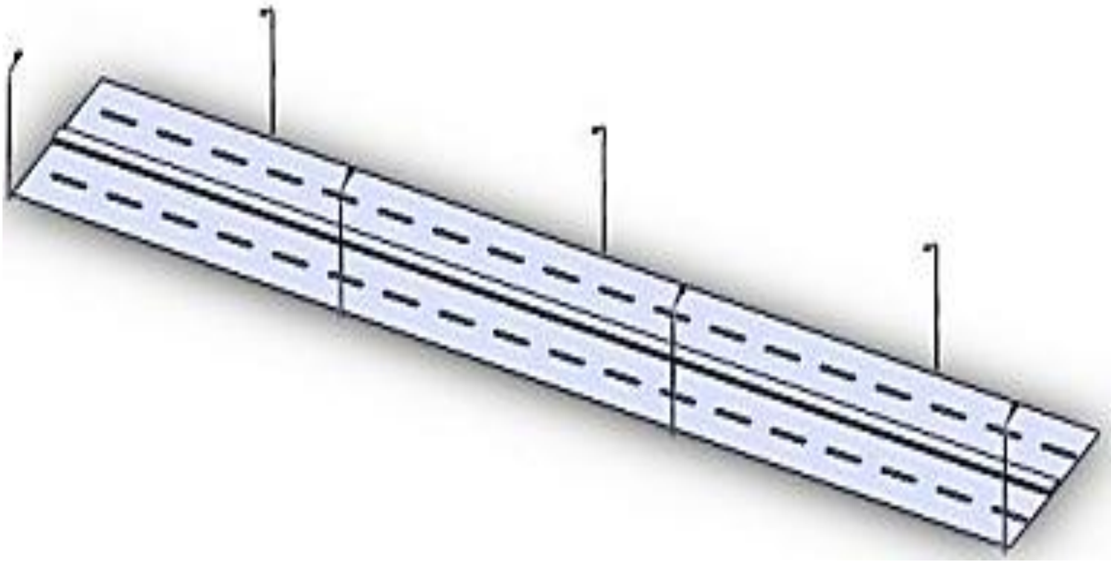

Figure 2.18 Two-sided arrangement offset/Staggered luminaire arrangement. (Yoomak and Ngaopitakkul, 2019).

2.2.3.3 Twin central streetlight arrangement

This common configuration depicted in Figure 2.19 entails the installation of streetlight poles in the middle of the road and two luminaires are mounted on each pole. Some other variations of this arrangement may include more than 2 luminaires mounted per pole.

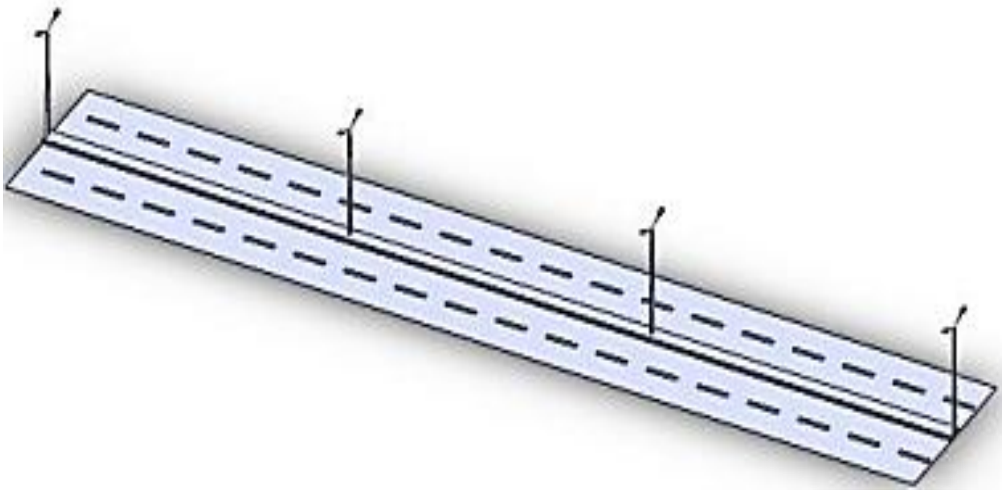

Figure 2.19 Twin central luminaire arrangement along the median. (Yoomak and Ngaopitakkul, 2019).

2.2.4 Review of road classification

In South Africa, the road design and subsequent classification are in consideration of the function, traffic volume during darkness, and other relevant factors. Each road class will accordingly have its appropriate criteria and metrics for conformance. The Class A roads are classified in a hierarchy as shown in Table 2.9.

- National Roads:
- Provincial Roads:
- Regional Roads:
- Municipal Roads:

Table 2.9 Class A road classification as per SANS10098-1 (Regent Lighting Solutions, 2023).

Road Class	Road Geographical Jurisdiction	Description	Example of roads in the Cape Town Metropolitan Area
A1	National	Major highways and expressways typically connect major cities or regions and speed limits on these routes usually surpass speeds of 90km/hr.	• N1 (National Route 1) • N2 (National Route 2)
A2	Provincial	Major roads usually connecting urban centres within a province and with speed limits not exceeding 90km/hr,	• M5 (Provincial Route 5) • M2 (Provincial Route 2)
A3	Regional	These are major arterial roads within a region or district. Their speed limits do not surpass 60km/hr.	• R300 (Regional Route 300) • R102(Regional Route 102)
A4	Municipal	Local roads within urban areas connect communities, residential areas, and major roads.	• Main Road, Claremont • Jip de Jager Drive, Bellville

Class A roads, usually receive significant investment and attention in terms of design, maintenance, and development as they are critical in the facilitation of trade and commerce, industry, and travel in various regions along their paths. For example, major highways connect major centres such as the N1 (Cape Town to Johannesburg), N2 (Cape Town to Durban), and N3 (Durban to Johannesburg) often have multiple lanes, allowing for safe and efficient movement of significant traffic volume.

Figure 2.20 below indicates the road classification according to the SANS10098-1 standard. The required different information such as the lighting distribution uniformity for each road type is shown. The data presented in Figure 2.20 is critical for design considerations.

Type of Road	Road Cross Section																							
	Without Median												With Median											
	Maximum traffic volume during darkness (motor vehicles per hour per lane)																							
	>600				300				100				>900				600				200			
	Ln	Uo	UL	TI	Ln	Uo	UL	TI	Ln	Uo	UL	TI	Ln	Uo	UL	TI	Ln	Uo	UL	TI	Ln	Uo	UL	TI
A1	2	0.4	0.7	15	1.5	0.4	0.7	20	1	0.4	0.6	20	2	0.4	0.7	15	1.5	0.4	0.7	20	1	0.4	0.6	20
A2	1.5	0.4	0.7	20	1	0.4	0.6	20	0.8	0.4	0.5	20	1.5	0.4	0.7	20	1	0.4	0.6	20	0.8	0.4	0.5	20
A3	1	0.4	0.6	20	0.6	0.4	0.5	20	0.5	0.4	0.5	20	1	0.4	0.6	20	0.8	0.4	0.5	20	0.5	0.4	0.5	20
A4	0.75	0.4	0.5	20	0.5	0.4	0.5	20	0.3	0.3	0.5	25	0.75	0.4	0.5	20	0.5	0.4	0.5	20	0.3	0.3	0.5	25

Figure 2.20. Class A road classification as per SANS10098-1 (Regent Lighting Solutions, 2024).

2.3 Review of solar-powered lighting configurations

There are various solar-powered streetlighting configurations prevalent in the market. These include off-grid and hybrid. The different types are described in the section below.

2.3.1 Off-grid Configuration

This system type consists of components as mentioned such as luminaire, solar panels, batteries, and charge controller just to mention a few. In this configuration, there is no grid connection, and thus the system is designed to operate independently.

2.3.2 Hybrid Configuration

This system type comprises more than one energy source to power the lighting load. A hybrid lighting system usually uses existing grid-connected luminaires. Their difference from off-grid solar lighting systems is that they have a secondary source of power e.g. wind and grid/mains supply connection. In a grid-connected system, the solar panel charges the batteries during the daytime for overnight discharge. In the event of battery over-discharge or lapsing of the set operation times for battery and solar power or battery failure, the main supply will power the LED light as a backup power source. In hybrid setups, the output source priority can be set up to suit the site requirements and application case considering all the available energy sources. The hybrid systems allow for grid support in periods of poor or bad weather.

2.3.3 Solar powered lighting classification

2.3.3.1 Integrated (all-in-one) solar streetlight system

The all-in-one streetlights are innovative and compact which combines all the typical components of a solar streetlight into one unit. This design allows for installation ease and reduced installation time. A typical all-in-one solar streetlight unit as shown in Figure 2.21, includes a motion sensor that is activated when movement is detected thereby increasing the brightness, making them more energy-efficient, and providing added security. Some of the all-in-one streetlights are post-top mounted and some are side-mounted fitting into the bracket of existing streetlight poles.

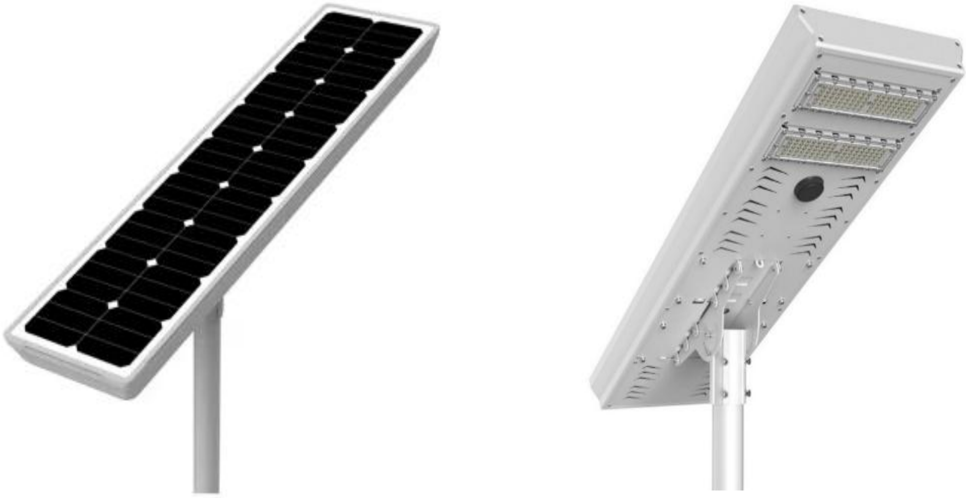

Figure 2.21 All-in-one streetlight system showing LEDs (left) and a top view showing the solar panel (right) (Philips Lighting, 2023)

2.3.3.2 Non-integrated solar streetlight systems

These are the solar streetlighting systems that are very common and the first to come to mind. The subcomponents of the systems are detached and non-integrated as individual parts though connected. This adds flexibility to the design as the components can be sized accordingly.

Figure 2.22 Non-integrated solar streetlight with battery on pole top (BEKA Schréder, 2023).

2.3.3.3 Differences between Non-integrated and integrated solar streetlights

The two distinctive solar streetlight types are compared below in Table 2.10.

Table 2.10 Solar streetlight type comparison.

Non-integrated solar streetlights	Integrated solar streetlights
Wider battery type selection range e.g. Lithium-ion, lead-acid, etc.	Limited battery type use as it uses lithium-ion batteries.
More backup time with the ability to add more batteries to meet the application requirements	Less backup time as it usually has a limited battery size to fit into the streetlight housing.
More flexibility of use as the solar panel can be directed accordingly whilst the lamp can be positioned.	Limited flexibility of use due to the solar panel and LED lamp being in the same direction as it is a compact and combined unit.
Enhanced ergonomic design.	It is more visually appealing.
Usually requires a bigger capital outlay.	Usually requires a smaller capital outlay.
The design is bulky as the components are separated though connected.	A compact design combining all the streetlight components into a singular unit.

2.3.4 Solar-powered lighting system architectures

Various authors have suggested various system architectures which they analysed in their study. Some of the suitable options are covered in the below section. These include: -

- Individualised solar lighting system with individual energy storage (Yoomak and Ngaopitakkul (2019).
- Centralised solar lighting system with individual energy storage (Chiradeja et al. (2020)

2.3.4.1 Solar-powered lighting system with individual energy storage

In this system architecture, each pole has individual energy storage for each luminaire and as a result, it will run independently. In this system, Yoomak and Ngaopitakkul (2019) suggested the use of an AC luminaire (220Vac input). Each pole has a solar panel mounted which is an energy-generation device and connected to an MPPT charge controller to charge the battery efficiently. In addition, the system comprises an inverter that converts DC (Direct current) electricity from the battery (energy storage) to AC (alternating current) which is usable by the AC luminaire.

In this arrangement shown in Figure 2.23, the lighting output control is on a pole-by-pole basis. Some losses occur during the DC-AC energy conversion which is a drawback of this system. Currently, there are many DC luminaire variants on the market which when deployed can improve the feasibility of the system by eliminating the cost of having an inverter incorporated into the system. DC luminaires are typically more efficient and the higher the efficacy, the smaller the batteries and solar PV sizes required leading to cost-effective solutions (Development Finance International, 2014).

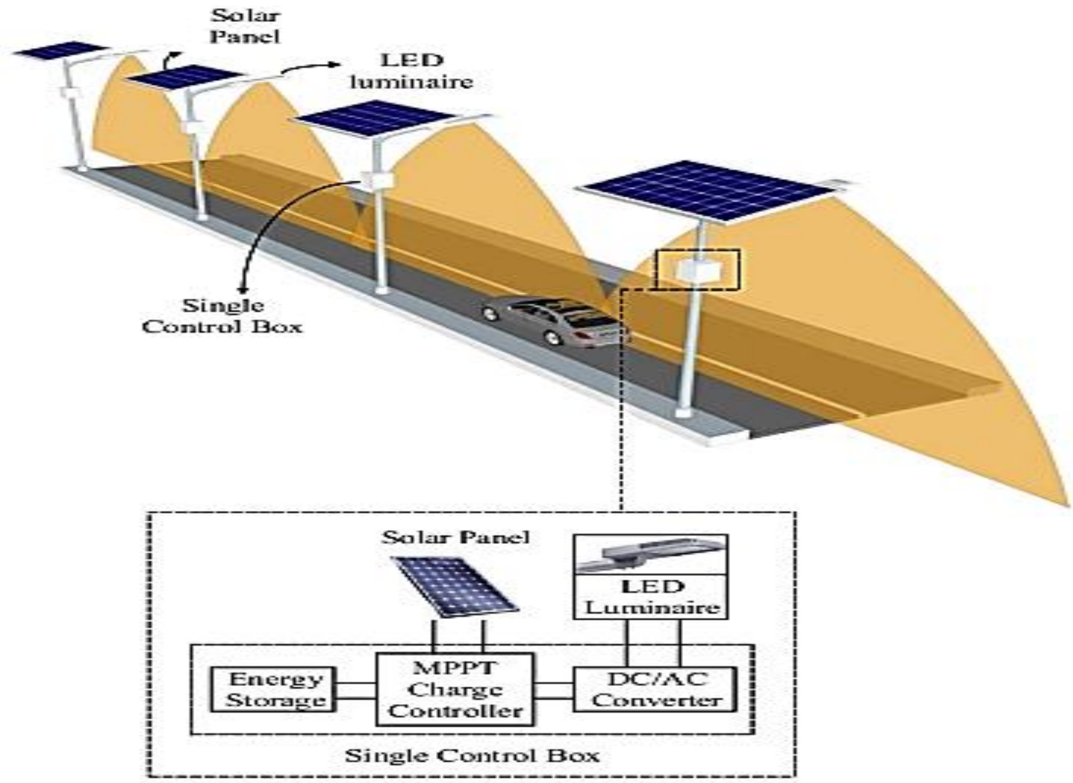

Figure 2.23 Diagram showing individualised solar lighting system (Adapted from Yoomak and Ngaopitakkul, 2019).

2.3.4.2 Solar-powered lighting system with centralized energy storage

Contrary to the above, in this system architecture, there is a centralised energy storage from where each luminaire is powered and as a result, it will operate independently. This system configuration shown in Figure 2.24 below, according to Yoomak and Ngaopitakkul (2019), maintained the use of an AC luminaire (220Vac input). However, the power output from each solar panel mounted on each pole is combined through a junction box and then connected to one MPPT charge controller. In addition, the system comprises a single inverter that converts DC (Direct current) electricity from the battery (energy storage) to AC (alternating current) which supplies power to multiple AC luminaires simultaneously instead of one.

In this arrangement, the lighting output control is centralised. In addition to the losses that occur during the DC-AC energy conversion, which is a drawback of this system, there is a higher technical risk. If for instance, there is a component failure, such as inverter failure, then all the lights connected to that inverter will be non-functional leading to user dissatisfaction, and various adverse effects associated with the absence of lighting on that road. There is a higher risk of vandalism and tampering, as the system components if stolen may easily be adapted for other uses such as home systems. For instance, the thief may use the inverter to power their household. There is a need to use components that reduce theft, vandalism, and technical risks.

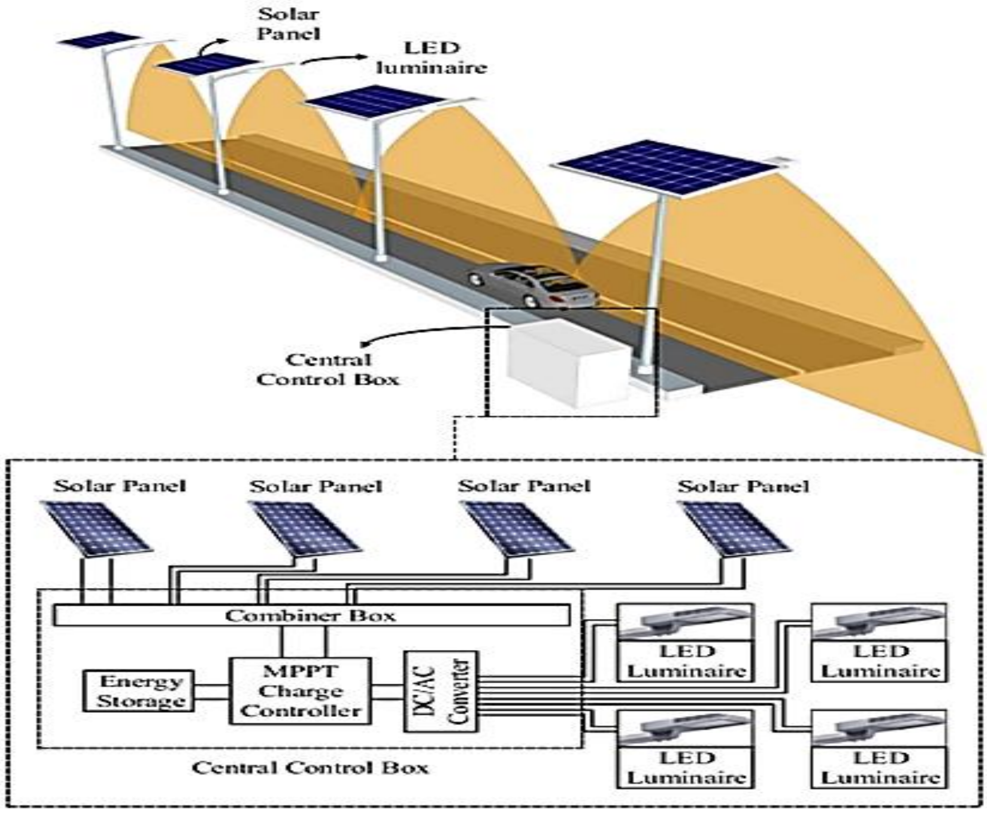

Figure 2.24 Diagram showing solar lighting system with centralised energy storage adapted from Chiradeja et al. (2020).

2.4 Economic and technical performance analysis

2.4.1 Economic analysis parameters

Ali and Ammari (2022) used the levelized cost of energy measured in $/kWh to assess the economic feasibility of the solar PV streetlight system. Pipattanasomporn et al. (2014) used other various metrics for comparison. They used net present value (NPV), savings-to-investment ratio (SIR), payback period, and adjusted internal rate of return (AIRR) for analysis. Karmiathi et al. (2018) used life cycle cost, cost of unit energy produced, NPV, and profitability index (PI). Katyara et al. (2018) used the metrics opted for by Karmiathi et al. (2018) except for the profitability index (PI). Rajeev and Nair (2012) used the simple payback period and the life cycle cost analysis (LCCA) method to compare solar-powered streetlights and conventional grid-connected options. Nugraha and Desnanjaya (2023) considered the simple payback period and net present value as the economic metrics for consideration. Hasan et al. (2019) considered various metrics namely the internal rate of return (IRR), net present value (NPV), benefit-cost ratio (BCR), and annual life cycle savings in a similar study in Bangladesh. The simple payback method is not necessarily ideal as it doesn't consider inflation rates, system components' lifetime, and operating and maintenance costs.

2.4.2 Reliability and technical performance of key parameters

Solar photovoltaic technologies are believed to have a low efficiency-to-cost ratio which has reportedly hampered their adoption in other areas (Fashina et al., 2012). The authors propose that ensuring the reliability and long-term technical performance of solar PV systems is essential to boost investor confidence. They noted that the failure of solar PV systems is primarily attributed to battery and charge controller failure which contributed 14.29% and 28.6% respectively (Fashina et al., 2012). For instance, they concluded that due to exposure to high-temperature conditions and uncleaned solar panels, the battery life is halved. Their study noted that their higher dust accumulation on the solar panel surface which is mounted horizontally hence the recommendation to have a tilted mounted panel.

2.4.3 Time length of period of assessment

Numerous studies such as by Rajeev and Nair (2012), Karmiathi et al. (2018), and Katyara et al. (2018) conducted a techno-economic analysis of conventional lighting versus solar-powered streetlights over twenty years. However, Mardikaningsih et al. (2016) compared the two options over twenty-five years. Archibong et al. (2020) compared solar-powered streetlights against diesel-powered lighting over eight years. Tahkamo and Halonen (2015) selected the length of the assessment period to be thirty years. The researcher will consider the length of the assessment period to be twenty years.

2.4.4 Contribution of Good Lighting to Community Safety and Well-being

Kaplan and Chalfin (2021) concluded that brighter street lighting makes people feel safer when outdoors at night as compared to dimmer traditional lighting. In addition, the authors found out that more than 50% of road users from their survey, were prepared to pay extra charges to enable the adoption of brighter, efficient lighting. Murray and Feng (2015) noted that adequate lighting reduces criminal activity through enhanced visibility and improved perpetrator detection.

2.4.5 Review Discussion

This literature review was made up of different subsections. It explored solar streetlighting systems looking at the different building blocks and the impact of environmental variables on photovoltaic (PV) panels and overall system technical performance. Studies by Karmiathi et al. (2018) and Mardikaningsih et al. (2016) underscored the variability in solar energy generation potentials, highlighting the need for tailored approaches in different geographical contexts. Insights from Yousif et al. (2019) and Mahmood and Majeed (2022) shed light on the environmental and economic dimensions of solar energy utilisation, emphasizing the importance of sustainable energy practices and temperature regulation for optimal system efficiency. Additionally, research by Benghanem et al. (2023) and El-din et al. (2014) revealed the relationship between temperature fluctuations and PV panel efficiency, proposing valuable insights for enhancing solar energy systems' design and operation.

2.5 Review recommendations for future studies

2.5.1 Vandalism and theft prevention

Further studies must explore strategies by leveraging other technologies to curb vandalism and theft prevention of solar street lighting. Potential theft and vandalism have become a deterrent in the deployment of solar street lighting projects. There is a need to investigate how solar streetlighting can be remotely monitored to ensure there is continuous visibility of the system's technical performance, and fault detection just to mention a few.

2.5.2 Advanced temperature control strategies

There is a need to conduct future research into innovative temperature control mechanisms, such as active cooling or thermal management systems, to mitigate the impact of temperature fluctuations on solar panel efficiency. The studies must investigate the feasibility and effectiveness of such strategies in energy output optimisation.

2.5.3 Smart grid and technology integration

Future studies must investigate the integration of solar street lighting systems with smart grid technologies to enable grid interaction, demand response, and energy management capabilities. In addition, the investigation of the integration of solar streetlighting and other smart technology such as emergency calls, security cameras, Wi-Fi modems, ambient conditions monitoring, vehicle and pedestrian counters, and EV charging points will be important to create value from every streetlight pole installed. There is a need to investigate the integration of smart technologies, such as IoT (internet of things) sensors and data analytics, to enhance the monitoring and control of solar energy systems. Future studies must explore how real-time data can be leveraged to optimize system performance and energy utilisation.

2.5.4 Impact of dust and soiling

Future in-depth studies should investigate the impact of dust accumulation and soiling on solar panel efficiency in the different areas where solar PV systems are to be deployed. In tandem with this, there is a need to explore innovative cleaning solutions or solar panel coatings as mitigatory initiatives on the adverse dust and soiling effects. The economic and environmental implications of maintenance practices on system performance must also be researched in-depth.

2.5.5 Impact assessment studies

The researcher recommends comprehensive impact assessment studies to evaluate the social, economic, and environmental benefits of solar street lighting. For instance, South Africa's accurate statistics on lighting's effect on crime decrease are unavailable. Future research must assess the effects of improved lighting on public safety, crime rates, community well-being, and economic development and be well-documented to provide evidence-based insights for decision-makers.

2.5.6 Lifecycle analysis

Another future study avenue must focus on the lifecycle analysis of solar street lighting systems to assess their environmental footprint, including manufacturing, installation, operation, and end-of-life disposal. The study must consider factors such as embodied energy, carbon emissions, and resource depletion to inform sustainable design and procurement practices.

2.5.7 Public-private partnerships

There is a need for further studies to focus on how public-private partnerships can be leveraged and facilitated for the deployment of solar streetlighting projects through collaborative funding, expertise sharing, and resource pooling. Case studies must be done on how such projects are financed across the world and we may be able to replicate it in our setting.

2.5.8 Human-centric design

Further research studies must prioritise user-centred design principles in the planning and implementation of solar streetlighting projects particularly for Africa to enhance user experience and safety. The studies must be multi-faceted considering factors such as light quality, colour rendering, glare control, and lighting aesthetics to create well-lit, comfortable, and visually appealing urban environments.

2.5.9 Resilience planning

Upcoming studies must lead to resilience plans for solar streetlighting systems to address potential risks and vulnerabilities, such as extreme weather events, cyber threats, and equipment failures. The studies must help develop contingency protocols, and disaster recovery strategies to ensure continuous operation and service reliability.

2.5.10 Cross-disciplinary research and development

The researcher recommends future cross-disciplinary research collaborations between academics, lighting designers and manufacturers, urban planners, practising engineers, sociologists, and environmental scientists to address complex challenges in solar streetlighting through research development. By fostering interdisciplinary approaches to innovation, problem-solving, and knowledge exchange, there will be holistic and sustainable urban lighting solutions for the greater good.

By addressing these recommendations in future studies, researchers can advance the knowledge frontier in solar energy systems and their applicability to contribute to the development of sustainable and efficient renewable energy solutions.

Chapter 3, the subsequent chapter, is a key element of the dissertation. It explores the methodology which was used in conducting the research. The research design inclusive of the use of simulation tools is also discussed. The alignment of the research objectives with the methodology is presented.

CHAPTER THREE

RESEARCH DESIGN AND METHODOLOGY

3.0 Introduction

This chapter outlines the research methodology employed. The research design, which aligns with the research's objectives is outlined. The data collection, processing and analysis are presented. The chapter substantiates the analytical techniques used, such as DIALux simulation software for modelling lighting performance and financial analysis tools for economic viability evaluation. This systematic approach fosters clarity, and transparency thereby enhancing the research's credibility and providing a solid foundation for the study's findings. The research used mainly quantitative data collection and analysis methods. This approach offered a viable strategy for exploring research questions by leveraging the strengths of quantitative research methodologies. This approach provided a more holistic and in-depth understanding of the variables under investigation. The research involved a combination of primary and secondary data sources, including surveys, interviews, and document analysis.

The selection of a quantitative research approach for this study was influenced by several key factors supported by existing literature. By design, quantitative research focuses on objective measurement and statistical analysis providing a robust framework for this study evaluating the effectiveness and economic viability of solar-powered lighting systems. Creswell and Creswell (2017) suggests that a quantitative approach in research enables researchers to draw conclusions from data which are scalable, generalised and applicable to other similar conditions. The scalability and applicability of research findings from quantitative research approaches is further corroborated by Johnson and Onwuegbuzie (2004). The application of research findings across different settings as suggested by Johnson and Onwuegbuzie (2004) is essential in deriving and proposing policy recommendations in the context of broader urban design basing on this study's outcomes. Ahmad et al. (2019) and Sukamolson (2007) suggest that this quantitative research approach enhances objectivity in measurement and reduces research bias leading to enhanced result accuracy, reliability and validity. This study's primary aim focuses on the comparison of the cost-effectiveness and technical performance of solar-powered streetlighting systems against conventional grid-powered lighting. Venkatesh et al. (2013) suggests that employing the quantitative research approach enables the comparative analysis of the numerical data on capital costs, operational expenses and energy savings. The differences and similarities in their performances are thus clearly presented and crucial for making informed decisions regarding future infrastructural investments. Bryman (2016) suggests that the well-structured nature of this quantitative research approach ensures consistency allowing for replicability and easier comparison across similar studies in different settings.

However, the selected quantitative approach has its own shortcomings. Creswell (2018) notes that focusing excessively on numerical data may lead to overlooking some contextual factors critical to the overall understanding of the research problem. Bryman (2016) suggests that risk of misinterpretation of quantitative results due to the violation of assumptions in the analysis or misapplication of statistical techniques may arise. In addition, Ahmad et al. (2019) notes that the rigidity of the quantitative research structure can restrict the researcher's ability to adapt their inquiries based on new findings or feedback from participants, thereby inhibiting a deeper exploration of complex issues. Ahmad et al. (2019) further notes that predetermined hypotheses in quantitative research approaches can limit the exploration of other variables and possibly overlooking other significant relationships that could provide enhanced insights.

In conclusion, despite the aforementioned limitations, the quantitative research approach's ability to provide clear and measurable insights renders it suitable and effective for this study. The quantitative research approach aligns with the research aims and objectives, ensuring a solid foundation for data-driven conclusions. Selection of the quantitative research methodology is therefore both justified and strategically beneficial for attaining the study's objectives. The proposed research was structured in the integral steps below:

3.1 Research methodology

This research aimed to comprehensively address the research objectives through a systematic and structured approach:

Research Objective 1: To determine the optimal solar lighting system architecture of equivalent functionality to the conventional grid-powered lighting tailor-made for Cape Town.

To achieve this research objective, a multi-step methodology was employed. First, an in-depth literature review was conducted to understand existing solar lighting system architectures, streetlight configurations, and their applicability to the unique characteristics of Cape Town. The lighting requirements and urban layout of different areas within Cape Town were analysed to inform the system design. The researcher considered a 1km stretch of tarmac dual carriageway with two lanes per side under the road classification within the Cape Town Metropolitan area. DIALux simulation software was subsequently utilized to model and determine the lighting output from an LED luminaire suitable to replace HPS lamp streetlights. The proposed solar lighting system configuration, accounting for variables such as lumen output and meteorological data, shading, and potential obstructions was determined. A comparison between the proposed solar streetlight system and the conventional grid-powered lighting was done thereby assessing their performance and functionality. This objective was achieved in section 4.1 of this document.

Research Objective 2: To determine cost-effectiveness by comparing initial investment, ongoing expenses, and long-term financial benefits of solar lighting versus conventional grid-powered lighting.

The cost-effectiveness evaluation involved a blend of quantitative analyses. Data was collected on upfront costs, particularly the sub-system components' prevalent prices, installation expenses, and operational maintenance costs associated with solar street lighting systems. Energy consumption and related costs for both options were estimated based on historical data and anticipated usage patterns. Future electricity tariffs were estimated using historical average annual electricity tariff increases. Long-term financial benefits of solar lighting systems, including energy savings were forecasted. By factoring in the prevalent interest rate, financial/economic metrics such as net present value (NPV), discounted payback period, and internal rate of return (IRR) were calculated to evaluate cost-effectiveness. Sensitivity analysis assessed the impact of varying parameters such as component pricing and electricity tariff on the cost-effectiveness results. This objective was achieved in section 4.3 of this document.

Research Objective 3: To determine the energy consumption and potential savings from solar-powered lighting in Cape Town.

This objective was achieved in section 4.3. The energy consumption and potential savings achieved through solar-powered lighting were assessed. Potential savings were calculated based on the optimum proposed design versus the existing grid-powered traditional lamp. A comparison was made between the energy consumption data from solar lighting systems and from conventional grid-powered systems. By analysing these data, the energy savings achieved by solar lighting systems were quantified.

Research Objective 4: To evaluate solar-powered streetlighting's technical suitability in replacing conventional streetlighting under Cape Town meteorological conditions using simulation tools.

Assessing the technical feasibility involved a combination of data collection and simulation. Meteorological data from the NASA database, including solar irradiance, weather patterns, and temperature fluctuations, were gathered for the Cape Town Metropolitan area. The output from this simulation tool was used to design the solar lighting system under varying weather conditions. The researcher ensured the lumen output of the proposed solar-powered streetlighting system complies with the set standards such as EN13201:2015. The assessment of the systems' durability was crucial for estimating operation and maintenance costs, replacement costs, and overall economic viability. The different system components were considered including factors such as battery cycle life and durability of other components. In addition, pole-to-pole spacing for the proposed solar streetlighting was determined. The optimal spacing ensuring illumination uniformity across the target area while minimizing energy consumption and installation costs was determined using DIALux. Considering the lighting requirements, beam angles, and recommended spacing guidelines helped determine the most efficient arrangement of lighting poles. The luminous efficacy of the proposed LED luminaire was assessed to see how it affects system design, cost, and its reliability. The objective was achieved in sections 4.1, 4.2 and 4.3.

Data analysis enabled the determination of technical feasibility. This comprehensive methodology ensured a structured approach to addressing each research objective, yielding robust results and insights into the techno-economic assessment of solar-powered lighting in the Cape Town Metropolitan area.

3.2 Data collection design and analysis methodology

The data was collected from both primary and secondary sources. The primary data for this study was collected from the City of Cape Town Open Data portal, manufacturer's datasheets, and marketing materials from lighting and component suppliers. The researcher considered a 1km stretch of tarmac dual carriageway with two lanes per side under the road classification within the Cape Town Metropolitan area. By limiting the research study to a 1km stretch, a focused and manageable scope for the techno-economic assessment is achieved. The 1km road length allows for detailed analysis of system performance, energy consumption and the cost effectiveness. The 1km length serves as pilot project framework which is scalable for longer and similar routes in Cape Town. Choosing a shorter length would limit the study's scope whilst selecting a longer stretch could complicate the data collection and analysis. In addition, tarred dual carriageways are representative of common road types in the city of Cape Town context enhancing their suitability for a case study. On the other hand, since dual carriageways typically support higher traffic volumes, investigating the lighting requirements is important. The researcher extracted geographical location coordinates for Cape Town for further processing in the NASA database simulation tool. The solar streetlighting system design was concluded by combining this data with the DIALux simulation program output system design. The complex lighting requirements of dual carriageways necessitated a thorough lighting design suing DIALux and evaluation of the proposed solar streetlighting system.

Secondary data was collected through desk research from relevant sources, such as municipal records and reports, energy and lighting policy documents, textbooks, and academic literature. The data analysis involved the use of software such as DIALux and Microsoft Excel to determine the financial/economic metric values and data visualisation through graphs. The summary of the steps taken in this study is shown in Figure 3.1 below.

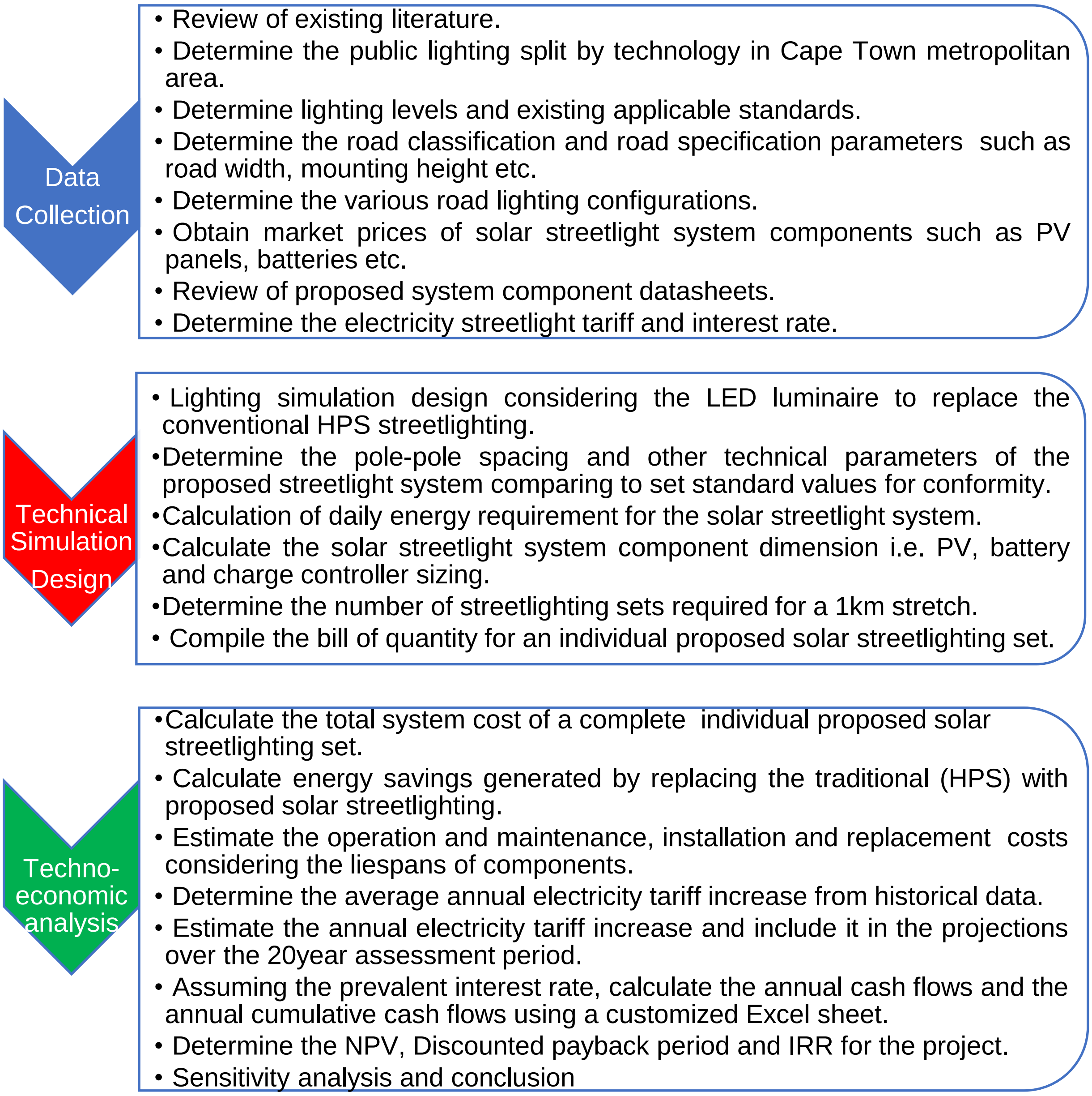

Figure 3.1 Summary of methodology showing key steps of the research study.

3.3 Data analysis

The data analysis was critical for the evaluation of techno-economic viability of solar-powered lighting systems in the Cape Town Metropolitan Area. In this study, comparative analysis of the different lighting technologies was conducted. In addition, the performance metrics of solar-powered lighting systems were compared against conventional HPS street lighting systems. This enabled the researcher to calculate the energy savings accumulated from switching from conventional streetlighting to solar-powered streetlighting. A comprehensive cost-benefit analysis was performed to assess the financial implications of transitioning to solar-powered street lighting. The analysis revealed the upfront costs of the solar PV streetlighting system components as well as the system setup costs. Key expenses such as operation and maintenance, component replacement costs, and potential energy savings were calculated. The analysis also considered the historical trends in electricity tariffs to project future operational costs. The economic analysis projected the long-term financial benefits of solar lighting systems over a 20-year period.

The DIALux simulation tool was employed to model the lighting performance of the proposed solar street lighting systems as part of the technical simulation analysis. The lighting design simulation assessed the proposed solar PV streetlighting system configuration, including pole spacing and luminaire selection for optimal lighting output. Climatology data from the NASA online simulation portal including solar irradiance was analysed and integrated into the proposed system design to derive the capital expenditure. The simulation output results were analysed providing critical insights into the expected lighting performance for determining the technical feasibility of the proposed solar PV streetlight solution.

To evaluate the overall economic feasibility of the solar-powered lighting systems, several financial metrics were calculated and analysed. The net present value (NPV) was calculated to determine the present value of future cash flows generated by the proposed solar streetlighting project. A positive NPV indicated a financially viable investment. The internal rate of return (IRR) was calculated to assess the return on investment and evaluate the attractiveness of the project. The payback period was also calculated to determine the time required to recover the initial investment through savings generated by the solar PV streetlighting solution.

Lastly, a sensitivity analysis was conducted to evaluate how variations in key parameters would impact the economic viability of solar-powered lighting systems. This included identifying key variables such as electricity tariffs and battery pricing for sensitivity testing. Identifying the key variables with most substantial impact on the project’s financial metrics is very important. Different scenarios were developed to assess the impact of the changes in these variables on the proposed project's economic viability as indicated by the NPV and IRR.

The sensitivity analysis provides basis for informed decision making which is useful for the evaluation of solar streetlighting projects by the city's decision makers. For instance, the results from the sensitivity analysis provides clearer insights on the project's economic viability under various scenarios. In addition, sensitivity analysis enhances the credibility of this study's findings. The sensitivity analysis provides understanding of the project's risks and benefits. The results of the sensitivity analysis highlighted the robustness of the investment under various market conditions, providing valuable insights for stakeholders considering the adoption of solar lighting technologies. In summary, the sensitivity analysis is crucial in this study as it provides insights into the impact of key variable on the overall feasibility and economic viability of the proposed solar street lighting project. By clearly articulating the project's sensitivities, this research provides enhanced understanding of the project's robustness to potential changes over its lifecycle.

3.4 Conclusion

The methodology described in this chapter provides a strong basis for the subsequent analysis and discussions in the dissertation. The systematic approach ensures the credibility and relevance of the research findings and their applicability to the broader discourse on renewable energy applications. The next chapter explores the research's results and findings derived from the methodology described above. The chapter will offer a comprehensive cost analysis to evaluate the economic feasibility of the proposed solar streetlighting system.

CHAPTER FOUR

SIMULATION AND RESULTS

4.0 Introduction

This chapter presents the results and findings derived from the methodology which was outlined in the previous chapter. The chapter presents results from the DIALux lighting simulation. The chapter provides a comprehensive cost analysis, inclusive of capital outlays, operational costs, and long-term financial benefits of implementing solar streetlighting systems. Financial metrics such as net present value (NPV), internal rate of return (IRR), and discounted payback periods, are calculated to evaluate the economic viability of the proposed solar streetlighting systems. The research findings and a sensitivity analysis are discussed. The chapter concludes with a summary of the key findings, highlighting the suitability of solar-powered lighting systems as a sustainable and cost-effective alternative to conventional streetlighting.

4.1 Lighting design output

As stated in the sections above, the DIALux simulation was conducted for a tarmac dual carriageway consisting of two lanes per side as shown in Figure 4.1. This exemplifies some of the roads within the Cape Town metropolitan area.

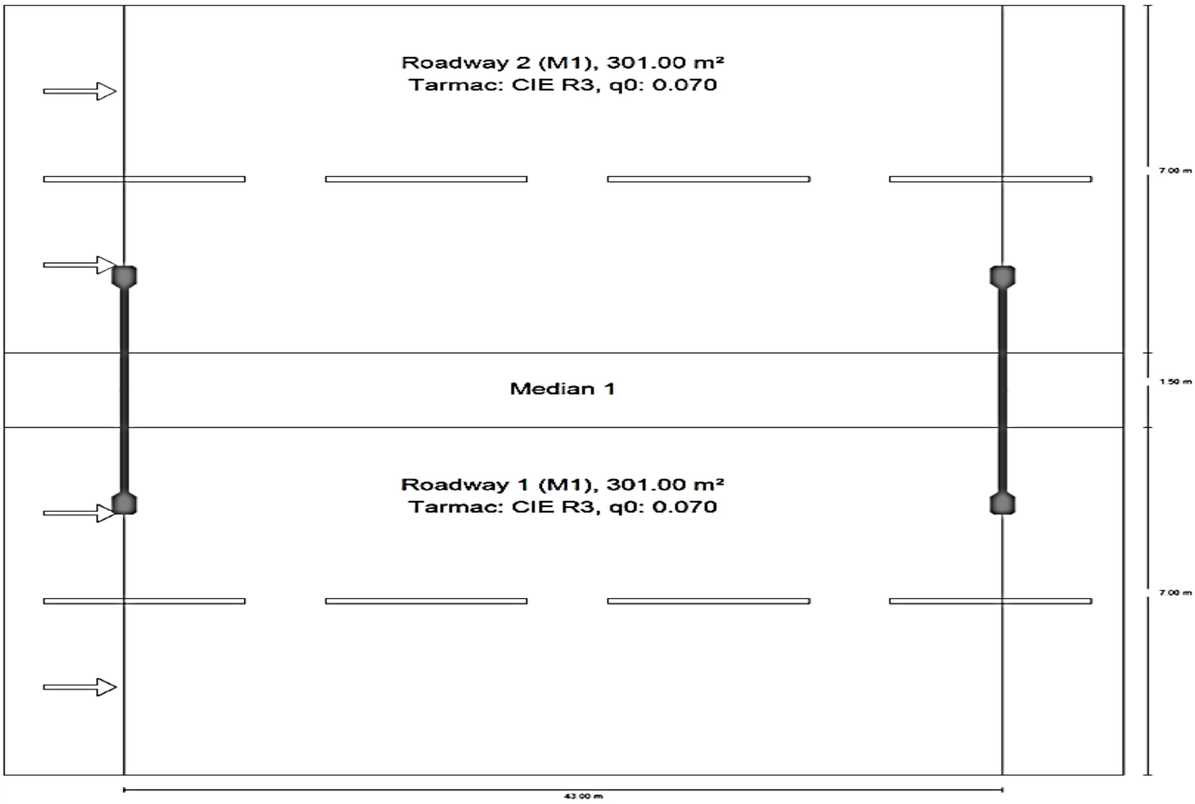

Figure 4.1 Dual carriage roadway schematic showing the median luminaire arrangement from DIALux (DIALux, 2024)

The specifications for the LED luminaire (BRP384 LED 320 757 174W DM A5) manufactured by Philips Lighting are shown in Table 4.1 below.

Table 4.1 LED luminaire specifications. (Philips Lighting, 2024).

Power rating	174W
Lumen output	32 000lm
Efficiency	99.99%
Luminous efficacy	183.9lm/W
Colour rendering index (CRI)	100
Lifetime	100 000hours

The high-power LED luminaire selected for HPS lamp replacement matched the lumen output provided by the 250W HPS Lamp which is typically around 30000 - 32000lumens. The LED luminaire has a luminous efficacy of 183.9lm/W and an exceptional lifespan of 100 000 hours. The LED luminaire is 24Volts DC powered eliminating the need for an inverter to convert DC power from the battery to AC power. This ensures higher system efficiency as there are no losses during power conversion.

The luminaire's mounting height is 10 metres which is suitable for the road type mentioned above as per the SANS standards. The maintenance factor of 0.80 was considered in the system simulation design, indicating that the luminaire can provide 80% of its initial lumen output at the lapse of its rated lifespan. The boom inclination angle of 10° has been considered in the simulation design. The power consumption of the LED lamp is 8 004W/km (without dimming) as compared to 16 500W/km when using a 250W HPS lamp. The results in Figure 4.2 showed that the pole-to-pole spacing for the selected high-power LED luminaire is 43m, meaning that for a 1km stretch, you need fewer LED luminaires than similar HPS luminaires for identical light output. Some of the key metrics are shown in Table 4.2 below.

Table 4.2 Summary of key metrics for the system configurations (DIALux, 2024).

Pole-to-pole distance	43m
Mounting Height	10m
Light Point overhang	1.5m
Boom inclination	10°
Maintenance Factor	0.80
Consumption	8 004W/km
Max. luminous intensities Any direction forming the specified angle from the downward vertical, with the luminaire installed for use.	≥ 70°: 516 cd/klm ≥ 80°: 342 cd/klm ≥ 90°: 11.1 cd/klm

The summary of the simulation design for both sides of the dual carriageway road (Roadway 2 and Roadway 1). The simulation is according to the EN13201:2015 lighting standard. The excerpt from the DIALux simulation program is shown in Table 4.3 below. All the technical parameters such as lighting distribution are calculated against the set standard. From the summary below, all the parameters are achieved meaning 100% conformance. The full simulation report will be attached in the appendix section. A DIALux excerpt of the summary of results for valuation fields according to EN 13201:2015 are shown in Table 4.3 below. A maintenance factor of 0.80 was used for calculating for the installation.

Table 4.3 Summary of project outputs from DIALux (DIALux, 2024).

	Symbol	Calculated	Target	Check
Roadway 2 (M1)	L_{av}	2.27cd/m^2	≥ 2.00 cd/m^2	✓
	U_o	0.53	≥ 0.40	✓
	U_l	0.71	≥ 0.70	✓
	TI	10%	≤ 10%	✓
	R_a	0.80	≥ 0.35	✓
Roadway 1 (M1)	L_{av}	2.27cd/m^2	≥ 2.00 cd/m^2	✓
	U_o	0.53	≥ 0.40	✓
	U_l	0.71	≥ 0.70	✓
	TI	10%	≤ 10%	✓
	R_a	0.80	≥ 0.35	✓

4.2 Solar streetlighting design

4.2.1 Solar resource assessment

The solar resource assessment was performed by using the NASA online platform and an excerpt is shown in Figure 4.2. The online platform allows the user to input geographical coordinates, the time range for climatology data as well as other parameters related to PV panels and solar fluxes. The NASA simulation tool provided climatological data for the Cape Town area. Cape Town's monthly average irradiation is shown in Table 4.4 below.

Table 4.4 Monthly averaged irradiation for Cape Town (kWh/m2/day). (NASA, 2024).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Average Solar Irradiation (kWh.m^2/day	7.36	7.34	5.73	5.79	4.37	4.05	4.4	4.77	5.83	6.66	7.11	7.21

Khalil et al. (2017) suggested that the solar panel design should consider the lowest irradiation values noting that this will guarantee reliable performance throughout the year as the system will be sufficient for periods of solar irradiation in the year. The solar panel size must be sufficient to charge the battery in periods of low solar irradiation. According to the NASA results shown in Table 4.4 and Figure 4.3, Cape Town receives the lowest average insolation in June with a value of 4.05kWh/m2/day. In general, the winter months (May, June and July) in Cape Town exhibit lower solar irradiance levels. However, the accurate solar panel sizing is critical in ensuring the solar panel's energy output to meet the operational demands of the street lighting system during this period. The proposed system's flexibility is important in ensuring adequate and consistent operation even in months of lower solar irradiance. This justifies the system viability from a technical viewpoint. The proposed system's guaranteed performance in the winter months offers long term economic benefits in comparison to conventional streetlighting. The economic viability shown by metrics such as project energy savings undoubtedly justifies the implementation of the proposed solar streetlighting project. In conclusion, based on the data presented in Table 4.4 and Figure 4.3 and the analysis conducted in my study, the research clearly justifies the feasibility of solar-powered street lighting systems even during seasonal variations particularly in the winter months (May, June and July).

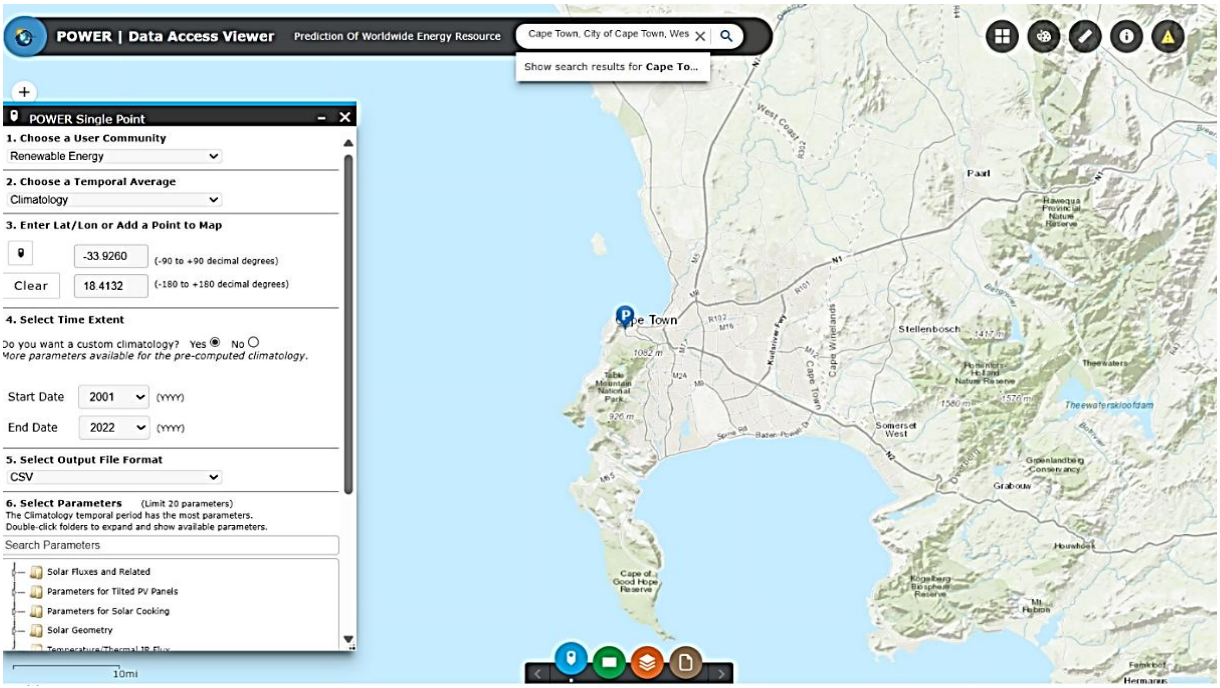

Figure 4.2 Excerpt from the NASA simulation tool (NASA, 2024).

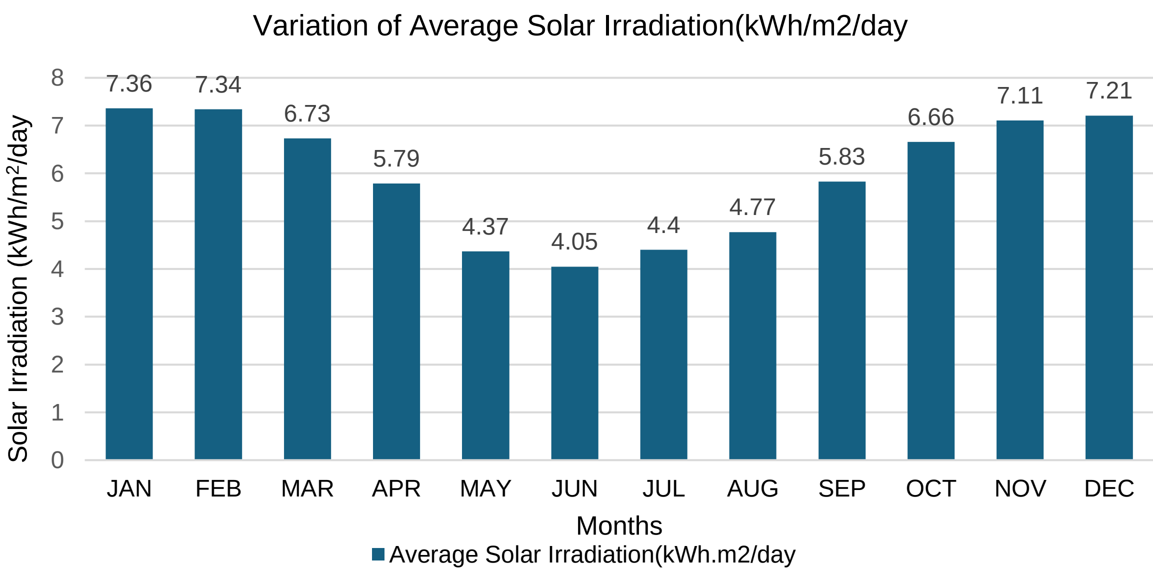

Figure 4.3 Average solar irradiation variation (NASA, 2024).

The LED luminaire was selected as the electrical load with a wattage of 174W with a maximum luminous output of 32000lumens to match a 250W HPS. The nominal voltage is 24V DC. The lamp's efficacy is approximately 184lm/W. The daily schedule below shows that the lamp will not always run at maximum power to conserve energy. The light will burn at 100% brightness from 6 pm - 10 pm, 70% brightness from 10 pm till 2 am, dropping down to 50% brightness between 2 am to 4 am and lastly provide 100% brightness from 4 am to 6 am. The lamp's total daily operating hours are 12 hours.

Table 4.5 Lighting output dimming profile.

Brightness level 1	100%
Duration level 1	4 hours
Brightness level 2	70%
Duration level 2	4 hours
Brightness level 3	50%
Duration level 3	2 hours
Brightness level 4	100%
Duration level 4	2 hours

The energy required per night (daily consumption) by each luminaire, E_{daily}, is thus a summation of the energy consumed during the distinct phases of the night. The energy consumed in each phase of the night is calculated by multiplying the power output of the lamp in Watts by the duration of each phase in hours. This is as shown in equation [4.1] below.

$$E_{daily} = P_{lamp}\ (t_1 p_1 + t_2 p_2 + t_3 p_3 + t_4 p_4) \quad [4.1]$$

where

- E_{daily} is the total daily energy consumption.
- P_{lamp} is the luminaire's maximum power output (174W in your example).
- t_1, t_2, t_3, and t_4 are the corresponding durations of each of the four periods as specified in Table 4.5.
- p_1, p_2, p_3, and p_4 are the corresponding luminaire's brightness values for each period indicated as percentages.

E_{daily} =(174W*100%*4hrs) + (174W*70%*4hrs) + (174W*50%* 2hrs) + (174W*100%*2hrs)

= 1705.2Wh

4.2.2 Solar PV panel sizing (W_{peak})

The solar PV panel sizing considers the meteorological conditions by including the peak sunshine hours (PSH) for the Cape Town metropolitan area as shown earlier. In addition, the design considers the potential system losses. For example, Rajab et al. (2017) in their study attributed 5% of the system's losses to dust effect. The solar PV panel sizing for each lamp is calculated as suggested by Rajeev and Nair (2012) as shown in equation [4.2] below.

$$\boldsymbol{W}_{peak} = \frac{E_{daily}}{\boldsymbol{\eta}_{\text{battery}} \times \boldsymbol{\eta}_{\text{charge controller}} \times \text{PSH} \times \text{MF}} \qquad [4.2]$$

where

- E_{daily} is the total daily energy consumption of each luminaire.
- $\boldsymbol{\eta}_{\text{battery}}$ is the battery efficiency
- $\boldsymbol{\eta}_{\text{charge controller}}$ is the charge controller efficiency which is 0.97
- PSH is the peak sunshine hours
- MF is the mismatch factor which is 0.85

$$\boldsymbol{W}_{peak} = \frac{1705.2\text{Wh}}{(0.995 \times 0.97 \times 4.05\text{h} \times 0.85)}$$

$$= \underline{\underline{513\text{W}_\text{p}}}$$

In this project, the recommended solar PV panel sufficient for each lamp should be greater than 513Wp. The next size up that the market currently provides is 520Wp which is a good fit for this project application. For this project, each streetlight system will have 2 solar panels (1 for each lamp). Karmiathi et al. (2018) recommended a tilt angle of between 5 and 15 degrees to allow for natural cleaning.

4.2.3 Battery sizing

The battery capacity, $C_{battery}$, sizing as suggested by Karmiathi et al. (2018) is calculated as shown in equation [4.3].

$$C_{battery} = \frac{E_{daily} \times \mathbf{N}}{\text{V}_\text{s} \times \text{DOD} \times \boldsymbol{\eta}_{output}} \qquad [4.3]$$

where

- **N** is the number of days of autonomy also known as the number of days of self-support by the battery. In this case, we are considering 1 day of self-support/autonomy.
- E_{daily} is the energy required per night (daily consumption) by each luminaire
- V_s, is the nominal system's battery voltage which is 24VDC.
- The depth of discharge (DOD) for the specified lithium-ion battery is set at 90% i.e. 0.9
- $\boldsymbol{\eta}_{output}$ is the system's output efficiency

Karmiathi et al. (2018) suggested that output efficiency will be a product of the charge controller's efficiency (97%) and the battery's capacity efficiency (99.5%) as shown in the product datasheets. The battery capacity is calculated as below.

$$C_{battery} = \frac{1705.2Wh \times 1}{24\text{V} \times 0.9 \times 0.97 \times 0.995}$$

$$= \underline{\underline{82\text{Ah}}}$$

It follows that the appropriate battery capacity is 24V 82Ah for each lamp. However, the market provides 24V 100Ah battery capacity models. As such, for this project, each pole will have 2 units of 24V 100Ah lithium battery which was selected providing system redundancy of about 22% thereby reducing the chances of blackout. The battery specifications are shown in Table 4.6 below.

Table 4.6 Battery specifications (Geewiz, 2023).

Battery Technology	$LiFePO_4$
Rated voltage	25.6V
Rated capacity	100AH
Capacity efficiency	99.5%
Cycle life	90% at 4000cycles
Depth of discharge	90%

4.2.4 Solar charge controller sizing

The solar charge controller selected for the project will have an integrated LED driver making it a combo unit. Its efficiency is critical to the proper functionality of the overall system. The LED driver unit must be able to support the connected lighting load. The solar charge controller's maximum limit of solar PV power supply and the voltage and current inputs must be satisfied. The streetlight system will include two charge controller-LED driver units, one for each lamp and connected to each battery. This ensures that should there be any malfunction of one of the units or on the battery, there is still light output from one of them instead of a blackout. The charge controller-LED driver unit can handle the connected solar PV panel output in terms of wattage, input voltage, and current output. In addition, the controller-LED driver units can power the lighting load as well as enable the dimming functionality. The sizing of the charge controller follows the approach taken by Aboagye et al. (2020) which first calculates the input current through the controller, I_c. The input current is calculated as shown in equation [4.4].

$$I_c = I_{sc} \times N_{PV,parallel} \times SF \qquad [4.4]$$

where

- I_c is the input current flowing through the controller

- I_{sc} is the short circuit current of solar PV panel
- $N_{pv,\ parallel}$ is the number of solar PV panels in parallel
- SF is a safety factor of 1.25

$$I_c = 12.76\text{A} \times 1 \times 1.25$$
$$= \underline{\underline{15.95\text{A}}}$$

An acceptable charge controller-LED driver should accept a minimum PV input current of 16A. The selected charge controller-LED driver has a maximum solar PV input current of 20A as shown in Table 4.7.

Table 4.7 Charge controller-LED driver specifications. (SRNE, 2023).

Maximum Solar Power Input	520W
Maximum Solar PV Input Current	20A
Maximum Load Output	200W
Load Input Voltage	12/24V
Typical Efficiency	97%

4.2.5 Other components

The system design included other components to complete the solar-powered streetlighting system. A pole mounting bracket kit for the solar PV panels was included in the bill of materials. In addition, the 4mm^2 solar PV cable for connecting the applicable components and optional battery boxes was also included in the costing.

4.3 Economic analysis

4.3.1 Electricity tariff consideration

The electricity tariff in South Africa has been increasing considerably over the past 10 years as shown in Figure 4.4. This study accordingly considers the electricity tariff changes that may occur over the project's term. The average tariff percentage increase from 2014 to date was calculated and the result which is 10.56% was assumed as the year-to-year electricity tariff percentage increase during the 20-year assessment period.

4.3.2 The capital cost

The system cost per pole is the summation of the cost of the system components as shown below. All the components' costs are included in the table 4.8 below. Considering the 1km stretch, twenty-three solar-powered LED lighting systems mounted on the existing lighting poles are considered. The total capital cost for the 1km stretch is thus calculated as shown in equation [4.5] below.

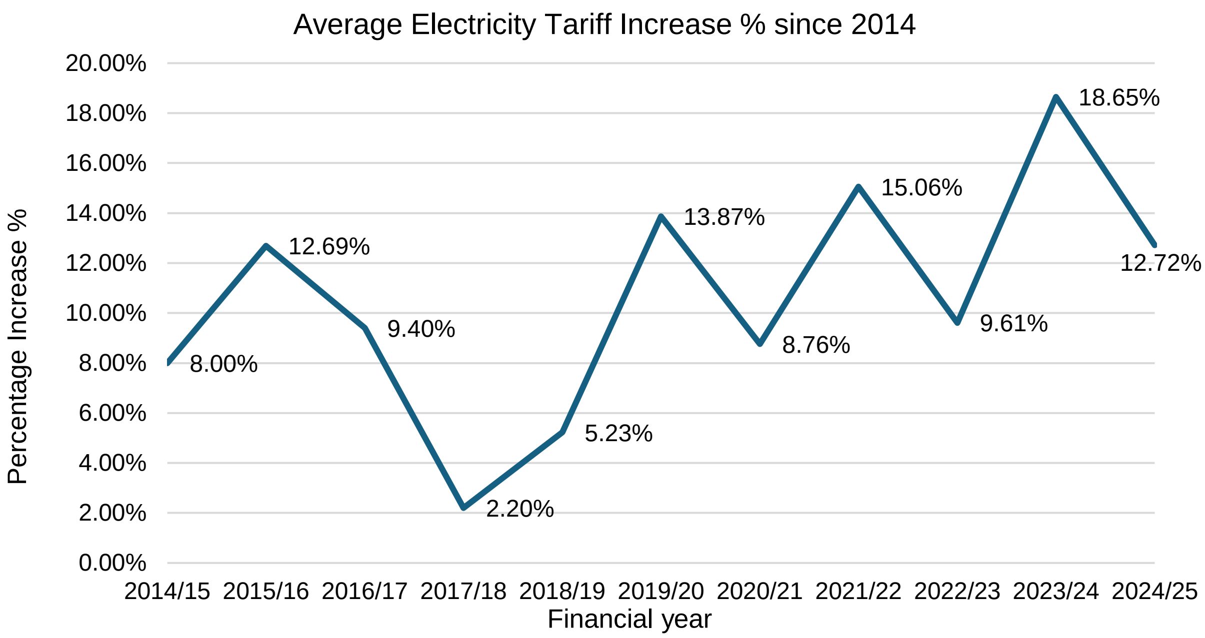

Figure 4.4 Average historical annual electricity tariff percentage increase. (Eskom, 2024).

Table 4.8 Cost breakdown for an individual solar streetlight system.

Qty	Description	Unit Cost/R	Total /R
2	BRP384 LED 320 757 174W DM Luminaire	R 3 317.61	R 6 635.21
2	520Wp Monocrystalline PV panel	R 1 629.55	R 3 259.10
2	Charge Controller with Integrated Driver	R 1 726.61	R 3 453.21
2	25.6V 100AH $LiFePO_4$ Battery	R 9 385.00	R18 770.00
2	12.5m of 4mm2 PV cable	R 180.00	R 360.00
2	Battery Box	R 430.50	R 861.00
1	2-Solar Panel Pole Mounting Bracket (Portrait Orientation)	R 3 500.00	R 3 500.00
Price per 1 solar streetlighting set			**R36,838.52**

$$\mathbf{C}_{\text{capital}} = \text{Cost of 1 pole} - \text{mounted system} \times \text{ Number of poles per 1km} \qquad [4.5]$$

where $\mathbf{C}_{\text{capital}}$ is the proposed system's capital cost

$\mathbf{C}_{\text{capital}}$ = R 36 838.52 * 23

= R 847 285.96

4.3.3 Installation costs

Hasan et al (2019) apportioned 3% of the total system upfront investment to the installation costs whilst Allwyn et al. (2021) proposed that the installation costs are 10% of the capital investment of the system. However, Karmiathi et al. (2018) noted the installation costs to be 5% of the total system upfront costs. Katyara et al. (2018) in a similar study in Pakistan estimated that the labour and deployment costs amounted to 9.65% of the system's upfront investment. This research assumes that 10% of the system capital cost is apportioned to installation costs. The installation costs are calculated as shown in equation [4.6].

$$\mathbf{C}_{\text{installation}} = 0.10 \times \mathbf{C}_{\text{capital}} \quad [4.6]$$

$$= 0.10 \times \text{R } 847\ 285.96$$

$$= \underline{\underline{\text{R } 84\ 728.60}}$$

4.3.4 Annual operation and maintenance costs

Different studies have various opinions on the system's annual operation and maintenance cost estimation. Hasan et al. (2019), Karmiathi et al. (2018) and Allwyn et al. (2021) suggested that the annual operation and maintenance cost is approximately 1% of the capital cost. On the other hand, Katyara et al. (2018) and Mardikaningsih et al. (2016) recommended that the annual operation and maintenance cost be 2% of the project's capital cost. For this study, the researcher assumes that the annual operation and maintenance cost at 2% of the upfront capital cost which is close to the average of the studies mentioned earlier. The researcher suggests that 2% will be a reasonable and acceptable value. The proposed system maintenance costs are calculated as shown in equation [4.7] below.

$$\mathbf{C}_{\text{maintenance}} = 0.02 \times \mathbf{C}_{\text{capital}} \quad [4.7]$$

$$= 0.02 \times \text{R } 847\ 285.96$$

$$= \underline{\underline{\text{R } 16\ 945.72}}$$

4.3.5 Replacement costs

The replacement costs are the costs associated with purchasing replacement units of system components once their rated lifespan has elapsed. These replacement costs are determined by considering the lifespan of each component and how frequently they need to be replaced within the 20-year assessment period. C_{unit}, which is the unit cost of each system component is recorded in Table 4.8 above showing the system cost breakdown. The cost breakdown shows that the batteries are the most expensive part of a solar streetlight system, contributing over 50% of the total system cost. The lithium-ion batteries' lifespan considered for the project is rated at 2000 cycles. There are 365 cycles per year translating to 1 cycle daily. The lifespan for the battery, $\mathbf{L}_{\text{battery}}$ in years is calculated in equation [4.8].

$$\mathbf{L}_{\text{battery}} = \frac{\text{Rated Cycle life}}{\text{Number of cycles per year}} \quad [4.8]$$

$$= \frac{2000}{365}$$

$$= \underline{\underline{5.48 \text{ years}}}$$

This means that the replacement of the battery is done at least five years from the date of installation. During a 20-year project lifespan, the replacement will be done at least 3 times at the start of year 6, year 12, and year 18 respectively.

The LED luminaire's lifespan considered herein is rated at 100 000 operating hours. The daily operation hours for the LED luminaire are 12 hours translating to 4 380hours for a 365day annual period. The lifespan for the LED luminaire, $\mathbf{L}_{luminaire}$ in years is calculated as shown in equation [4.9] below.

$$\mathbf{L}_{\text{luminaire}} = \frac{\text{Rated luminaire lifespan}}{\text{Luminaire total annual operating hours}} \quad [4.9]$$

$$\mathbf{L}_{\text{luminaire}} = \frac{100\ 000\text{hrs}}{4380\text{hrs/year}}$$

$$= \underline{\underline{22{,}83 \text{ years}}}$$

This means that the replacement of the LED luminaire is only done after 22 years. During a 20-year project lifespan, the luminaire will thus not be replaced. In contrast, the HPS luminaire's lifespan considered herein is rated at 20 000 operating hours. The daily operation hours for the HPS luminaire are just like the LED luminaire are 12 hours translating to 4380 hours annually. The lifespan for the HPS luminaire in years, $\mathbf{L}_{\text{luminaire,HPS}}$ is calculated as shown in equation [4.10] below.

$$\mathbf{L}_{\text{luminaire,HPS}} = \frac{\text{Rated luminaire lifespan}}{\text{Luminaire total annual operating hours}} \quad [4.10]$$

$$\mathbf{L}_{\text{luminaire,HPS}} = \frac{20\ 000\text{hrs}}{4380\text{hrs/year}}$$

$$= \underline{\underline{4{,}57 \text{ years}}}$$

This means that the HPS luminaire can be done at least four (4) times during the 20-year project lifespan. The solar panels are rated with a minimum lifespan of twenty-five (25) years. Accordingly, they will not be replaced during the 20 years of assessment. This research assumes that by sizing it properly and integrating it with the system, the charge controller will only be replaced once during the 20 years.

The total cost of replacement, $C_{replacement}$ is the summation of the applicable system component replacement costs i.e., batteries and controller. This is calculated in equation [4.11].

$$\mathbf{C}_{\text{replacement,battery}} = C_{\text{batt},6th\ year} + C_{\text{batt},12th\ year} + C_{\text{batt},18th\ year} \quad [4.11]$$

= R 18 770.00 + R 18 770.00 + R 18 770.00

= <u>R 56 310.00.</u>

$\mathbf{C}_{\text{replacement,controller}}$ is the replacement cost of the controller which happens in the 16th year. The cost of the controller is considered to be R1 726.61 as per Table 5.6 showing the system cost breakdown. The total replacement costs occurring during the project's duration, $\mathbf{C}_{\text{replacement}}$, are thus calculated as follows in equation [4.12].

$$\mathbf{C}_{\text{replacement}} = \mathbf{C}_{\text{replacement},battery} + \mathrm{C}_{\text{replacement ,controller}} \qquad [4.12]$$

= R 56 310 + R1 726.61

= R 58 036.61

From the simulation result, the pole-to-pole spacing for the proposed LED lamp is 43m whilst for the 250W HPS it is 30m distance from pole to pole. Each pole has two luminaires mounted. For a 1km stretch, the number of luminaires is calculated as shown in equation [4.13] below.

$$\mathbf{N}_{\text{ luminaires}} = \frac{Number\ of\ luminaires\ mounted\ on\ pole\ \ x\ Length\ of\ road\ section}{Pole\ to\ pole\ spacing\ between\ luminaires} \qquad [4.13]$$

$$\mathbf{N}_{\text{ LED}} = \frac{2\ x\ 1000m}{43m}$$

$=$ 46 luminaires (23 streetlight poles)

$$\mathbf{N}_{\text{ HPS}} = \frac{2\ x\ 1000m}{30m}$$

$=$ 66 luminaires (33 streetlight poles)

The total installed power of the HPS lamps per km, $P_{\text{HPS,total}}$ can be calculated as shown in equation [4.14] below.

$$\mathrm{P}_{\text{HPS,total}} = \mathrm{P}_{\text{HPS}} \times \mathbf{N}_{\text{ HPS}} \qquad [4.14]$$

= 250W × 66

= 16 500W per km

Since two luminaires are mounted per pole, the total wattage drawn by HPS streetlights is 16 500W drawn from the grid per km. The energy drawn by the 2 HPS luminaires per year per kilometre is calculated by multiplying the annual operating hours of the lamps by the amount of energy drawn per kilometre as shown in equation [4.15].

$$\mathrm{E}_{\text{HPS,total}} = \mathrm{P}_{\text{HPS,total}} \times \text{ Annual operating hours} \qquad [4.15]$$

= 16 500W × 4 380h

= 72 270kWh

The annual energy cost of running 250W HPS grid-connected lamps over a 1km stretch(as it stands) denoted by $\mathbf{C}_{\text{energy,HPS}}$ can also be calculated using the 2022/23 City of Cape Town streetlight tariff inclusive of tax, the 2023/2024 and 2024/2025 tariff escalations as shown in equation [4.16].

$$\mathbf{C}_{\text{energy,HPS}} = \mathbf{C}_{\text{streetlight tariff}} \times \mathbf{E}_{\text{HPS,total}} \times \mathbf{T}_{2023/2024} \times \mathbf{T}_{2024/2025} \qquad [4.16]$$

where

- $\mathbf{C}_{\text{streetlight tariff}}$ is the 2022/2023 City of Cape Town tax-inclusive streetlight tariff
- $\mathrm{E}_{\text{HPS,total}}$ is the total energy consumption of HPS lamps over a 1km stretch.
- $\mathbf{T}_{2023/2024}$ is the 2023/2024 annual electricity tariff escalation rate.
- $\mathbf{T}_{2024/2025}$ is the 2024/2025 annual electricity tariff escalation rate.

$\mathbf{C}_{\text{energy,HPS}}$ = R2.455/kWh x 1.15 x 72 270 kWh x 1.1865 x 1.1272

= R 272 882.77

The annual energy cost savings for switching from HPS to LED (assuming the LED will be grid-powered) lighting are calculated as shown in equation [4.17].

$$\mathbf{C}_{\text{savings}} = (\mathbf{E}_{\text{HPS,total}} - \mathbf{E}_{\text{LED,total}}) \times \mathbf{C}_{\text{streetlight tariff}} \times \mathbf{T}_{2023/2024} \times \mathbf{T}_{2024/2025} \times \mathbf{T}_{\text{ann,increase}} \qquad [4.17]$$

where

- $\mathbf{C}_{\text{streetlight tariff}}$ is the 2022/2023 City of Cape Town tax-inclusive streetlight tariff
- $\mathrm{E}_{\text{HPS,total}}$ and $\mathrm{E}_{\text{LED,total}}$ is the total energy consumption of HPS and LED lamps over a 1km stretch respectively.
- $\mathbf{T}_{2023/2024}$ is the 2023/2024 annual electricity tariff escalation rate.
- $\mathbf{T}_{2024/2025}$ is the 2024/2025 annual electricity tariff escalation rate.
- $\mathbf{T}_{\text{ann,increase}}$ is the project's annual average electricity tariff escalation rate project of 10.56%.

For year 1, the annual energy cost savings (without dimming) are as follows: -

$\mathbf{C}_{\text{savings,Year 1 (no dimming)}}$ = [(0.250kW × 12 × 365 × 66) - (0.174kW × 12 × 365 × 46)] × (R2.455/kWh ×1.15 × 1.1865 ×1.1272 ×1.1056)

= [(72 270) – (35 057.52)] × (R2.455/kWh × 1.15 ×1.1865 × 1.1272 × 1.1056)

= R155 549.50

For year 1, the annual energy cost savings (with dimming) consider that the LED lamp will have a daily energy consumption of 1705.2Wh i.e., 1.7052kWh/day. The annual energy cost savings with dimming, $\mathbf{C}_{\text{savings,Year 1 (with dimming)}}$, are calculated as follows: -

$\mathbf{C}_{\text{savings,Year 1 (with dimming)}}$ = [(0.250kW ×12 × 365 × 66) - (1705.2 ×365 × 46)] × (R2.455/kWh × 1.1865 × 1.1272 × 1.1056)

= [(72 270) – (28,630.31)] × (R2.455/kWh × 1.15×1.1865 × 1.1272 ×1.1056)

= R182 413.91

The calculations show that in the year 1, 17.27% more energy cost savings are attained when the dimming profile is employed. The dimming profile conserves energy and prolongs lamp life as suggested by Pipattanasomporn et al. (2014).

4.4 Financial metrics of the project

The interest rate was assumed to be 8.25% as suggested by the South African Reserve Bank (SARB, 2024). The Internal rate of return (IRR) of the project was calculated from the Excel sheet. The IRR by considering the cells that have annual cumulative cash flow values. The IRR of the project is 15.51%, which is significantly higher than the current interest rate. The payback period is in the 5th year as shown in the graph below of the cumulative cash flow over the project's lifespan. The payback period is 5.73 years. This means the project will generate net positive cash flows for a further fourteen (14) years till the end of the project tenure, which is a good indication of project feasibility. In addition, the (net present value) NPV of the project is also calculated from the annual cumulative cash flow values. At the end of the project, i.e., the end of twenty years, the NPV will be R18 707 815.25. The NPV is greater than 0 meaning the project will create a positive value. The project is thus economically feasible. The project feasibility determination table is shown in Table 4.9 below.

Table 4.9 Project feasibility determination table.

Project Financial Metric	Criteria	Financial/ Economic Metric Value	Economic Feasibility Verdict
Net Present Value (NPV)	• If the NPV is greater than or equal to 0, then the project will be economically feasible. • If the NPV is less than 0, then the project will not be economically feasible.	R18 707 815.25	The project is deemed economically feasible.
Internal Rate of Return (IRR)	• If the IRR is greater than the interest rate, then the project will be economically feasible. • If the IRR is less than the interest rate, then the project will not be economically feasible.	15.51%	The project is deemed economically feasible.

Table 4.10 below summarises the economic analysis showing the various related costs as well as the annual cash flows. The replacement costs are included according to when they occur

during the project's term. Figure 4.5 which follows graphically shows the cumulative cash flows during the project term as well as marking the discounted payback period. A detailed analysis and summary of the findings shown in Table 4.10 and Figure 4.5 is provided below.

4.5 Summary of economic analysis

A summary of the economic analysis is presented in the section below.

a) Initial investment and installation costs

The proposed project requires a capital outlay of R847 285.96 which is inclusive of the system component costs and installation costs. The installation costs amount to R84 728.60 bringing the combined total initial expenditure is R932 014.56.

b) Annual operation and maintenance (O&M) costs

The annual operation and maintenance costs amount to R16 945.72, which remains constant throughout the project term to ensure regular maintenance. Though the costs are recurrent, they are relatively low in comparison to the projected energy savings. This cements the proposed project's overall cost-effectiveness.

c) Replacement costs

The proposed project incurs additional costs of R18 770.00 each for battery replacement in 6^{th}, 12^{th} and 18^{th} year. The charge controller-LED driver cost of R1 726.61 is incurred in the 16^{th} year.

d) Electricity tariff escalation

The tariff is projected to increase annually, from R4.18 per kWh in 1^{st} year to R28.15 per kWh by 20^{th} year at a base case of 10.56%. This indicates an upward trend of electricity tariffs significantly influencing the energy cost savings from solar-powered LED streetlighting adoption.

e) Energy consumption and cost comparison

The HPS lighting has a fixed energy demand of 72 270 kWh whilst the solar-powered LED lighting energy demand is 28 630.31 kWh. This highlights the exceptional efficiency of LED technology resulting in 60.38% energy savings. The cost impact of the HPS is substantially greater than that of LED. Due to the rising electricity tariffs, the energy cost for HPS lighting increases significantly from R302 088.60 in the 1^{st} year to R2 034 683.71 in the 20^{th} year. The annual energy cost for the proposed solar-powered LED streetlighting starts at R119 674.69 in 1^{st} year reaching R806 055.36 in the 20^{th} year.

f) Annual energy cost savings

The estimated energy cost savings from replacing the HPS lighting with LED lighting increases each year due to electricity tariff increases. For instance, the estimated energy savings in 1st year amounted to R182 413.91 and are projected to reach R1 228 628.34 in the 20th year.

g) Cash flow analysis

The first year shows a negative cash flow of -R932 014.56 corresponding to the initial investment and installation costs at project inception. From 1st year onwards, the proposed project generates positive cash flows, mainly from the estimated energy savings. The project has a payback period of 5.73 years as shown in Figure 4.6. The discounted cash flow (DCF) shown in Table 4.9 provides a more realistic view of the project's financial performance, considering the time value of money.

h) Long-term economic performance

In the 20th year, the projected cumulative cash flow amounts to R3 030 203.24, highlighting significant net savings. The net positive cumulative cash flow demonstrates the project's financial viability with an attractive return on investment.

Table 4.10 Economic analysis table showing cash flows

Year	Cash Investment /R	Installation Cost/R	Replacement Costs/R	Annual Operation and Maintenance Costs /R	Electricity tariff (R/kWh)	Energy consumption HPS (kWh)	Energy Cost HPS/R	Energy Consumption LED (kWh)	Energy Cost LED/R	Electricity Savings (from HPS to LED)/R	Undiscounted Annual Cash Flow /R	Discounted cash flow /R	Cumulative Cash Flow /R
0	-R847,285.96	-R84,728.60	R0.00	R0.00	R3.78	0	R0.00	0.00	R0.00	R0.00	-R932,014.56	1.000	-R932,014.56
1				-R16,945.72	R4.18	72270	R302,088.60	28630.31	R119,674.69	R182,413.91	R152,857.45	0.924	-R779,157.10
2				-R16,945.72	R4.62	72270	R333,989.16	28630.31	R132,312.33	R201,676.82	R157,646.46	0.853	-R621,510.65
3				-R16,945.72	R5.11	72270	R369,258.41	28630.31	R146,284.52	R222,973.89	R162,421.27	0.788	-R459,089.38
4				-R16,945.72	R5.65	72270	R408,252.10	28630.31	R161,732.16	R246,519.94	R167,190.46	0.728	-R291,898.92
5				-R16,945.72	R6.25	72270	R451,363.52	28630.31	R178,811.08	R272,552.44	R171,962.10	0.673	-R119,936.82
6			-R18,770.00	-R16,945.72	R6.91	72270	R499,027.51	28630.31	R197,693.53	R301,333.98	R165,078.49	0.621	R45,141.68
7				-R16,945.72	R7.63	72270	R551,724.81	28630.31	R218,569.96	R333,154.85	R181,542.82	0.574	R226,684.49
8				-R16,945.72	R8.44	72270	R609,986.95	28630.31	R241,650.95	R368,336.00	R186,365.92	0.530	R413,050.42
9				-R16,945.72	R9.33	72270	R674,401.58	28630.31	R267,169.29	R407,232.28	R191,219.62	0.490	R604,270.04
10				-R16,945.72	R10.32	72270	R745,618.38	28630.31	R295,382.37	R450,236.01	R196,110.08	0.453	R800,380.11
11				-R16,945.72	R11.41	72270	R824,355.68	28630.31	R326,574.75	R497,780.93	R201,043.16	0.418	R1,001,423.28
12			-R18,770.00	-R16,945.72	R12.61	72270	R911,407.64	28630.31	R361,061.04	R550,346.60	R198,774.64	0.386	R1,200,197.92
13				-R16,945.72	R13.94	72270	R1,007,652.29	28630.31	R399,189.09	R608,463.20	R211,059.46	0.357	R1,411,257.38
14				-R16,945.72	R15.42	72270	R1,114,060.37	28630.31	R441,343.46	R672,716.92	R216,153.20	0.330	R1,627,410.58
15				-R16,945.72	R17.04	72270	R1,231,705.15	28630.31	R487,949.33	R743,755.82	R221,310.68	0.304	R1,848,721.26
16			-R1,726.61	-R16,945.72	R18.84	72270	R1,361,773.21	28630.31	R539,476.77	R822,296.44	R226,051.02	0.281	R2,074,772.29
17				-R16,945.72	R20.83	72270	R1,505,576.46	28630.31	R596,445.52	R909,130.94	R231,835.87	0.260	R2,306,608.16
18			-R18,770.00	-R16,945.72	R23.03	72270	R1,664,565.34	28630.31	R659,430.17	R1,005,135.17	R232,707.00	0.240	R2,539,315.16
19				-R16,945.72	R25.46	72270	R1,840,343.44	28630.31	R729,066.00	R1,111,277.44	R242,671.51	0.222	R2,781,986.67
20				-R16,945.72	R28.15	72270	R2,034,683.71	28630.31	R806,055.36	R1,228,628.34	R248,216.57	0.205	R3,030,203.24
										R11,135,961.95			R18,707,815.25

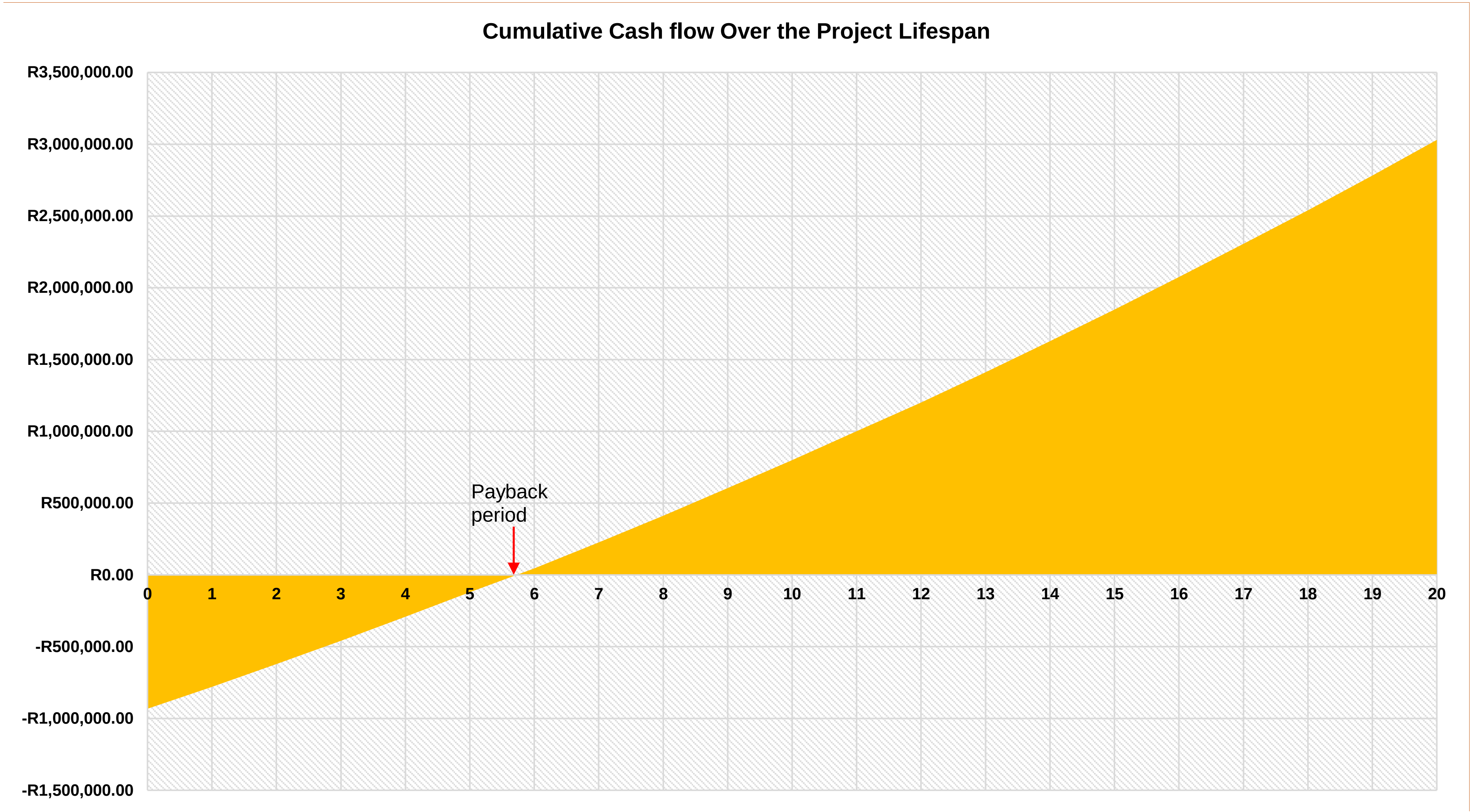

Figure 4.5 Cumulative cash flow over the project lifespan.

4.6 Sensitivity analysis

The sensitivity analysis was performed to evaluate the robustness of the model and to determine the effects of changes on key variables such as electricity tariffs and battery pricing. We have seen a downward trend in battery pricing whilst there is an upward trend in the electricity tariff. For the electricity tariff, the researcher considered the effects of an 8%, 10%, and 13.12% annual electricity tariff increase. Each of the financial metrics is considered i.e., NPV, IRR, and discounted payback period. The base case is the calculated average electricity tariff increase of 10.56%. The outcome is shown in the Table 4.11 below.

Table 4.11 Sensitivity analysis for annual tariff increase.

	Annual Electricity Tariff Increase			
	8% (Base Case - 2.56%)	**10%** (Base Case - 0.56%)	**10.56%** (Base Case)	**13.12%** (Base Case + 2.56%)
Internal Rate of Return (IRR)	12.61%	14.89%	15.51%	18.28%
Net Present Value (NPV)	R12 918 362.48	R17 332 536.68	R18 714 674.55	R25 908 316.62
Discounted Payback Period(years)	6.10	5.80	5.73	5.41

The lowest IRR calculated value is 12.61% whereby the annual electricity tariff increase is 8%. Though it is lower than the base case's calculated IRR of 15.51%, the IRR of 12.61% is still higher than the interest rate of 8.25%. A 2.56% decrease in the annual electricity tariff from the base case results in a 2.91% decrease in the IRR whilst a 2.56% increase in the annual electricity tariff from the base case results in a 2.56% IRR increase. At an 8% electricity tariff increase value, the NPV is R12 918 362.48 which is lower than the NPV for the base case whilst the discounted payback period is 6.10 years which is higher than the 5.73 years recorded for the base case.

The outcome shows that the project will still be viable should there be a lower tariff increase than the average calculated electricity tariff hike of 10.56%. At a 13.12% electricity tariff increase, which is 2.56% more than the base case's, the IRR will be 18.28% and the discounted payback period is 5.41 years which is slightly lower than the 5.73 years recorded in the base case. The NPV at 13.12% electricity tariff increase will be R25 908 316.62 which is 38.44% more than the NPV for the base case.

Table 4.3 Sensitivity analysis of battery pricing changes.

		Battery Pricing Decrease		
	Base Case	**10%**	**15%**	**20%**
Internal Rate of Return (IRR)	15.51%	15.53%	15.54%	15.55%
Net Present Value (NPV)	R18 714 674.55	R18 741 373.63	R18 757 384.66	R18 772 897.10
Discounted Payback Period(years)	5.73	5.72	5.72	5.73

4.7 Comparison with results from previous studies

Various studies in different study areas experience different conditions. This study revealed a discounted payback period of 5.73 years for a solar streetlighting project which is competitive for solar energy related projects considering the assessment period of 20 years. Wu et al. (2009) observed a payback period of 3.3 years whilst Ibrahim et al. (2021) observed a similar payback period of over 3 years for a solar-powered LED streetlighting replacement project. Al-Kurdia et al. (2015) revealed a payback period of 3.15 years for solar-powered streetlights. These studies have significantly shorter payback period indicating quicker return on investments. However, other studies have findings similar to my research's findings indicating consistency in the financial performances of the solar streetlighting projects. For instance, Katyara et al. (2018) and Rajeev and Nair (2012) observed payback periods of approximately 5.384 for their proposed solar-powered LED system comparable to the 5.9 years reported by Rajeev and Nair (2012) when they used CFL technology with lead acid battery technology.

This study observed an internal rate of return (IRR) of 15.51% showing a strong return on investment. The shorter payback periods recorded by Wu et al. (2009), Allwyn et al. (2021) and Ibrahim et al. (2021) as discussed in the section above, implying their IRRs are higher than the 15.51% from this research. However, this research's IRR of 15.51% still reflects a strong investment potential, especially given the rising electricity costs.

This study's calculated NPV is R18 707 815.25 indicating a strong economic viability showing favourable economic conditions for solar energy related investments in Cape Town. In contrast, Karmiathi et al. (2018) observed a negative NPV for solar-powered LED streetlights indicating the project was not financially viable. Pipattanasomporn et al. (2014) observed that the NPV for LED streetlights was lower to that of the HPS streetlights. This indicated a less favourable financial scenario to replace conventional HPS streetlights with grid-powered LED streetlights.

Orejon-Sanchez et al. (2021) and Al-Kurdia et al. (2015) observed significant energy savings of 35% and 50% respectively by switching from conventional streetlights to solar-powered streetlights. Pipattanasomporn et al. (2014) revealed energy savings more than 50% by replacing conventional streetlighting with more efficient LED lighting. This current study observed 60.38% savings by replacing conventional HPS lamps with high-power solar-powered LED streetlighting. These attractive energy savings are similar to the values observed in previous reported studies as explained above.

In summary, the comparison of this study's NPV, IRR, and payback period with previous studies reveals that the current research on solar-powered street lighting in Cape Town presents a solid business case. The discounted payback period of 5.73 years though longer than some studies, remains competitive indicating the project's viability in Cape Town’s economic environment. Overall, the findings suggest that the proposed project’s financial viability as an alternative to conventional lighting solutions.

4.8 Conclusion

The above analysis revealed that replacing grid-connected HPS with solar-powered LED lighting results in significant estimated energy savings and a favourable payback period. The project’s long-term financial viability is further demonstrated amidst the rising electricity tariffs. The upcoming chapter, Chapter 5 concludes the dissertation. The research’s findings and outcomes are reiterated including a comprehensive analysis. This chapter addresses the implications of the study’s outcomes concluding the simulation results. In addition, recommendations for future research are explored.

CHAPTER FIVE

CONCLUSION

5.0 Introduction

The research's focus was to determine if solar streetlighting is technically and economically viable to replace conventional streetlighting. This techno-economic analysis has evaluated and demonstrated the feasibility of implementing solar PV streetlighting in the Cape Town Metropolitan area. The major findings show that the proposed system offers a compelling blend of technical and economic merits. The major findings of the techno-economic analysis are described below.

5.1 Financial viability

The proposed solar-powered streetlight project's capital outlay for a 1km long dual carriageway amounted to R847 285.96. The project has an internal rate of return (IRR) of 15.51%, a net present value (NPV) of R18 707 815.25 and a discounted payback period of 5.73 years. The projected energy savings over the project's term amounted to R11 135 961. This highlights the project's financial viability.

5.2 Technical feasibility

From a technical standpoint, the solar PV system is fully capable of meeting the required lighting standards ensuring a user-friendly, safe, and well-lit environment. The proposed high-powered 174W LED luminaire substitutes the 250W high-pressure sodium lamp resulting in an estimated 60.38% energy saving. The proposed individual solar streetlight system comprising of two 520Wp solar panels, two 24VDC 100Ah batteries, and a 20A charge controller-LED driver unit amongst other components, is fully capable of delivering the required lighting.

Solar streetlight systems are a good alternative to grid-powered traditional lighting. The improvement of LED lighting technology, photovoltaic panels, and lithium-ion battery technologies coupled with their attractive prices in the market and the ever-increasing electricity tariffs in South Africa have improved the business case for the solar streetlight system. The proposed solar-powered LED streetlight can replace traditional lighting as its lighting output matches the former without negatively affecting functionality. The Cape Town metropolitan area has lower solar irradiation in winter which coincides with the rainy season. The researcher recommends that the system design considers the periods of lowest solar irradiation to ensure that the streetlight systems perform all around the year and use monocrystalline solar panels which attain more power generation output than polycrystalline PV panel variants.

5.3 Dissertation deliverables

This research work has different deliverables which are summarised below according to the focus sub-areas.

5.3.1 Technical analysis

- A DIALux simulation report showing the proposed lighting performance is included as an appendix for this research work. The proposed system's design was based on the results shown in the DIALux simulation report.
- The technical specifications of the selected major proposed system's components.
- Estimated annual energy savings calculations were conducted for the project term.

5.3.2 Economic analysis

- A comprehensive breakdown of initial investment costs inclusive of the component sourcing, installation costs and ongoing operational expenses such as operational maintenance and component replacement.
- A customised Excel workbook used as a financial modelling tool to evaluate the economic viability of the proposed solar streetlight project. The metrics derived from the Excel tool include the internal rate of return, net present value and discounted payback period.
- Sensitivity analyses conducted evaluating the impact of key variables such annual electricity tariff and battery pricing changes on the economic performance of the proposed solar streetlighting project over its term.

5.3.3 Possible application of the research outputs

The research work has several potential applications which are detailed below.

a) Urban infrastructure planning and implementation

The research's findings are useful for urban lighting infrastructure decision-making processes. The techno-economic feasibility demonstrated in the study can be used to strategically adopt solar-powered streetlighting as a suitable replacement for conventional grid-powered lighting. City planners, project developers and other stakeholders in Cape Town and other areas globally can incorporate sustainable lighting solutions to improve energy consumption and enhance the overall urban outlook and infrastructural resilience.

b) Local employment and industry growth

The research demonstrates the suitability of replacing conventional lighting with solar-powered lighting solutions. The adoption by the city authorities could stimulate local industry growth leading to sustainable job creation and economic development within the city.

c) Energy policy and sustainability

The publication of the research findings will help policymakers to develop policies that promote renewable energy adoption. Lobby groups can also advocate for incentivised regulations to promote environmental friendliness.

d) Investment attraction decisions

The research study which highlights the financial viability and attractive potential business returns may attract private investment in solar streetlighting projects. Innovative business models for solar streetlighting projects can be crafted to suit the investor’s criteria. The investment in solar streetlighting project implementation will result in socioeconomic benefits.

e) International collaboration and knowledge sharing

The publication of the research’s findings will contribute to the global knowledge base on sustainable urban lighting and the incorporation of solar PV energy applications. There is also a potential for collaboration with other researchers and stakeholders in other areas within and outside South Africa.

5.4 Recommendations for future study

Lithium-ion batteries typically require more capital investment than lead-acid batteries. The researcher however recommends that lithium-ion batteries be used in all the deployed solar streetlight systems due to their superior technical performance characteristics. The researcher recommends that there be a study to see how GPS devices and low-power cameras can be integrated with solar streetlight systems to curb the threat of vandalism and theft. Considering the huge capital outlay that may be required to deploy the solar streetlight system, the researcher recommends that there be consideration of other business models and ways of attaining finances to ensure the city’s cash flow is not hampered. For instance, in some cities in Africa, advertising companies install advertising placards on streetlight poles to advertise for their clients’ customer base. The city will generate revenue from the rental of this advertising space by companies. This revenue will go a long way in ensuring that operation and maintenance are done timeously, and that visible security officers can be deployed to ensure that there is no theft and can be redeployed in the project amongst many possibilities.

5.5 Anticipated publications

The researcher will submit this work to the university's digital archives such as the electronic dissertation repository and library to enable sharing of this research work with other colleagues. This will ensure wider visibility within the University's and broader academic community. In addition, the researcher will seek to publish the research work in several reputable academic journals and platforms such as Energies, AIMS Energy, International Journal of Low-carbon technologies just to mention a few. The researcher is also keen to present at various relevant industry events and energy forums such as Enlit Africa and Africa Renewables Investment Summit, provided there is an opportunity to do so. The possible anticipated journal articles to be published are as follows:-

- Machisa, S. T., Yan, B., Muvunzi, R. and Krishnamurthy, S. 2024. Techno-economic assessment of solar-powered lighting: A case study of the Cape Town Metropolitan Area. *International Journal of Engineering Research.*
- Machisa, S. T., Yan, B., Muvunzi, R. and Krishnamurthy, S. 2024. Techno-economic assessment of solar-powered lighting: A case study of the Cape Town Metropolitan Area. *International Journal of Low-carbon technologies.*
- Machisa, S. T., Yan, B., Muvunzi, R. and Krishnamurthy, S. 2024. Techno-economic assessment of solar-powered lighting: A case study of the Cape Town Metropolitan Area. *Energies.*
- Machisa, S. T., Yan, B., Muvunzi, R. and Krishnamurthy, S. 2024. Techno-economic assessment of solar-powered lighting: A case study of the Cape Town Metropolitan Area. In Proceedings of the Africa Renewables Investment Summit.
- Machisa, S. T., Yan, B., Muvunzi, R. and Krishnamurthy, S. 2024. Techno-economic assessment of solar-powered lighting: A case study of the Cape Town Metropolitan Area. In Proceedings of the Enlit Africa.

5.6 Conclusion

In conclusion, this research study's findings demonstrate an attractive business case highlighting the importance of adopting renewable energy solutions in urban settings. The proposed solar streetlighting project contributes to energy savings noted in the financial viability assessment. The adoption of solar-powered solutions creates sustainable and climate resilient urban environments amidst the population growth and prevalent climate change in urban areas. The researcher recommends future studies to explore the integration of smart technologies and the socio-economic impacts of solar street lighting to provide further insights for policymakers and professionals such as energy engineers, investment bankers, urban planners just to mention a few.

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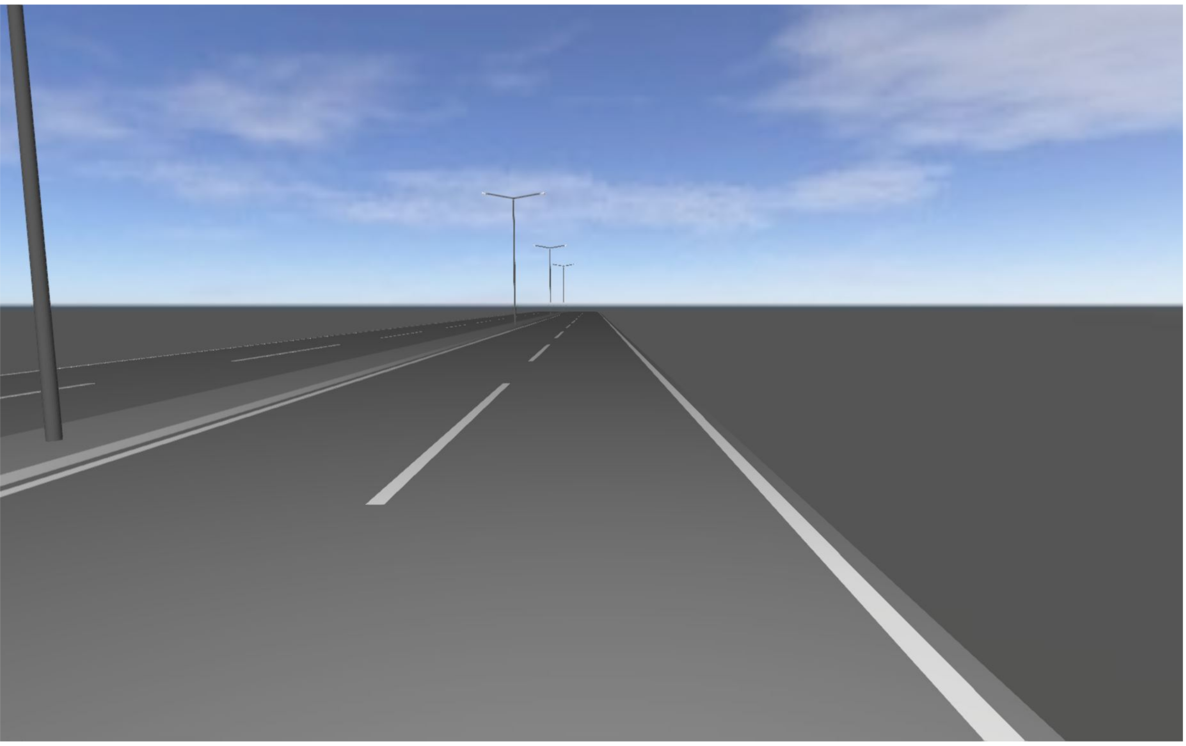
APPENDIX A: DIALux SIMULATION REPORT



DUAL CARRIAGEWAY HIGHWAY PROJECT

Content

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Luminaire list · · · 3

Product data sheets

Not yet a DIALux member - BRP384 LED 320 757 174W DM A5 (1x LED) · · · 4

Street 1 · Alternative 1

Summary (according to EN 13201:2015) · · · 5
Roadway 2 (M1) · · · 8
Roadway 1 (M1) · · · 15

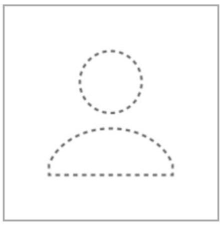
Luminaire list

Φ_{total}	P_{total}	Luminous efficacy
255984 lm	1392.0 W	183.9 lm/W

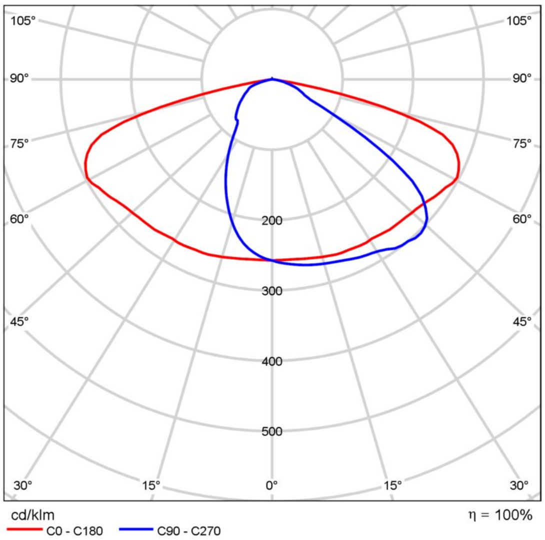
pcs.	Manufacturer	Article No.	Article name	P	Φ	Luminous efficacy
8	Not yet a DIALux member		BRP384 LED 320 757 174W DM A5	174.0 W	31998 lm	183.9 lm/W

Product data sheet

Not yet a DIALux member - BRP384 LED 320 757 174W DM A5



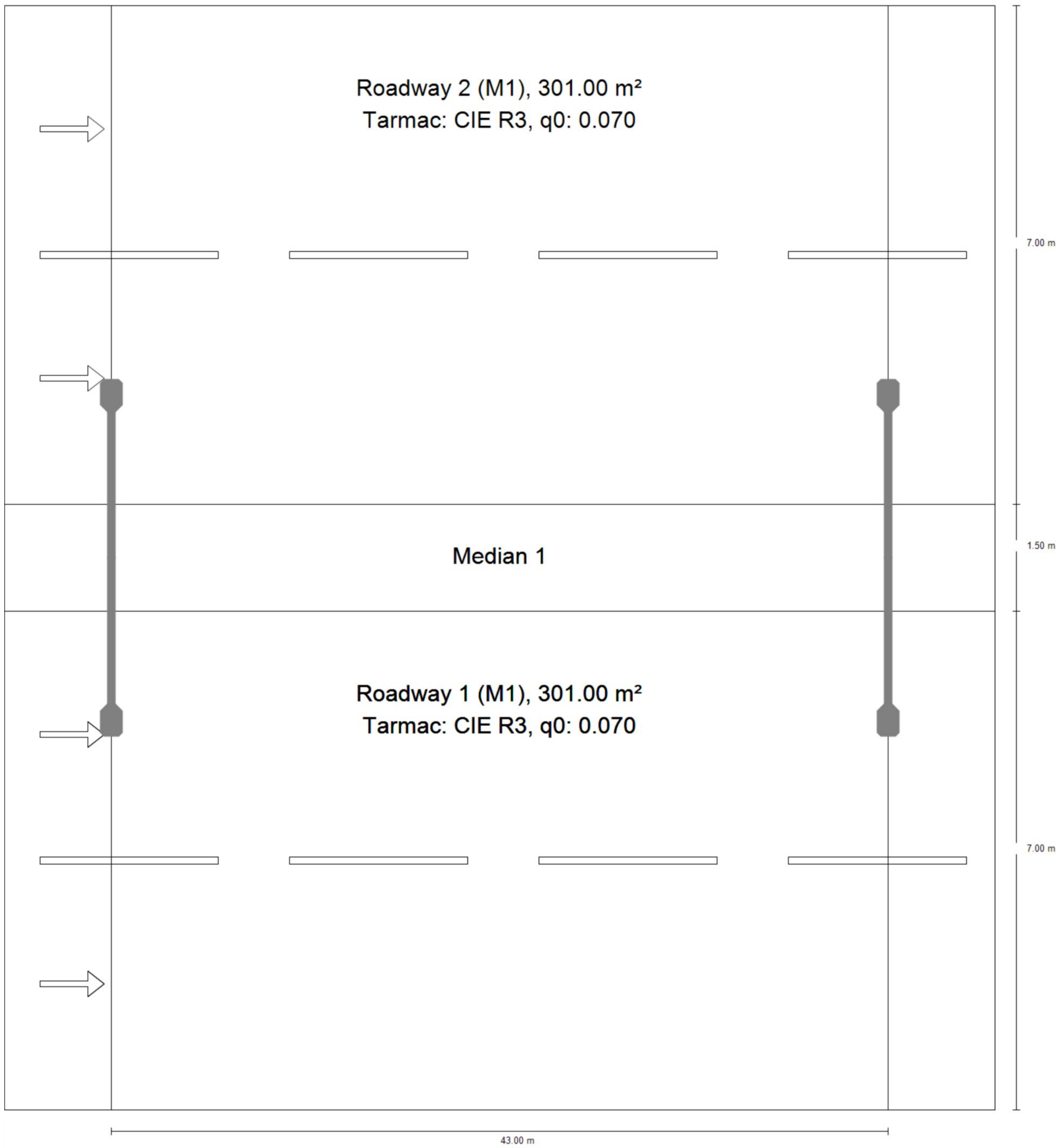
P	174.0 W
Φ_{Lamp}	32000 lm
$\Phi_{Luminaire}$	31998 lm
η	99.99 %
Luminous efficacy	183.9 lm/W
CCT	3000 K
CRI	100



Polar LDC

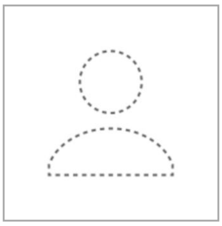
Street 1

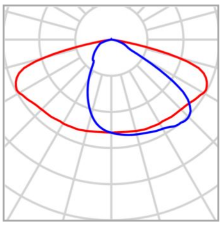
Summary (according to EN 13201:2015)



Street 1

Summary (according to EN 13201:2015)



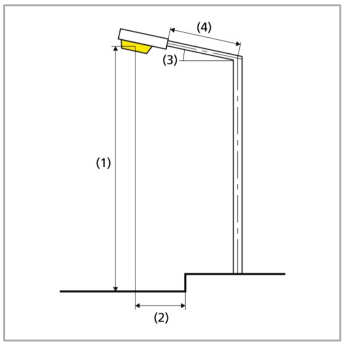


Manufacturer	Not yet a DIALux member
Article name	BRP384 LED 320 757 174W DM A5
Fitting	1x LED

P	174.0 W
Φ_{Lamp}	32000 lm
$\Phi_{Luminaire}$	31998 lm
η	99.99 %

BRP384 LED 320 757 174W DM A5 (Median, 2 per pole)

Pole distance	43.000 m
(1) Light spot height	10.000 m
(2) Light point overhang	1.500 m
(3) Boom inclination	10.0°
(4) Boom length	2.267 m
Annual operating hours	4000 h: 100.0 %, 348.0 W
Consumption	8004.0 W/km
ULR / ULOR	0.00 / 0.00
Max. luminous intensities Any direction forming the specified angle from the downward vertical, with the luminaire installed for use.	≥ 70°: 516 cd/klm ≥ 80°: 342 cd/klm ≥ 90°: 11.1 cd/klm
Luminous intensity class The luminous intensity values in [cd/klm] for calculation of the luminous intensity class refer to the luminaire luminous flux according to EN 13201:2015.	–
Glare index class	D.3
MF	0.80



Street 1

Summary (according to EN 13201:2015)

Results for valuation fields

A maintenance factor of 0.80 was used for calculating for the installation.

	Symbol	Calculated	Target	Check
Roadway 2 (M1)	L_{av}	2.27 cd/m²	≥ 2.00 cd/m²	✓
	U_o	0.53	≥ 0.40	✓
	U_l	0.71	≥ 0.70	✓
	TI	10 %	≤ 10 %	✓
	R_{EI}	0.80	≥ 0.35	✓
Roadway 1 (M1)	L_{av}	2.27 cd/m²	≥ 2.00 cd/m²	✓
	U_o	0.53	≥ 0.40	✓
	U_l	0.71	≥ 0.70	✓
	TI	10 %	≤ 10 %	✓
	R_{EI}	0.80	≥ 0.35	✓

Results for energy efficiency indicators

	Symbol	Calculated	Consumption
Street 1	D_p	0.016 W/lx*m²	–
BRP384 LED 320 757 174W DM A5 (Median)	D_e	2.3 kWh/m² yr	1392.0 kWh/yr

Street 1
Roadway 2 (M1)

Results for valuation field

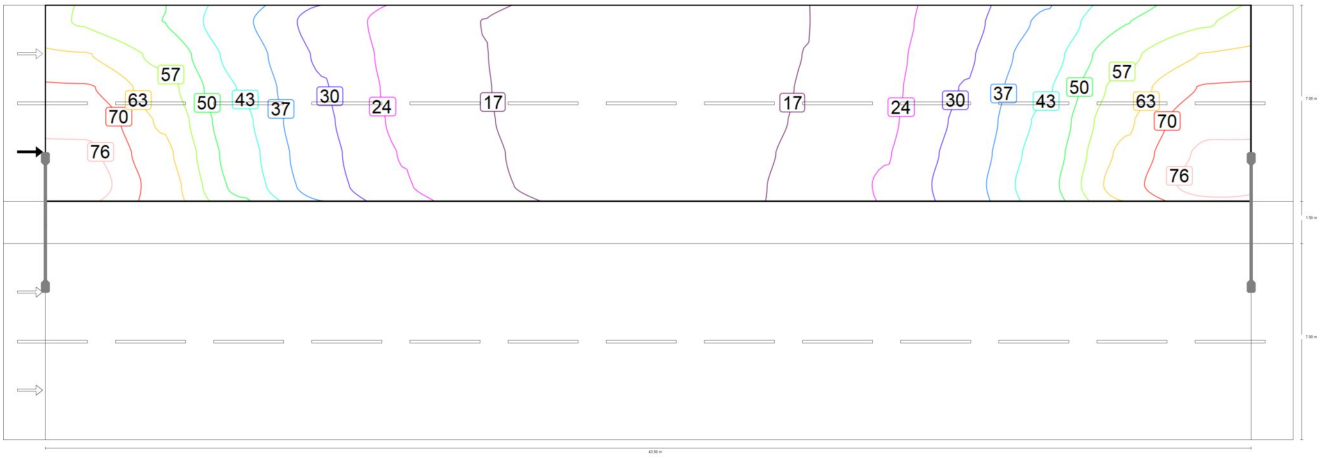
	Symbol	Calculated	Target	Check
Roadway 2 (M1)	L_{av}	2.27 cd/m²	≥ 2.00 cd/m²	✓
	U_o	0.53	≥ 0.40	✓
	U_l	0.71	≥ 0.70	✓
	TI	10 %	≤ 10 %	✓
	R_{EI}	0.80	≥ 0.35	✓

Results for observer

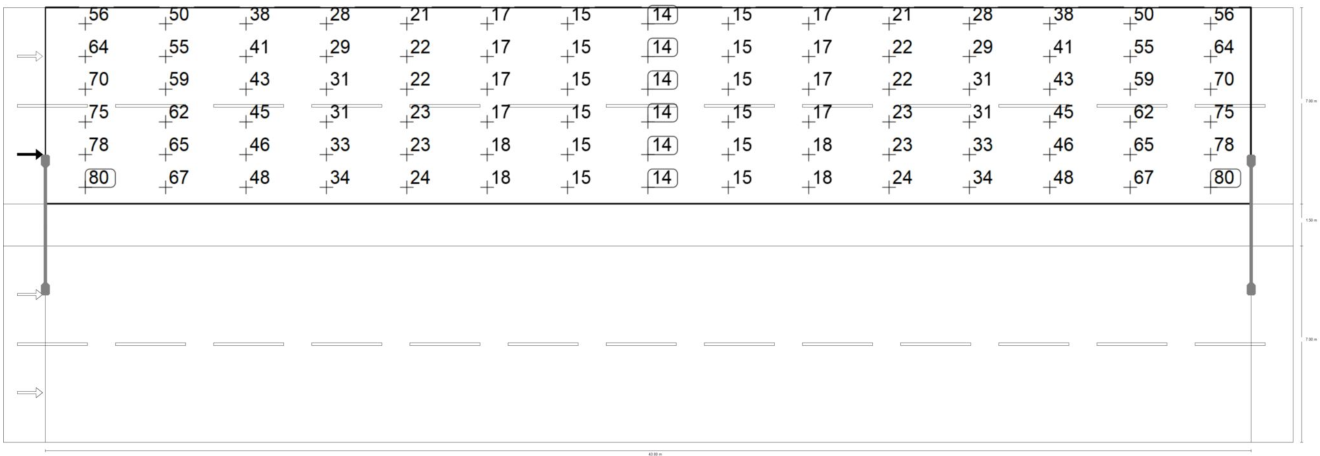
	Symbol	Calculated	Target	Check
Observer 1 Position: -60.000 m, 10.250 m , 1.500 m	L_{av}	2.27 cd/m²	≥ 2.00 cd/m²	✓
	U_o	0.53	≥ 0.40	✓
	U_l	0.72	≥ 0.70	✓
	TI	10 %	≤ 10 %	✓
Observer 2 Position: -60.000 m, 13.750 m , 1.500 m	L_{av}	2.41 cd/m²	≥ 2.00 cd/m²	✓
	U_o	0.56	≥ 0.40	✓
	U_l	0.71	≥ 0.70	✓
	TI	9 %	≤ 10 %	✓

Street 1

Roadway 2 (M1)



Maintenance value, horizontal illuminance [lx] (Iso-illuminance curves)



Maintenance value, horizontal illuminance [lx] (Value grid)

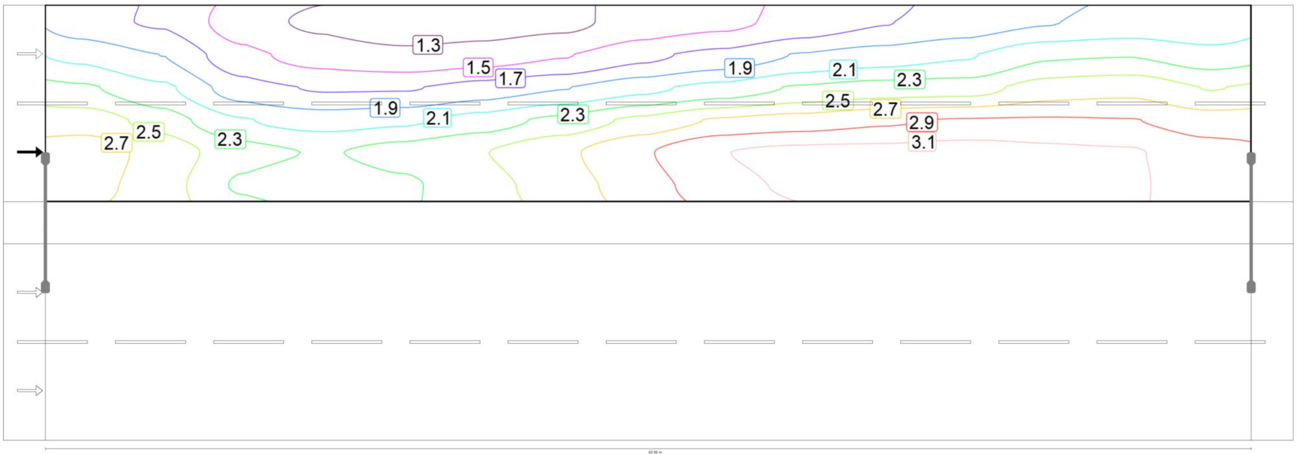
m	1.433	4.300	7.167	10.033	12.900	15.767	18.633	21.500	24.367	27.233	30.100	32.967	35.833	38.700	41.567
14.917	56.13	49.94	37.83	28.21	21.21	16.97	14.68	13.99	14.68	16.97	21.21	28.21	37.83	49.94	56.13
13.750	63.53	55.04	40.61	29.44	21.75	17.07	14.59	13.80	14.59	17.07	21.75	29.44	40.61	55.04	63.53
12.583	70.32	59.26	42.88	30.52	22.19	17.22	14.57	13.75	14.57	17.22	22.19	30.52	42.88	59.26	70.32
11.417	74.85	62.32	44.75	31.39	22.61	17.39	14.75	13.73	14.75	17.39	22.61	31.39	44.75	62.32	74.85
10.250	77.58	64.77	46.33	32.52	23.38	17.89	15.10	14.00	15.10	17.89	23.38	32.52	46.33	64.77	77.58
9.083	79.63	66.93	47.85	33.71	24.15	18.35	15.42	14.23	15.42	18.35	24.15	33.71	47.85	66.93	79.63

Maintenance value, horizontal illuminance [lx] (Value chart)

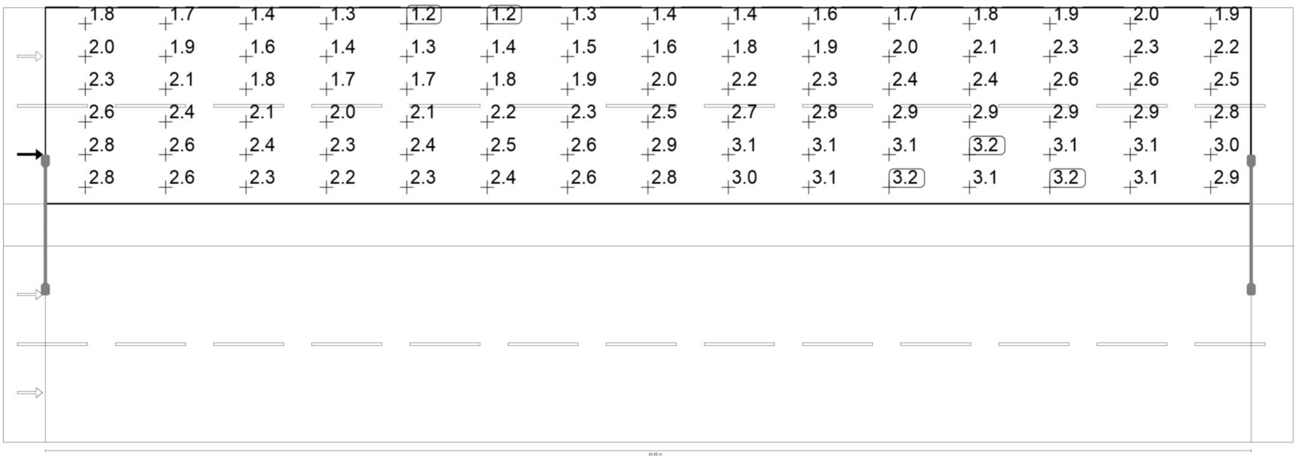
	E_{av}	E_{min}	E_{max}	g_1	g_2
Maintenance value, horizontal illuminance	35.5 lx	13.7 lx	79.6 lx	0.39	0.17

Street 1

Roadway 2 (M1)



Observer 1: Maintenance value, luminance with dry roadway [cd/m²] (Iso-illuminance curves)



Observer 1: Maintenance value, luminance with dry roadway [cd/m²] (Value grid)

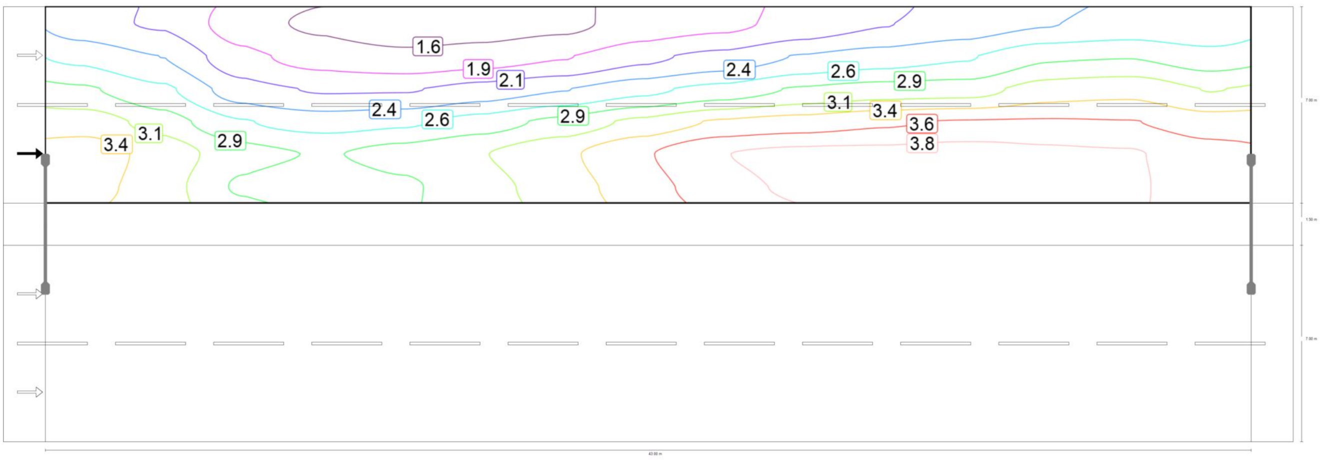
Street 1

Roadway 2 (M1)

m	1.433	4.300	7.167	10.033	12.900	15.767	18.633	21.500	24.367	27.233	30.100	32.967	35.833	38.700	41.567
14.917	1.77	1.67	1.38	1.26	1.20	1.21	1.25	1.38	1.45	1.56	1.68	1.78	1.87	1.96	1.89
13.750	2.04	1.89	1.56	1.41	1.35	1.39	1.48	1.64	1.76	1.91	1.99	2.07	2.26	2.28	2.18
12.583	2.32	2.13	1.78	1.67	1.68	1.78	1.88	2.03	2.16	2.31	2.38	2.40	2.58	2.63	2.48
11.417	2.60	2.39	2.10	2.00	2.05	2.18	2.34	2.54	2.71	2.78	2.85	2.89	2.90	2.89	2.77
10.250	2.78	2.61	2.35	2.28	2.36	2.48	2.64	2.86	3.08	3.12	3.14	3.16	3.13	3.10	2.96
9.083	2.75	2.57	2.26	2.18	2.26	2.41	2.59	2.79	3.01	3.11	3.18	3.15	3.17	3.12	2.92

Observer 1: Maintenance value, luminance with dry roadway [cd/m²] (Value chart)

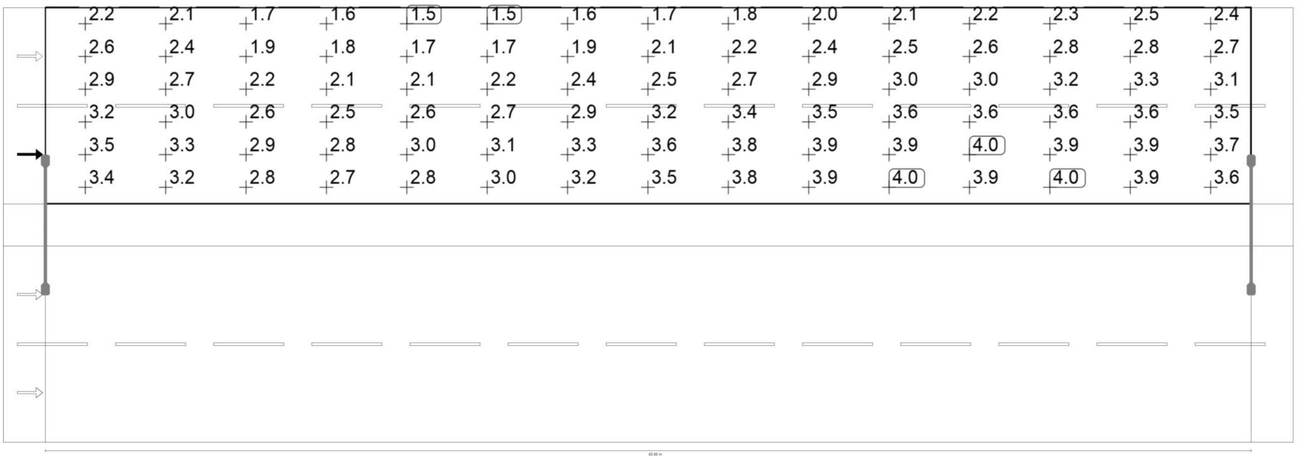
	L_{av}	L_{min}	L_{max}	g_1	g_2
Observer 1: Maintenance value, luminance with dry roadway	2.27 cd/m²	1.20 cd/m²	3.18 cd/m²	0.53	0.38



Observer 1: Luminance with new installation [cd/m²] (Iso-illuminance curves)

Street 1

Roadway 2 (M1)

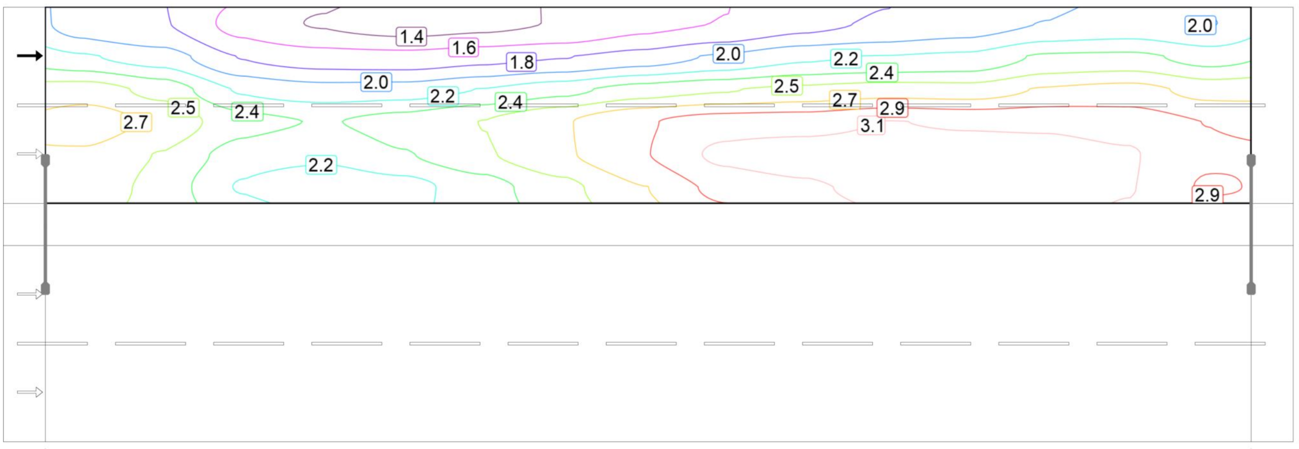


Observer 1: Luminance with new installation [cd/m²] (Value grid)

m	1.433	4.300	7.167	10.033	12.900	15.767	18.633	21.500	24.367	27.233	30.100	32.967	35.833	38.700	41.567
14.917	2.21	2.09	1.73	1.57	1.49	1.52	1.56	1.73	1.81	1.95	2.10	2.22	2.34	2.45	2.37
13.750	2.55	2.36	1.94	1.77	1.68	1.74	1.85	2.05	2.20	2.38	2.49	2.59	2.83	2.85	2.73
12.583	2.89	2.66	2.22	2.09	2.10	2.22	2.35	2.54	2.70	2.89	2.98	3.00	3.23	3.29	3.09
11.417	3.25	2.99	2.63	2.50	2.57	2.73	2.93	3.17	3.39	3.47	3.57	3.62	3.63	3.61	3.47
10.250	3.47	3.27	2.94	2.84	2.96	3.10	3.31	3.58	3.85	3.90	3.92	3.95	3.91	3.87	3.70
9.083	3.44	3.21	2.82	2.73	2.82	3.01	3.23	3.49	3.76	3.89	3.97	3.94	3.96	3.90	3.65

Observer 1: Luminance with new installation [cd/m²] (Value chart)

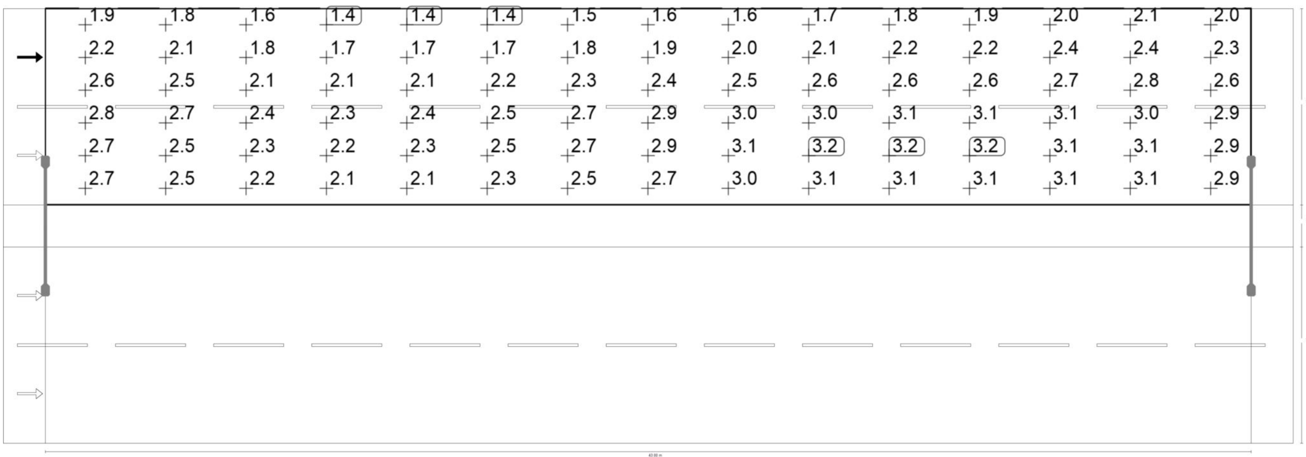
	L_{av}	L_{min}	L_{max}	g_1	g_2
Observer 1: Luminance with new installation	2.84 cd/m²	1.49 cd/m²	3.97 cd/m²	0.53	0.38



Observer 2: Maintenance value, luminance with dry roadway [cd/m²] (Iso-illuminance curves)

Street 1

Roadway 2 (M1)



Observer 2: Maintenance value, luminance with dry roadway [cd/m²] (Value grid)

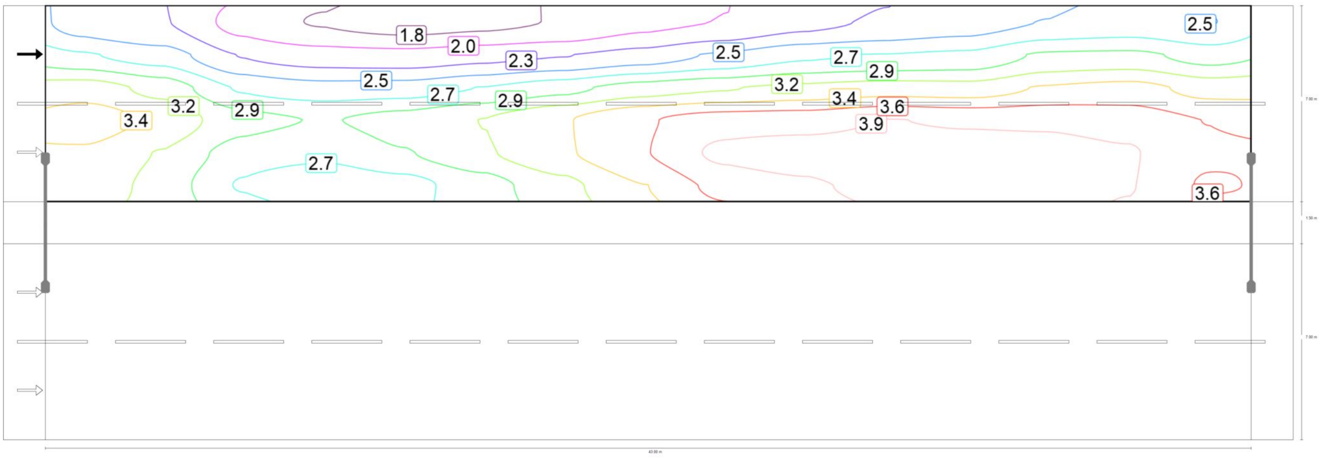
m	1.433	4.300	7.167	10.033	12.900	15.767	18.633	21.500	24.367	27.233	30.100	32.967	35.833	38.700	41.567
14.917	1.89	1.82	1.55	1.43	1.35	1.39	1.45	1.57	1.63	1.75	1.83	1.89	1.99	2.05	1.98
13.750	2.20	2.08	1.80	1.71	1.69	1.75	1.80	1.89	2.02	2.14	2.18	2.22	2.38	2.40	2.28
12.583	2.62	2.47	2.15	2.06	2.08	2.18	2.30	2.44	2.52	2.59	2.63	2.62	2.74	2.78	2.65
11.417	2.82	2.67	2.41	2.35	2.42	2.54	2.70	2.88	3.00	3.02	3.09	3.06	3.05	3.01	2.90
10.250	2.69	2.52	2.26	2.21	2.34	2.51	2.69	2.89	3.12	3.16	3.17	3.17	3.14	3.10	2.94
9.083	2.65	2.46	2.15	2.06	2.11	2.27	2.48	2.72	2.95	3.05	3.13	3.11	3.14	3.09	2.88

Observer 2: Maintenance value, luminance with dry roadway [cd/m²] (Value chart)

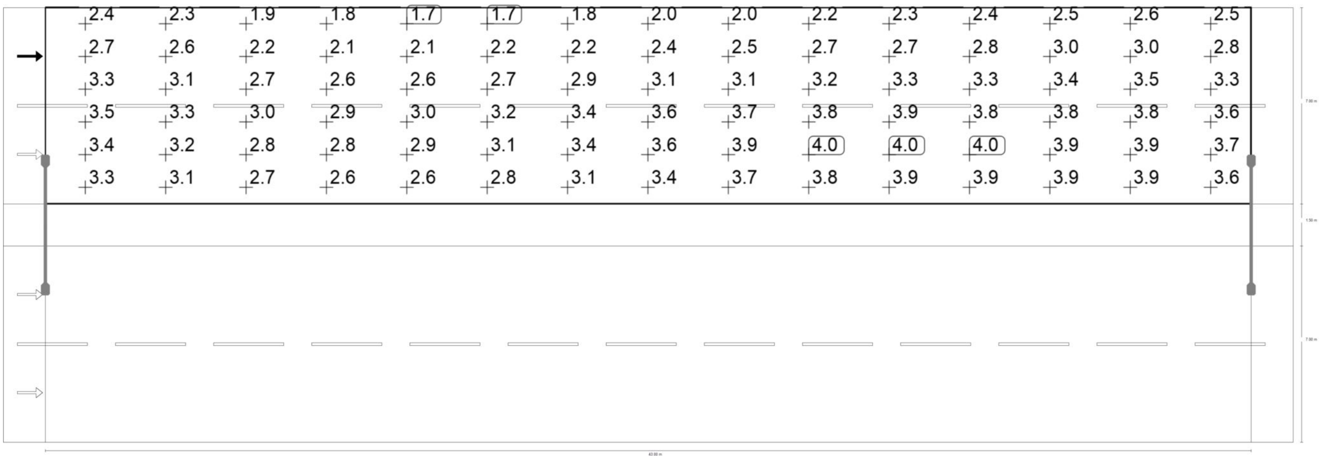
	L_{av}	L_{min}	L_{max}	g_1	g_2
Observer 2: Maintenance value, luminance with dry roadway	2.41 cd/m²	1.35 cd/m²	3.17 cd/m²	0.56	0.43

Street 1

Roadway 2 (M1)



Observer 2: Luminance with new installation [cd/m²] (Iso-illuminance curves)



Observer 2: Luminance with new installation [cd/m²] (Value grid)

m	1.433	4.300	7.167	10.033	12.900	15.767	18.633	21.500	24.367	27.233	30.100	32.967	35.833	38.700	41.567
14.917	2.37	2.27	1.94	1.78	1.69	1.74	1.82	1.97	2.03	2.18	2.29	2.37	2.49	2.56	2.48
13.750	2.74	2.60	2.24	2.14	2.12	2.19	2.25	2.36	2.52	2.68	2.72	2.77	2.98	3.00	2.85
12.583	3.28	3.09	2.68	2.57	2.59	2.72	2.87	3.05	3.15	3.23	3.29	3.27	3.42	3.48	3.31
11.417	3.52	3.34	3.01	2.93	3.02	3.17	3.38	3.60	3.75	3.77	3.86	3.82	3.82	3.77	3.62
10.250	3.36	3.15	2.83	2.76	2.92	3.14	3.37	3.62	3.91	3.95	3.97	3.96	3.93	3.87	3.67
9.083	3.32	3.08	2.69	2.57	2.64	2.84	3.10	3.39	3.69	3.81	3.91	3.89	3.93	3.86	3.60

Observer 2: Luminance with new installation [cd/m²] (Value chart)

	L_{av}	L_{min}	L_{max}	g_1	g_2
Observer 2: Luminance with new installation	3.01 cd/m²	1.69 cd/m²	3.97 cd/m²	0.56	0.43

Street 1

Roadway 1 (M1)

Results for valuation field

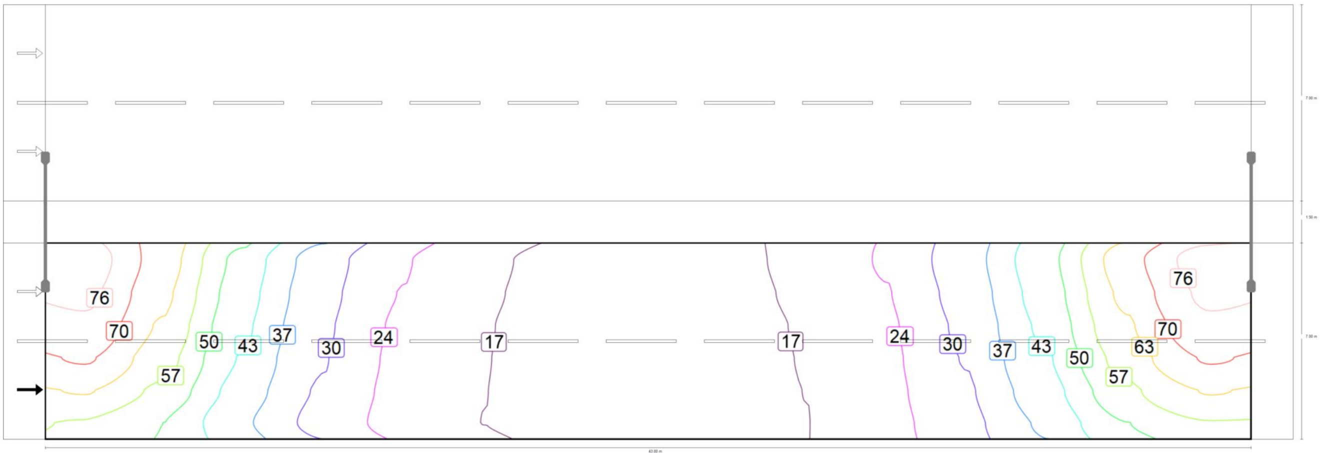
	Symbol	Calculated	Target	Check
Roadway 1 (M1)	L_{av}	2.27 cd/m²	≥ 2.00 cd/m²	✓
	U_o	0.53	≥ 0.40	✓
	U_l	0.71	≥ 0.70	✓
	TI	10 %	≤ 10 %	✓
	R_{EI}	0.80	≥ 0.35	✓

Results for observer

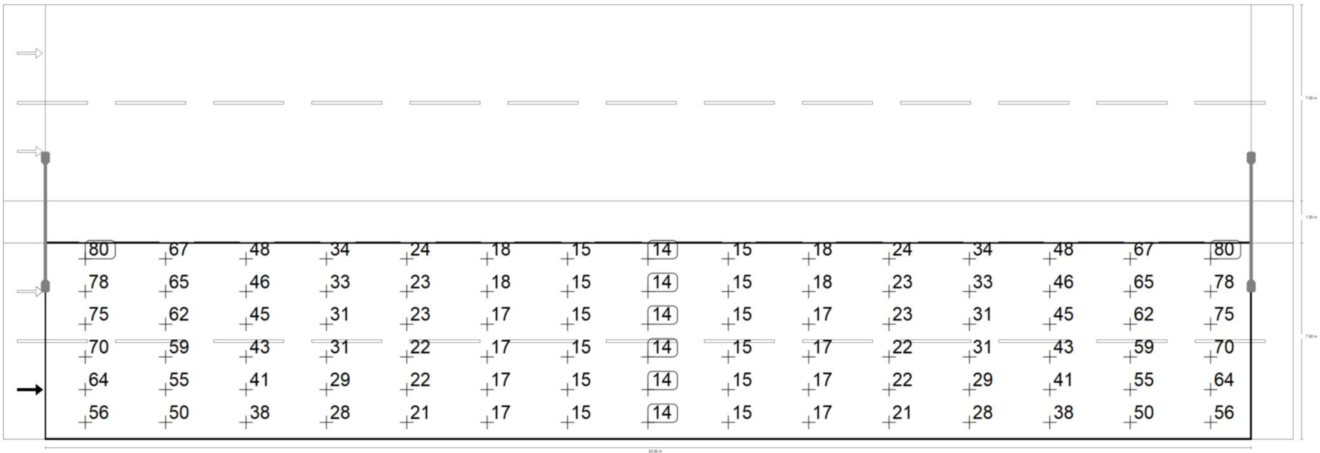
	Symbol	Calculated	Target	Check
Observer 1 Position: -60.000 m, 1.750 m, 1.500 m	L_{av}	2.41 cd/m²	≥ 2.00 cd/m²	✓
	U_o	0.56	≥ 0.40	✓
	U_l	0.71	≥ 0.70	✓
	TI	9 %	≤ 10 %	✓
Observer 2 Position: -60.000 m, 5.250 m, 1.500 m	L_{av}	2.27 cd/m²	≥ 2.00 cd/m²	✓
	U_o	0.53	≥ 0.40	✓
	U_l	0.72	≥ 0.70	✓
	TI	10 %	≤ 10 %	✓

Street 1

Roadway 1 (M1)



Maintenance value, horizontal illuminance [lx] (Iso-illuminance curves)



Maintenance value, horizontal illuminance [lx] (Value grid)

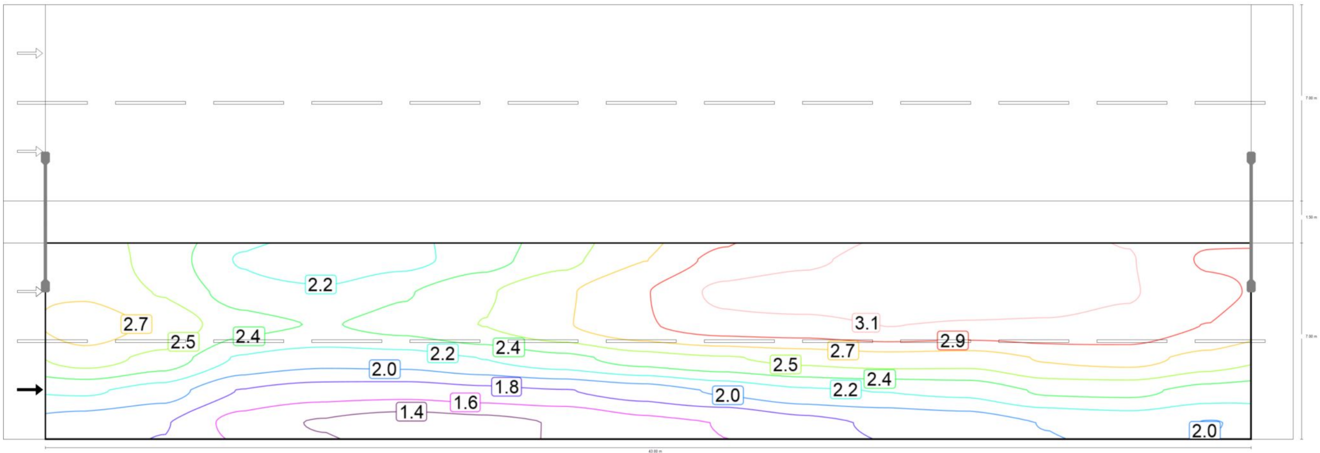
m	1.433	4.300	7.167	10.033	12.900	15.767	18.633	21.500	24.367	27.233	30.100	32.967	35.833	38.700	41.567
6.417	79.63	66.93	47.85	33.71	24.15	18.35	15.42	14.23	15.42	18.35	24.15	33.71	47.85	66.93	79.63
5.250	77.58	64.77	46.33	32.52	23.38	17.89	15.10	14.00	15.10	17.89	23.38	32.52	46.33	64.77	77.58
4.083	74.85	62.32	44.75	31.39	22.61	17.39	14.75	13.73	14.75	17.39	22.61	31.39	44.75	62.32	74.85
2.917	70.32	59.26	42.88	30.52	22.19	17.22	14.57	13.75	14.57	17.22	22.19	30.52	42.88	59.26	70.32
1.750	63.53	55.04	40.61	29.44	21.75	17.07	14.59	13.80	14.59	17.07	21.75	29.44	40.61	55.04	63.53
0.583	56.13	49.94	37.83	28.21	21.21	16.97	14.68	13.99	14.68	16.97	21.21	28.21	37.83	49.94	56.13

Maintenance value, horizontal illuminance [lx] (Value chart)

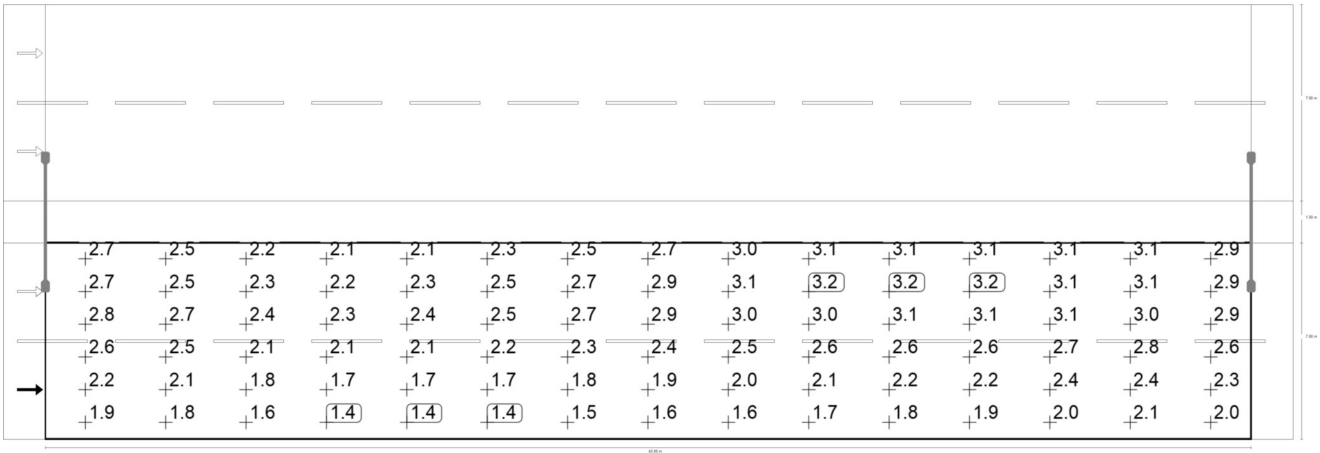
	E_{av}	E_{min}	E_{max}	g_1	g_2
Maintenance value, horizontal illuminance	35.5 lx	13.7 lx	79.6 lx	0.39	0.17

Street 1

Roadway 1 (M1)



Observer 1: Maintenance value, luminance with dry roadway [cd/m²] (Iso-illuminance curves)



2.7	2.5	2.2	2.1	2.1	2.3	2.5	2.7	3.0	3.1	3.1	3.1	3.1	3.1	2.9
2.7	2.5	2.3	2.2	2.3	2.5	2.7	2.9	3.1	3.2	3.2	3.2	3.1	3.1	2.9
2.8	2.7	2.4	2.3	2.4	2.5	2.7	2.9	3.0	3.0	3.1	3.1	3.1	3.0	2.9
2.6	2.5	2.1	2.1	2.1	2.2	2.3	2.4	2.5	2.6	2.6	2.6	2.7	2.8	2.6
2.2	2.1	1.8	1.7	1.7	1.7	1.8	1.9	2.0	2.1	2.2	2.2	2.4	2.4	2.3
1.9	1.8	1.6	1.4	1.4	1.4	1.5	1.6	1.6	1.7	1.8	1.9	2.0	2.1	2.0

Observer 1: Maintenance value, luminance with dry roadway [cd/m²] (Value grid)

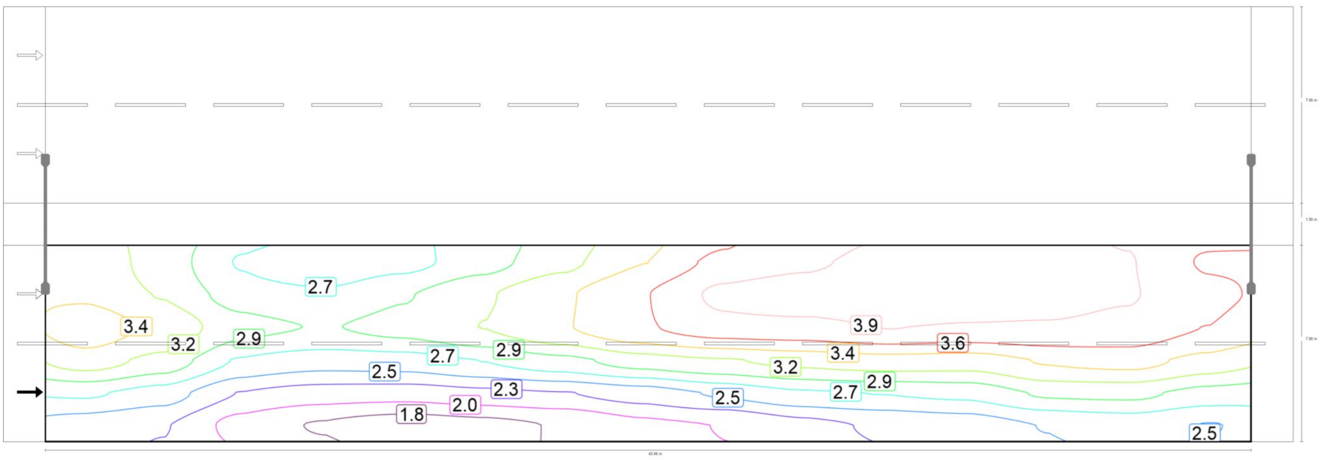
Street 1

Roadway 1 (M1)

m	1.433	4.300	7.167	10.033	12.900	15.767	18.633	21.500	24.367	27.233	30.100	32.967	35.833	38.700	41.567
6.417	2.65	2.46	2.15	2.06	2.11	2.27	2.48	2.72	2.95	3.05	3.13	3.11	3.14	3.09	2.88
5.250	2.69	2.52	2.26	2.21	2.34	2.51	2.69	2.89	3.12	3.16	3.17	3.17	3.14	3.10	2.94
4.083	2.82	2.67	2.41	2.35	2.42	2.54	2.70	2.88	3.00	3.02	3.09	3.06	3.05	3.01	2.90
2.917	2.62	2.47	2.15	2.06	2.08	2.18	2.30	2.44	2.52	2.59	2.63	2.62	2.74	2.78	2.65
1.750	2.20	2.08	1.80	1.71	1.69	1.75	1.80	1.89	2.02	2.14	2.18	2.22	2.38	2.40	2.28
0.583	1.89	1.82	1.55	1.43	1.35	1.39	1.45	1.57	1.63	1.75	1.83	1.89	1.99	2.05	1.98

Observer 1: Maintenance value, luminance with dry roadway [cd/m²] (Value chart)

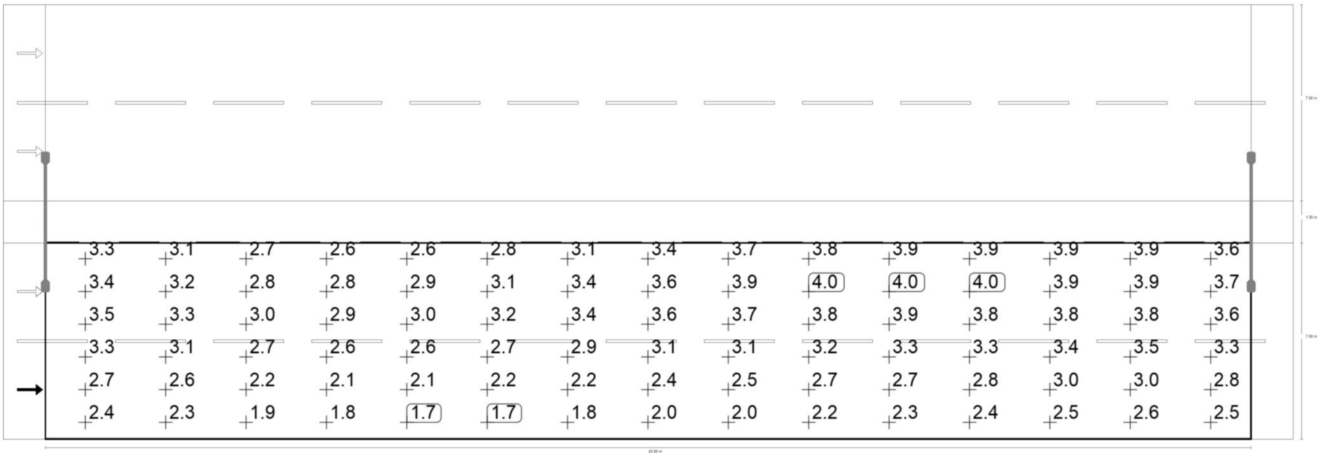
	L_{av}	L_{min}	L_{max}	g_1	g_2
Observer 1: Maintenance value, luminance with dry roadway	2.41 cd/m²	1.35 cd/m²	3.17 cd/m²	0.56	0.43



Observer 1: Luminance with new installation [cd/m²] (Iso-illuminance curves)

Street 1

Roadway 1 (M1)

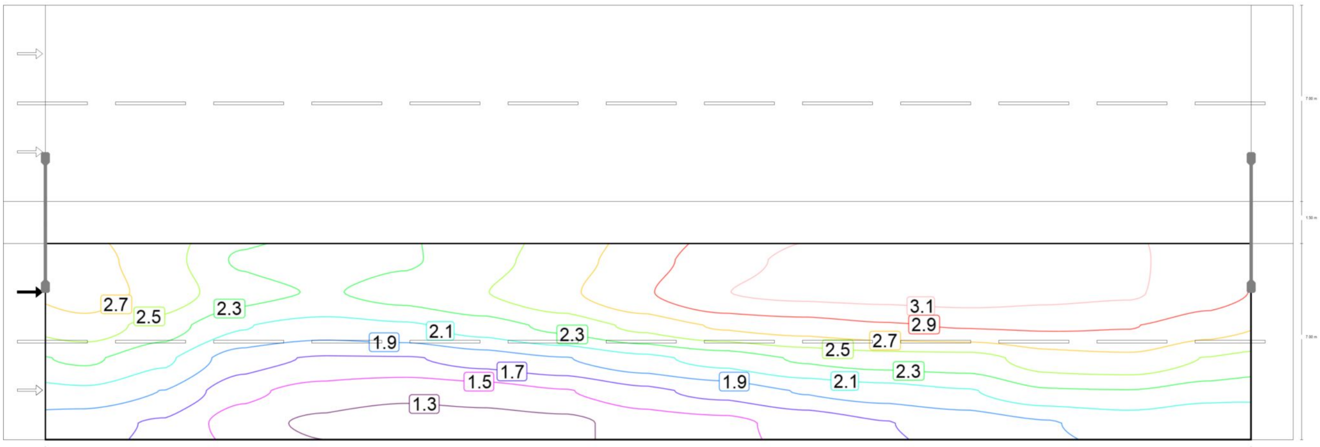


Observer 1: Luminance with new installation [cd/m²] (Value grid)

m	1.433	4.300	7.167	10.033	12.900	15.767	18.633	21.500	24.367	27.233	30.100	32.967	35.833	38.700	41.567
6.417	3.32	3.08	2.69	2.57	2.64	2.84	3.10	3.39	3.69	3.81	3.91	3.89	3.93	3.86	3.60
5.250	3.36	3.15	2.83	2.76	2.92	3.14	3.37	3.62	3.91	3.95	3.97	3.96	3.93	3.87	3.67
4.083	3.52	3.34	3.01	2.93	3.02	3.17	3.38	3.60	3.75	3.77	3.86	3.82	3.82	3.77	3.62
2.917	3.28	3.09	2.68	2.57	2.59	2.72	2.87	3.05	3.15	3.23	3.29	3.27	3.42	3.48	3.31
1.750	2.74	2.60	2.24	2.14	2.12	2.19	2.25	2.36	2.52	2.68	2.72	2.77	2.98	3.00	2.85
0.583	2.37	2.27	1.94	1.78	1.69	1.74	1.82	1.97	2.03	2.18	2.29	2.37	2.49	2.56	2.48

Observer 1: Luminance with new installation [cd/m²] (Value chart)

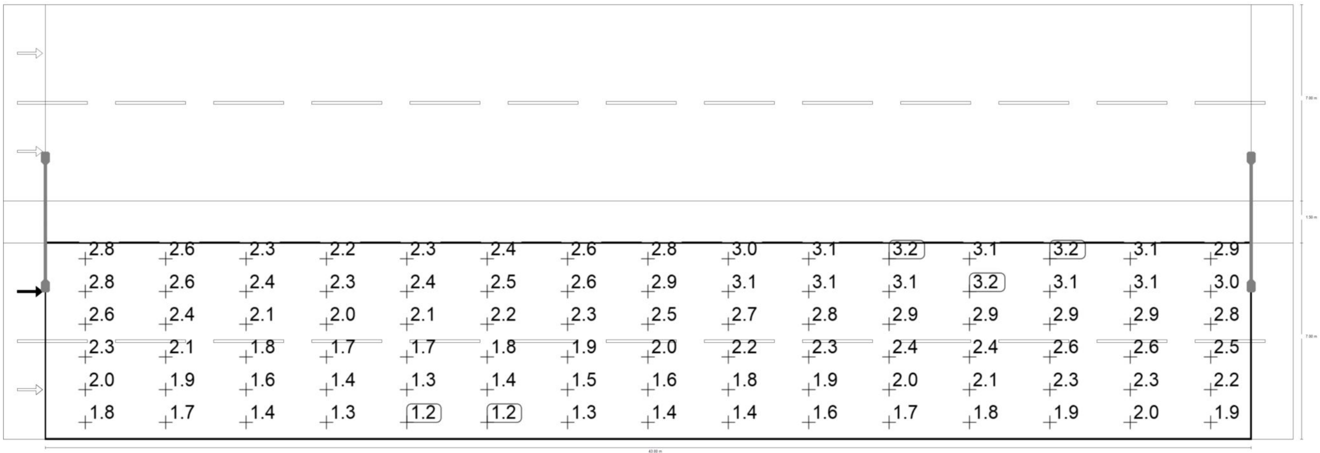
	L_{av}	L_{min}	L_{max}	g_1	g_2
Observer 1: Luminance with new installation	3.01 cd/m²	1.69 cd/m²	3.97 cd/m²	0.56	0.43



Observer 2: Maintenance value, luminance with dry roadway [cd/m²] (Iso-illuminance curves)

Street 1

Roadway 1 (M1)



Observer 2: Maintenance value, luminance with dry roadway [cd/m²] (Value grid)

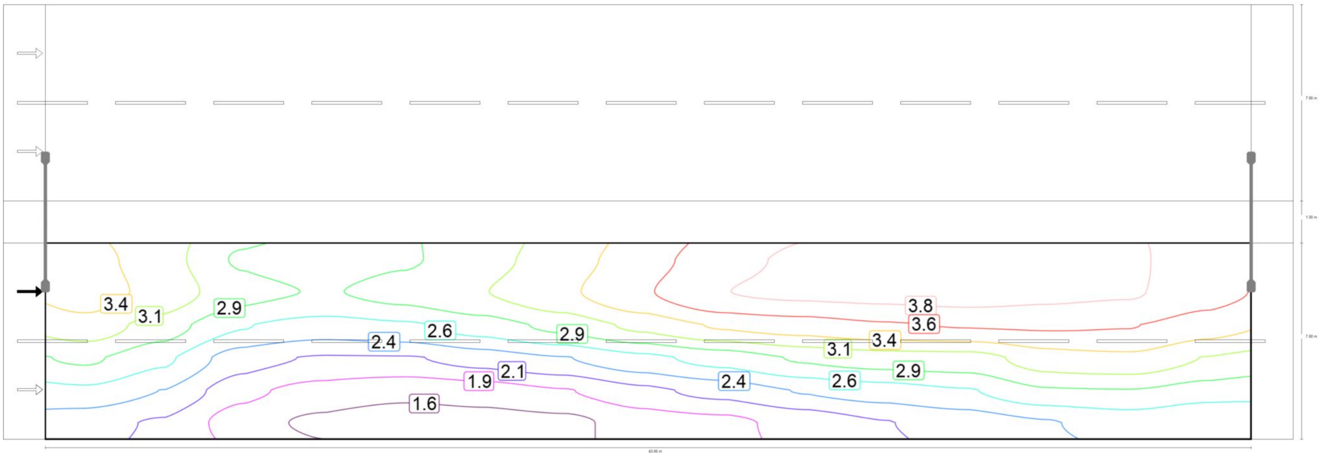
m	1.433	4.300	7.167	10.033	12.900	15.767	18.633	21.500	24.367	27.233	30.100	32.967	35.833	38.700	41.567
6.417	2.75	2.57	2.26	2.18	2.26	2.41	2.59	2.79	3.01	3.11	3.18	3.15	3.17	3.12	2.92
5.250	2.78	2.61	2.35	2.28	2.36	2.48	2.64	2.86	3.08	3.12	3.14	3.16	3.13	3.10	2.96
4.083	2.60	2.39	2.10	2.00	2.05	2.18	2.34	2.54	2.71	2.78	2.85	2.89	2.90	2.89	2.77
2.917	2.32	2.13	1.78	1.67	1.68	1.78	1.88	2.03	2.16	2.31	2.38	2.40	2.58	2.63	2.48
1.750	2.04	1.89	1.56	1.41	1.35	1.39	1.48	1.64	1.76	1.91	1.99	2.07	2.26	2.28	2.18
0.583	1.77	1.67	1.38	1.26	1.20	1.21	1.25	1.38	1.45	1.56	1.68	1.78	1.87	1.96	1.89

Observer 2: Maintenance value, luminance with dry roadway [cd/m²] (Value chart)

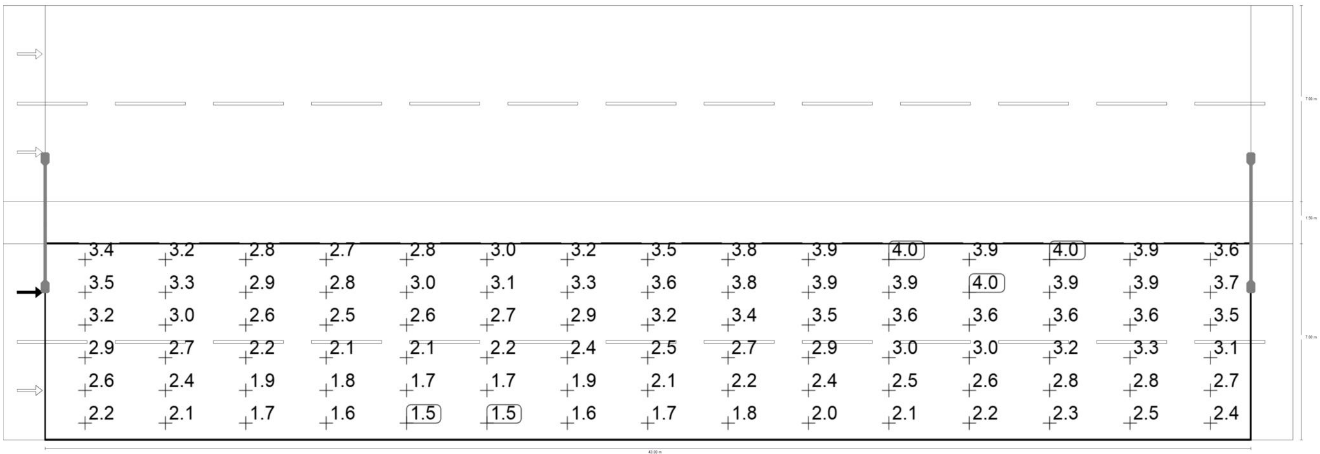
	L_{av}	L_{min}	L_{max}	g_1	g_2
Observer 2: Maintenance value, luminance with dry roadway	2.27 cd/m²	1.20 cd/m²	3.18 cd/m²	0.53	0.38

Street 1

Roadway 1 (M1)



Observer 2: Luminance with new installation [cd/m²] (Iso-illuminance curves)



Observer 2: Luminance with new installation [cd/m²] (Value grid)

m	1.433	4.300	7.167	10.033	12.900	15.767	18.633	21.500	24.367	27.233	30.100	32.967	35.833	38.700	41.567
6.417	3.44	3.21	2.82	2.73	2.82	3.01	3.23	3.49	3.76	3.89	3.97	3.94	3.96	3.90	3.65
5.250	3.47	3.27	2.94	2.84	2.96	3.10	3.31	3.58	3.85	3.90	3.92	3.95	3.91	3.87	3.70
4.083	3.25	2.99	2.63	2.50	2.57	2.73	2.93	3.17	3.39	3.47	3.57	3.62	3.63	3.61	3.47
2.917	2.89	2.66	2.22	2.09	2.10	2.22	2.35	2.54	2.70	2.89	2.98	3.00	3.23	3.29	3.09
1.750	2.55	2.36	1.94	1.77	1.68	1.74	1.85	2.05	2.20	2.38	2.49	2.59	2.83	2.85	2.73
0.583	2.21	2.09	1.73	1.57	1.49	1.52	1.56	1.73	1.81	1.95	2.10	2.22	2.34	2.45	2.37

Observer 2: Luminance with new installation [cd/m²] (Value chart)

	L_{av}	L_{min}	L_{max}	g_1	g_2
Observer 2: Luminance with new installation	2.84 cd/m²	1.49 cd/m²	3.97 cd/m²	0.53	0.38

APPENDIX B: SOLAR PANEL DATASHEET

www.jinkosolar.com

Solar JinKO
Building Your Trust in Solar

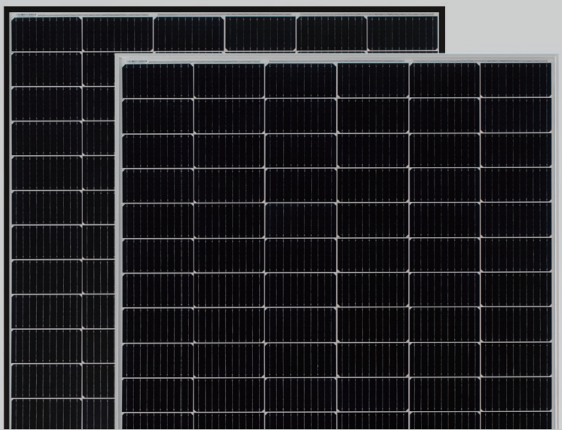
72M HC
520-540 Watt
MONOCRYSTALLINE MODULE

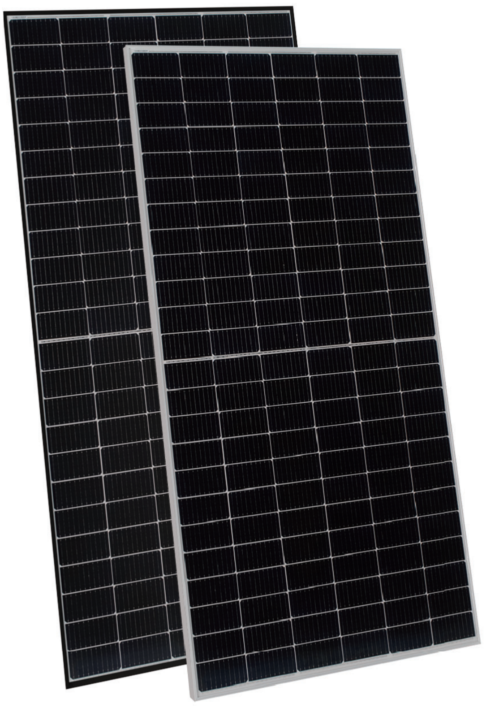
Positive power tolerance of 0~+3%

ISO9001:2015、ISO14001:2015、ISO45001:2018 certified factory.

IEC61215(2016), IEC61730(2016), certified products.

TIGER Pro





PV CYCLE   TÜVRheinland CERTIFIED   CE

POSITIVE QUALITY™ Continuous Quality Assurance   CLEAN ENERGY COUNCIL MEMBER

KEY FEATURES

Multi Busbar Solar Cell
MBB solar cell adopts new technology to improve the efficiency of modules , offers a better aesthetic appearance, making it perfect for rooftop installation.

PID-Resistance

PID Resistance
Excellent Anti-PID performance guarantee limited power degradation for mass production.

30 year

Higher Lifetime Power Yield:
0.55% annual power degradation
25 year linear power warranty

LOW LIGHT

Low-light Performance
Advanced glass and cell surface textured design ensure excellent performance in low-light environment.

2400 Pa
5400 Pa

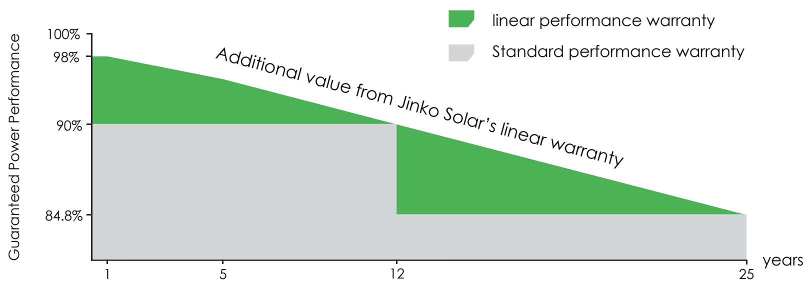
Severe Weather Resilience
Certified to withstand: wind load (2400 Pascal) and snow load (5400 Pascal).

NH
RESISTANT

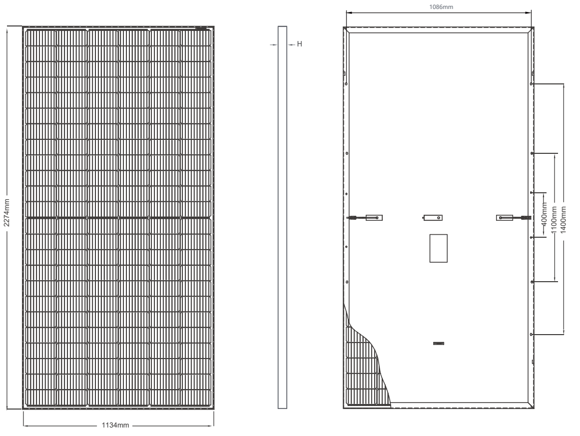
Durability Against Extreme Environmental Conditions
High salt mist and ammonia resistance certified by TUV NORD.

LINEAR PERFORMANCE WARRANTY

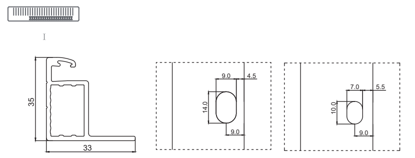
12 Year Product Warranty • 25 Year Linear Power Warranty
0.55% Annual Degradation Over 25 years



Engineering Drawings



Front　　Side　　Back



Length: ±2mm

Width: ±2mm

Height: ±1mm

Row Pitch: ±2mm

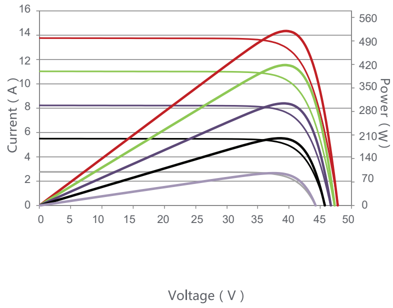
Packaging Configuration

(Two pallets = One stack)

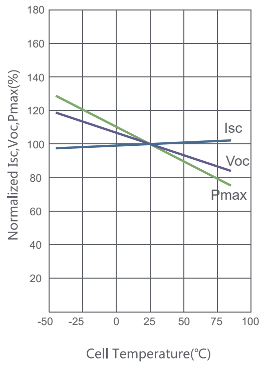
31pcs/pallets, 62pcs/stack, 620pcs/ 40'HQ Container

Electrical Performance & Temperature Dependence

Current-Voltage & Power-Voltage Curves (520W)



Temperature Dependence of Isc,Voc,Pmax



Mechanical Characteristics

Cell Type	P type Mono-crystalline
No.of cells	144 (6×24)
Dimensions	2274×1134×35mm (89.53×44.65×1.38 inch)
Weight	28.9 kg (63.7 lbs)
Front Glass	3.2mm,Anti-Reflection Coating, High Transmission, Low Iron, Tempered Glass
Frame	Anodized Aluminium Alloy
Junction Box	IP68 Rated
Output Cables	TUV 1×4.0mm² (+): 250mm , (-): 150 mm or Customized Length

SPECIFICATIONS

Module Type	MM520-72HLD-MBV		MM525-72HLD-MBV		MM530-72HLD-MBV		MM535-72HLD-MBV		MM540-72HLD-MBV	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	520Wp	387Wp	525Wp	391Wp	530Wp	394Wp	535Wp	398Wp	540Wp	402Wp
Maximum Power Voltage (Vmp)	40.41V	37.52V	40.48V	37.67V	40.56V	37.84V	40.63V	37.91V	40.70V	38.08V
Maximum Power Current (Imp)	12.87A	10.31A	12.97A	10.37A	13.07A	10.42A	13.17A	10.50A	13.27A	10.55A
Open-circuit Voltage (Voc)	49.10V	46.34V	49.18V	46.42V	49.26V	46.50V	49.34V	46.57V	49.42V	46.65V
Short-circuit Current (Isc)	13.57A	10.96A	13.64A	11.02A	13.71A	11.07A	13.79A	11.14A	13.85A	11.19A
Module Efficiency STC (%)	20.17%		20.36%		20.55%		20.75%		20.94%	
Operating Temperature(℃)	-40℃~+85℃									
Maximum system voltage	1500VDC (IEC)									
Maximum series fuse rating	25A									
Power tolerance	0~+3%									
Temperature coefficients of Pmax	-0.35%/℃									
Temperature coefficients of Voc	-0.28%/℃									
Temperature coefficients of Isc	0.048%/℃									
Nominal operating cell temperature (NOCT)	45±2℃									

*STC: Irradiance 1000W/m² Cell Temperature 25°C AM=1.5

NOCT: Irradiance 800W/m² Ambient Temperature 20°C AM=1.5 Wind Speed 1m/s

* Power measurement tolerance: ± 3%

APPENDIX C : CHARGE CONTROLLER-LED DRIVER DATASHEET

Gen4 SR-MES Series MES60/80/120/160/200/260/300(-R/-W)

Waterproof All-in-one Constant Current MPPT Charge Controller

SR-MES60-R/W

SR-MES80/120-R/W

SR-MES160-R/W

SR-MES200-R/W

Product Features

- Using MovingTrack MPPT maximum power tracking technology, higher tracking efficiency and faster speed
- Human motion infrared/microwave sensing function, with sensing delay time settable
- Both lead-acid battery and lithium battery are applicable, operating parameters can be set by remote control
- Using UltraGreen power control technology with extremely low power consumption and sleep current
- Lead-acid battery multi-stage constant voltage charging with temperature compensation;
- 10-period programmable load power/time control;
- Battery charge and discharge high and low temperature protection, with operating temperature settable;
- A variety of intelligent power modes are available for choice, with load power adjustable automatically according to the battery level;
- High precision digital step-up constant current control algorithm, ensuring high efficiency and high constant current accuracy;
- Infrared wireless communication, allowing for setting/reading parameters, reading status, etc;
- Multiple protections such as battery/PV reverse polarity protection, LED short-circuit/open-circuit/limited power protection, etc;
- Extensible to IoT remote communication monitoring function;
- Full aluminum housing, IP67 waterproof rating, applicable to a variety of harsh environments.

Products selection table

Product models	Description
MES-R/W	MPPT Solar Charge Controller (-R: infrared remote control; -W: wireless remote control)
MES-NB	With IoT remote control (built-in NB-Iot module)
MES-GP	With IoT remote control (built-in GPRS module)
MES-C	With IoT remote control (RS485 interface, external communication module is required)
MES-CT	With IoT remote control (TTL interface, external communication module is required)

Indicator and remote control status

States of probe indicator light are shown below:

Indicator Light	State of Indicator Light	Description of Indicator Light	State of Remote Controller System
Red	Normally on	Normal system	Idle/discharge
	Slow flash	Charging	Charge
	Fast flash	System failure	Short circuit/open circuit /over-discharge/PV over-temperature/ BV over-temperature/EBMS/over-temperature

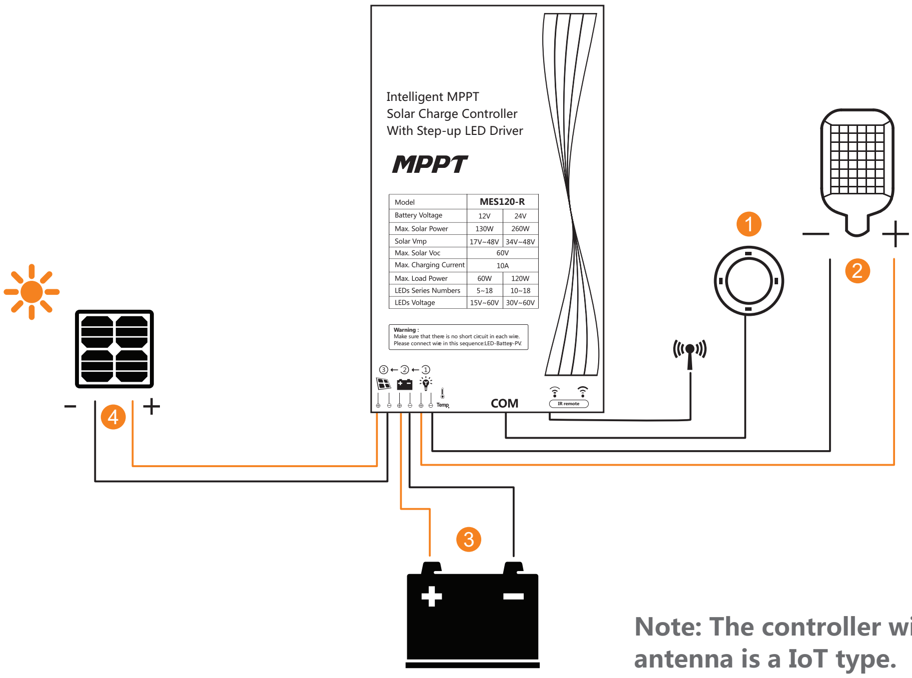
States of controller indicator light are shown below:

Indicator	Status	Description	Remote control system status
PV indicator	Steady on	Solar panel voltage is higher than light control voltage	Idle
	Off	Solar panel voltage is lower than light control voltage	Idle
	Slow flash	In charging	Charging
	Double flash	Fully charged	Fully charged
	Quick flash	BMS protection or BAT overvoltage or PV overvoltage or over temperature (ambient temperature) or power/ current limited charging	E-BMS Battery overvoltage PV panel overvoltage Over temperature Overcurrent
BAT indicator	Steady on	Battery works properly	Idle
	Off	Battery is not connected or lithium battery protection board over discharge protection	
	Quick flash	Battery over-discharge	Over discharge
LOAD indicator	Steady on	Load is turned on	Discharging
	Off	Load is turned off	Idle
	Slow flash	Load is open circuited	Open circuit
	Quick flash	Load is short circuited	Short circuit

Electrical wiring diagrams

A. Wiring diagram of the controller with built-in IoT module

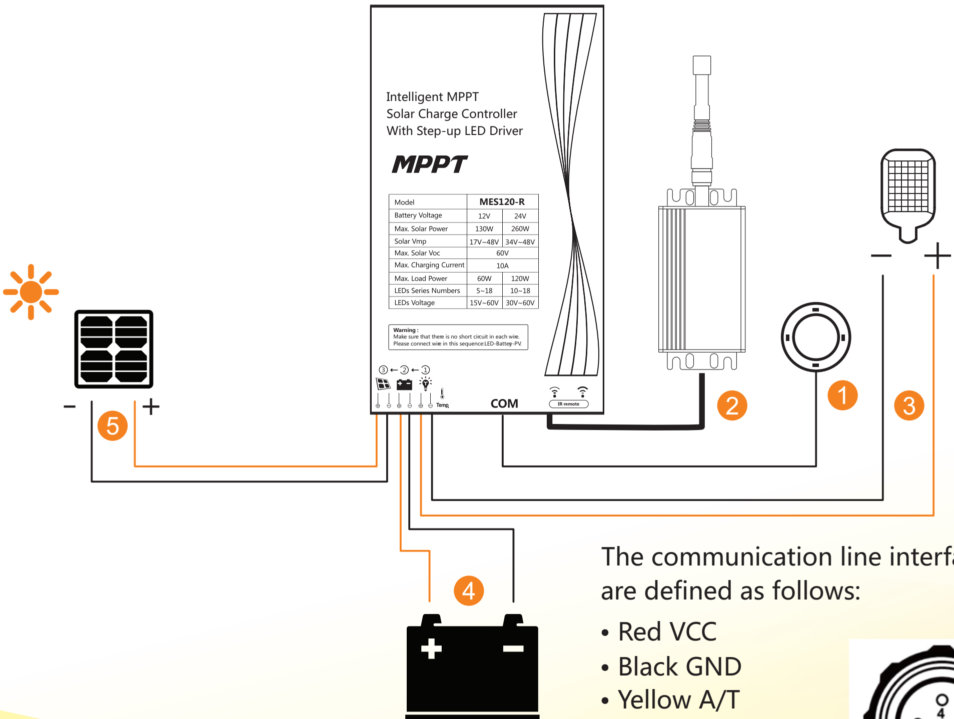
Wiring sequence: Firstly connect COM-IR/WB, then the load, then the battery and finally the solar panel.



Note: The controller with antenna is a IoT type.

B. Wiring diagram of the controller with external IoT module

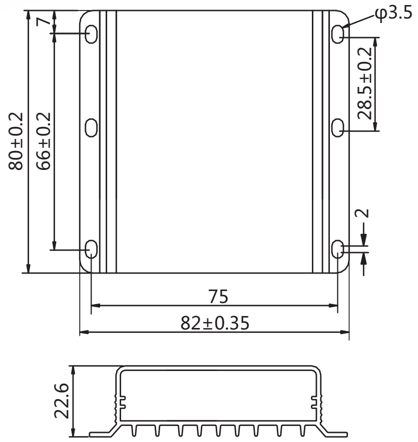
Wiring sequence: Firstly connect COM-IR/WB ,then the external IoT module, then the load, then thebattery and finally the solar panel.



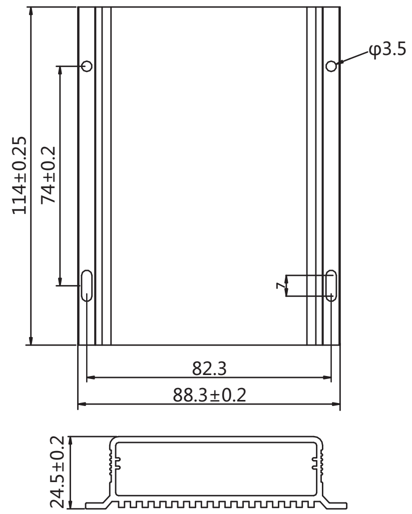
The communication line interfaces are defined as follows:

- Red VCC
- Black GND
- Yellow A/T
- White B/R

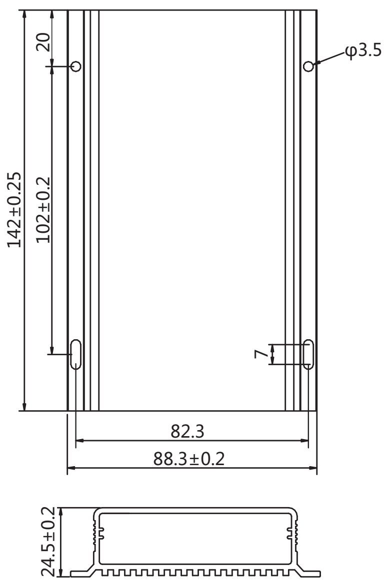
Installation method



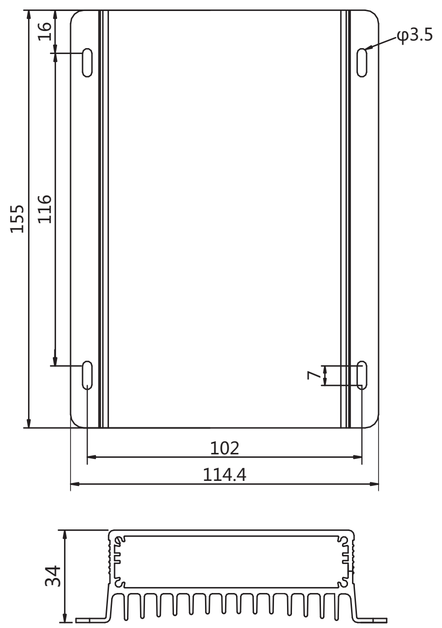
MES60 dimensions:
Overall dimensions: 80*82*22.6mm
Mounting dimensions: 66*75mm
Mounting hole diameter: φ3.5mm



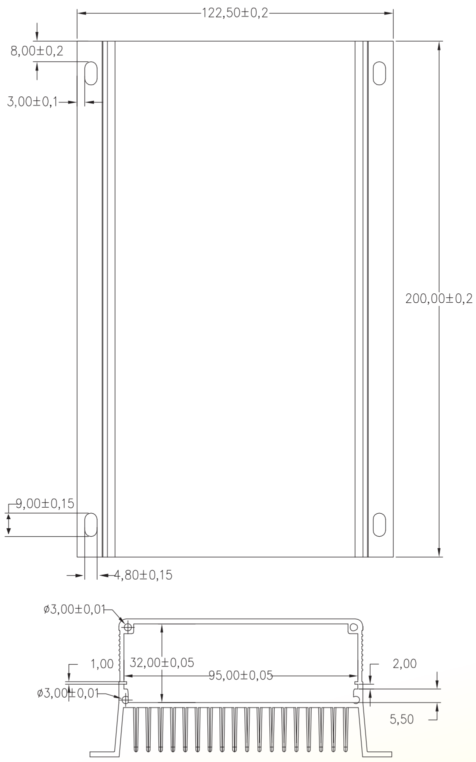
MES80/120 dimensions:
Overall dimensions: 114*88.3*24.5mm
Mounting dimensions: 74*82.3mm
Mounting hole diameter: φ3.5mm



MES160 dimensions:
Overall dimensions：142*88.3*24.5mm
Mounting dimensions: 102*82.3mm
Mounting hole diameter: φ3.5mm



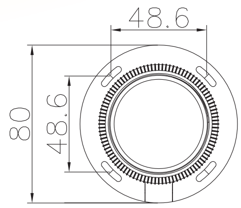
MES200 dimensions:
Overall dimensions: 155*114.4*34mm
Mounting dimensions: 116*102mm
Mounting hole diameter: φ3.5mm

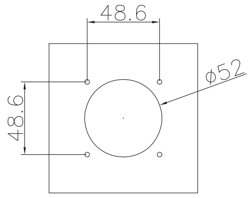


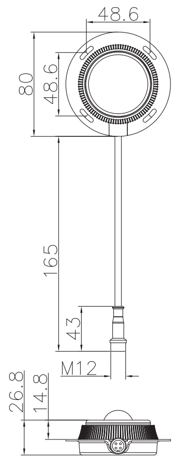
MES260/MES300 dimensions:
Overall dimensions: 200*122.5*56mm
Mounting dimensions: 175*113mm
Mounting hole diameter: φ3.5mm

Sensor size

The size of hole







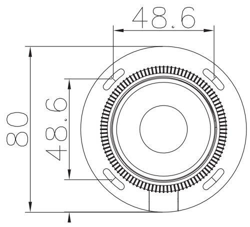
SR-WB5 dimensions:

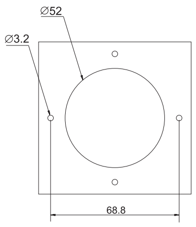
Overall dimensions: 80x80x26.8 (mm)

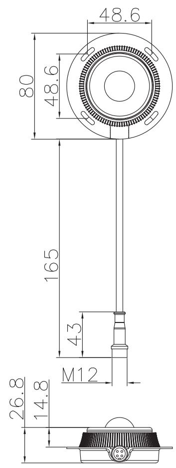
Mounting dimensions: 68.8x68.8 (mm)

Mounting hole diameter: 3.2 (mm)

The size of hole





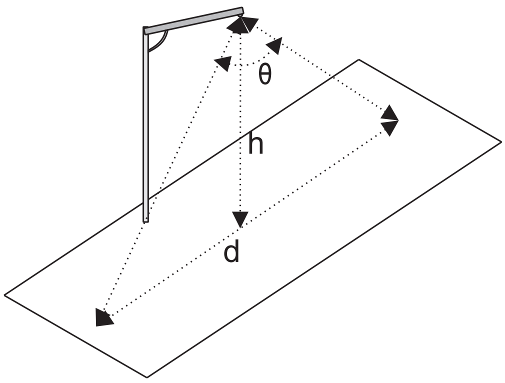


SR-IR5 dimensions:

Overall dimensions: 80x80x26.8 (mm)

Mounting dimensions: 68.8x68.8 (mm)

Mounting hole diameter: 3.2 (mm)



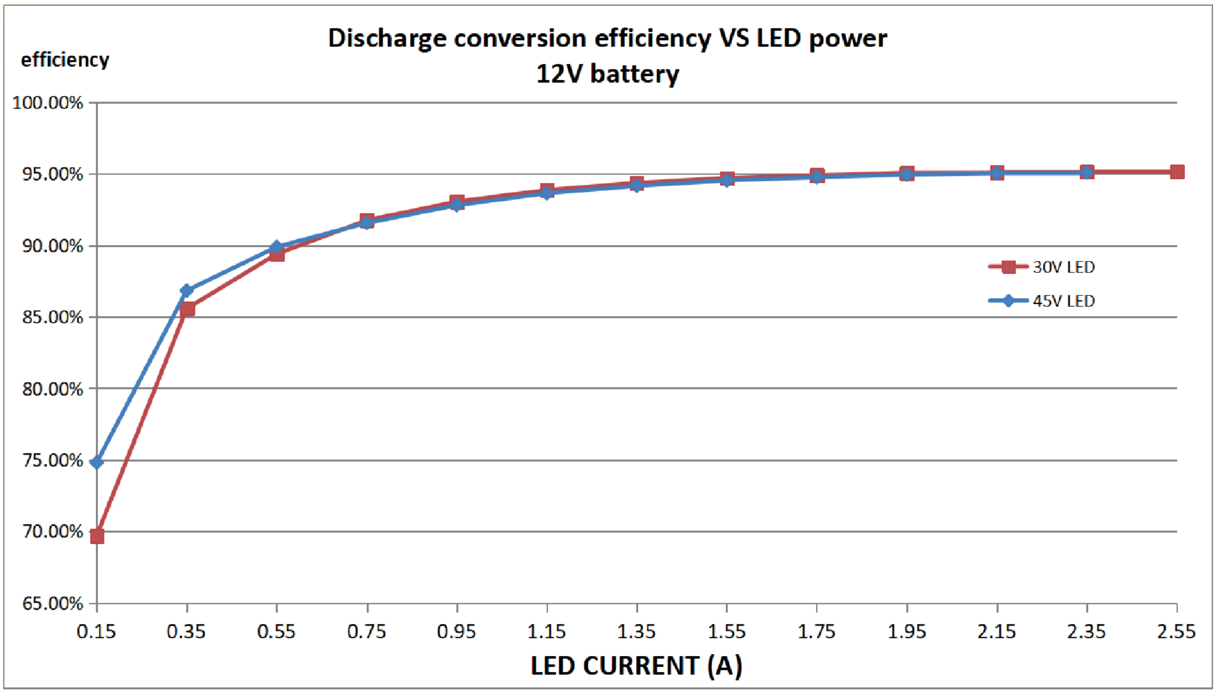
Inductive Type	θ(Angle)	h (Height of lamp rod)	d (Inductive width)
IR5 (infrared)	60°	6m	7m
Wb5 (microwave)	65°	8m	10m

Technical parameters

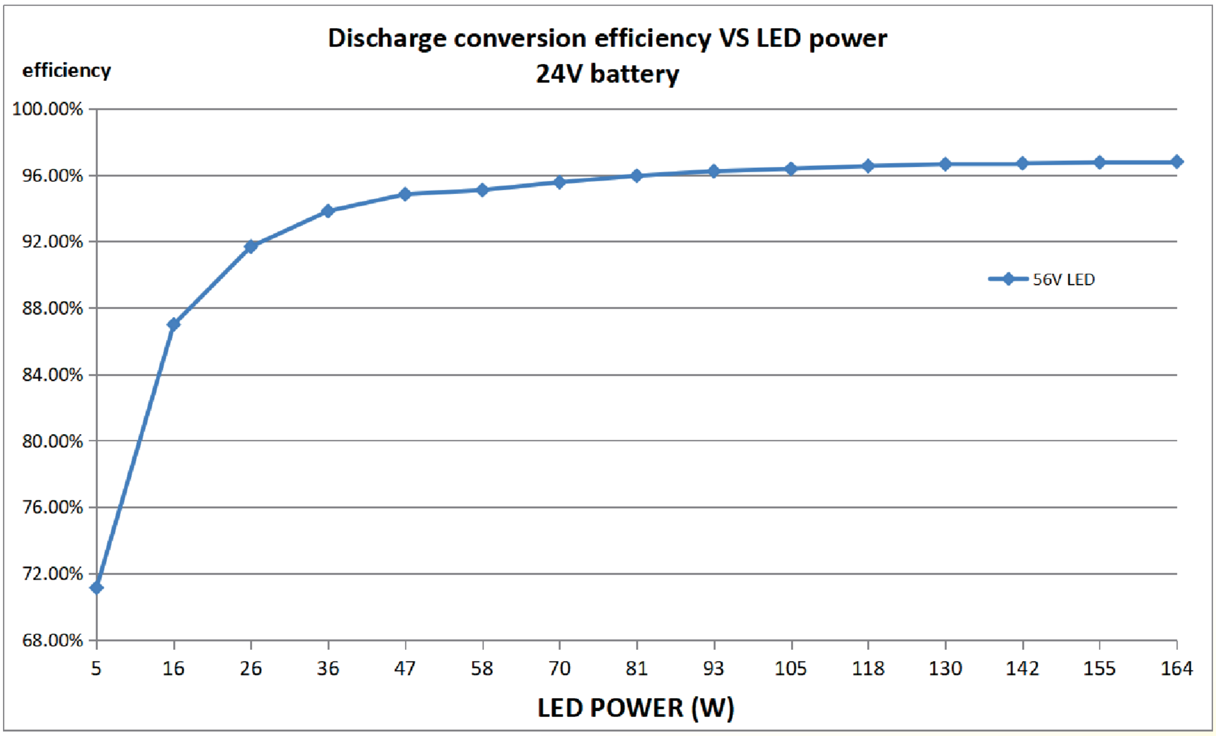
Items	Values							Adjustable	Default
Model	MES60	MES80	MES120	MES160	MES200	MES260	MES300		
Controller type	-R: infrared remote control ; -W: 2.4G wireless remote control ; -C: with 485 communication interface								
System voltage	12V		12V/24V						Lead-acid
Static power consumption	-R: ≤5mA -W: ≤20mA	-R: ≤6mA -W: ≤20mA	-R: 6mA/12V; 4mA/24V -W: 18mA/12V;13mA/24V		-R: 8mA/12V; 12mA/24V -W: 20mA/12V;16mA/24V				
Sleep power consumption	≤1mA				≤2mA				
Load current	50～3000mA		50～4200mA	50～5600mA		70～7000mA		√	330mA
Load voltage	15V～50V	15V～40V	15V～60V			15V～75V			
Maximum load power	60W/12V	80W/12V	60W/12V 120W/24V	80W/12V 160W/24V	100W/12V 200W/24V	130W/12V 260W/24V	150W/12V 300W/24V		
Load conversion efficiency	85%-96% ((Typical efficiency 95%)								
Load current accuracy	≤3%±30mA								
Intelligent power	High, Moderate, Low, Auto, USE, No							√	Medium
Load working period	9-Period + Pre-dawn lighting								
Period adjustment range	1min / 10min								
Power adjustment range	1% / 10%								
Maximum solar input power	130W/12V	200W/12V	130W/12V 120W/24V	200W/12V 400W/24V	260W/12V 520W/24V	400W/12V 800W/24V	550W/12V 1100W/24V		
Maximum charge current	10A	15A	10A	15A	20A	30A	40A		
Maximum solar input voltage	≤50V	≤35V	≤60V		≤100V				
MPPT Tracking efficiency	＞99%								
Charging conversion eff.	85%-98% (Typical efficiency97%)								
Over voltage	PB-16.0V; LI-overcharge voltage +2V; × 2, 24V system								16.0V
Limited charge voltage	PB-15.5V; LI-overcharge voltage +1V; × 2, 24V system								15.5V
Equalizing charge voltage	PB-14.6V; LI-None; ×2,24V system								14.6V
Equalizing charge interval	PB: 30 days；LI: no；								30D
Boost charge voltage (lead-acid) Charge voltage (lithium)	8.5V ～ 17.0V；×2,24V system							√	14.4V
Floating charge voltage (lead-acid) Charge return voltage (lithium)	8.5V ～ 17.0V；×2,24V system							√	13.8V
Over discharge voltage	8.5V ～ 17.0V；×2,24V system							√	11.0V
Over discharge return voltage	8.5V ～ 17.0V；×2,24V system							√	12.5V
Temperature compensation coefficient	PB: -3.0mV/℃/2V; lithium battery: no compensation								
Light control voltage	3V ～ 11V；×2,24V system							√	5V
Light control delay	0S～60S/2min ～ 60min							√	10S
High temperature charge	+40℃～+90℃							√	65℃
Low temperature charge	0℃ ～ -35℃							√	-35℃
Operating temperature	-35℃ ～ +65℃								
IP rating	IP67								
Protections	Battery reverse polarity protection, solar panel reverse polarity protection, solar panel over-voltage protection, lithium battery overcharge and over-discharge protection, lithium battery BMS overcharge detection protection, over temperature protection, load open circuit and short circuit protection,								
Weight	260g	400g		510g	770g	1800g			
Controller dimensions (mm)	80*82*22.6	114*88.3*24.5		142*88.3*24.5	155*114.4*34	200*122.5*56			
Controller mounting dimensions (mm)	66*75	74*82.3		102*82.3	116*102	175*113			
Mounting hole diameter (mm)	Φ3.5								

A typical curve

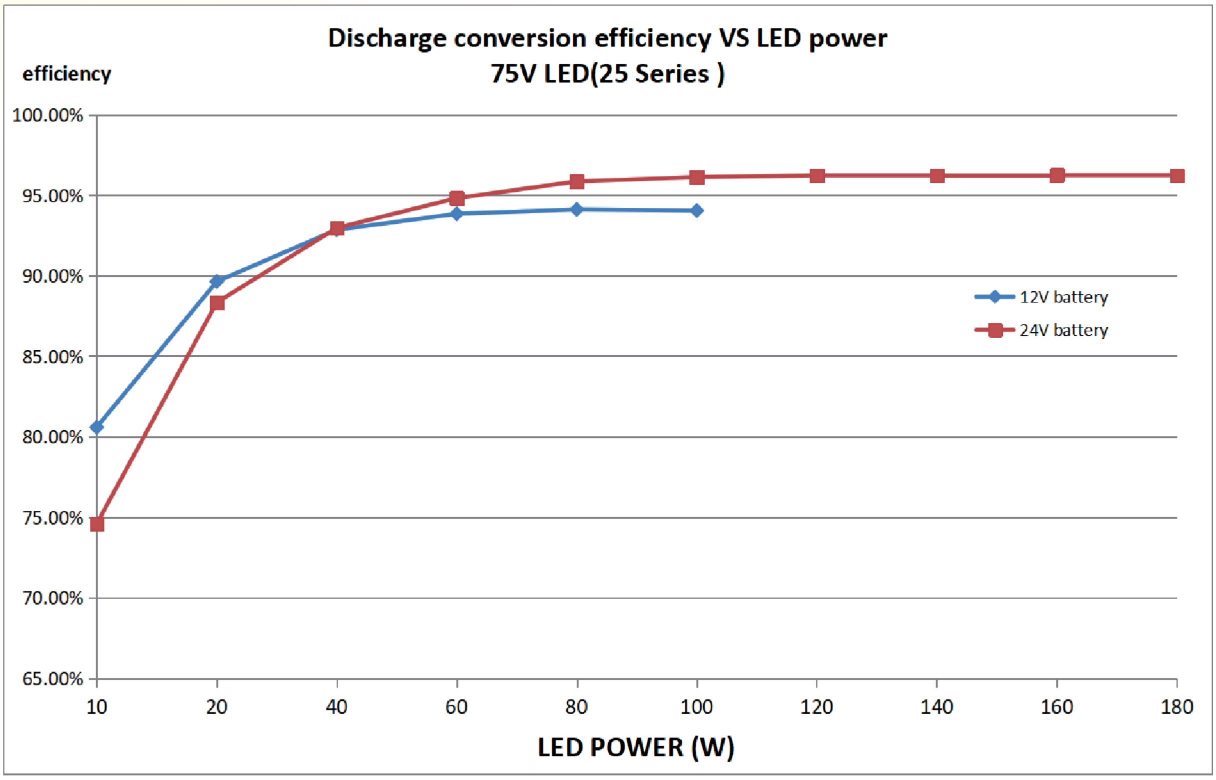
Discharge conversion efficiency VS LED power -12V battery



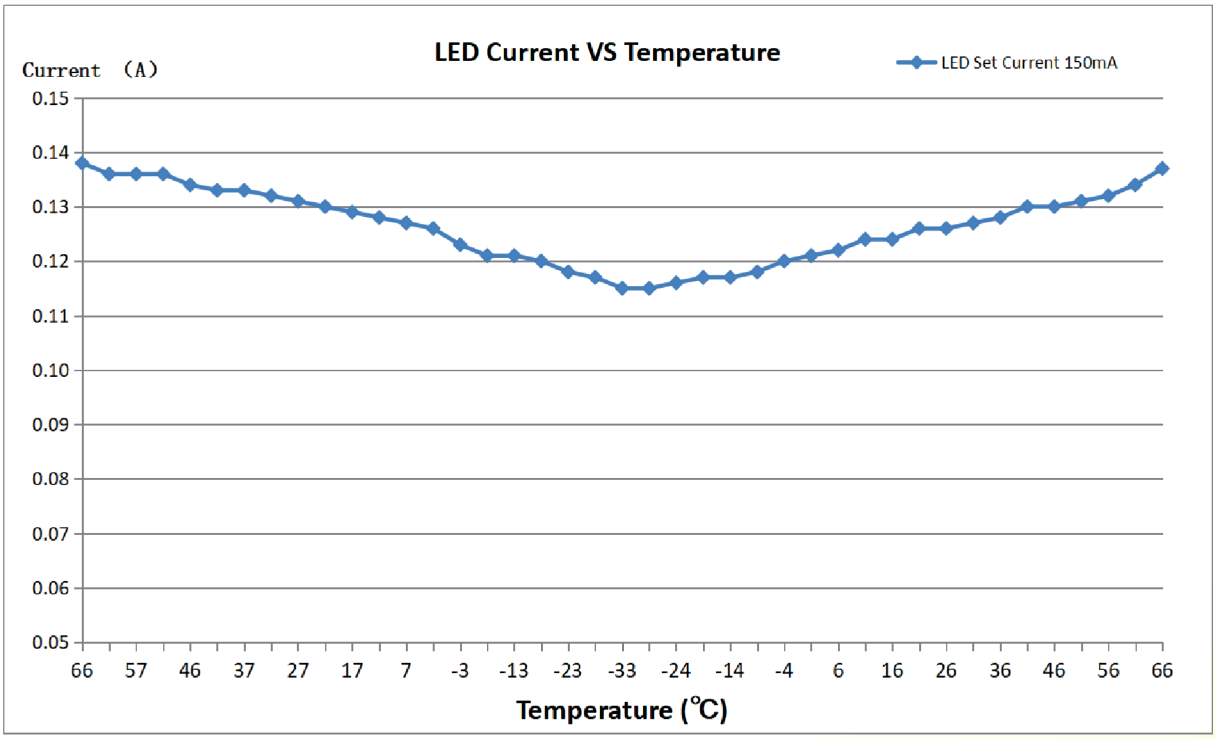
Discharge conversion efficiency VS LED power -24V battery



Discharge conversion efficiency VS LED power



LED Current VS Temperature



APPENDIX D : BATTERY DATASHEET

Lithium Ion Battery Pack Specification Confirmation

Customer: ____________________

Product name: LiFePO4 Battery Pack

Model: ____________________

Author	Checked by	Approved by

Customer confirmation	
Customer company:	
Signature	Company signature
Date:	Date:

Battery Pack Specification

1. Overview

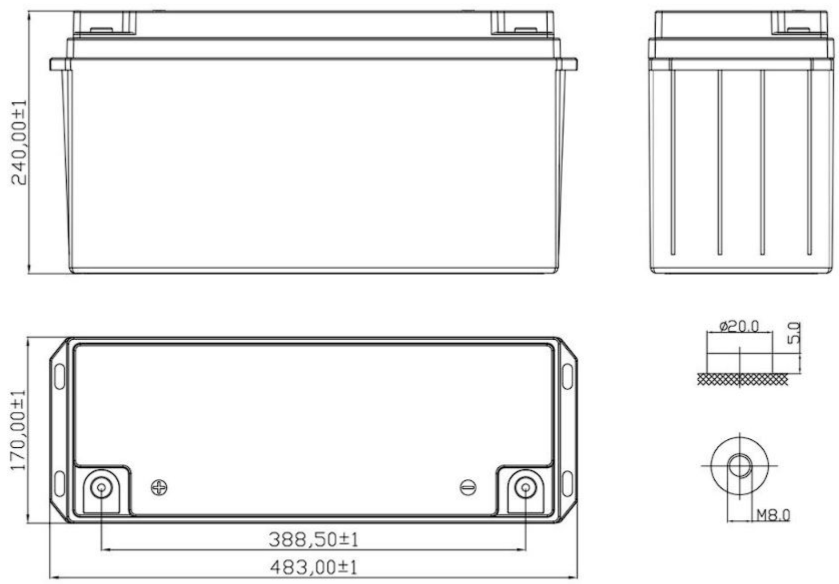
The 24100L is 25.6V100Ah Lithium iron phosphate battery module which designed for UPS, solar system, portable devices, energy storage and medical cart applications. This battery module integrated with intelligent BMS inside, has big advantages on safety, cycle life, energy density, temperature range and environmental protection. This product specification describes the type, size, structure, electrochemistry performance, service life, and BMS characteristics. This specification only applies to the battery module supplied.

2. Advantages

The battery module consists of single LFP cells, wire, BMS and container.

- Packed with high performance LFP single cell, long life, safety and wide temperature range;
- High energy density, small size, light weight, no pollution;
- High efficiency, fast charging;
- Built-in BMS, protect voltage, current, temperature in whole process;
- More than 5 years design life, Stable performance, maintenance-free.

3. Module Drawing

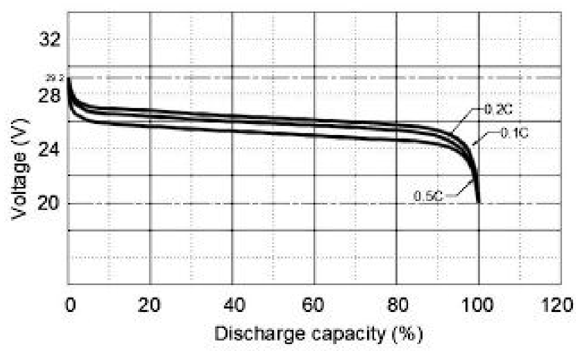


4. Parameters

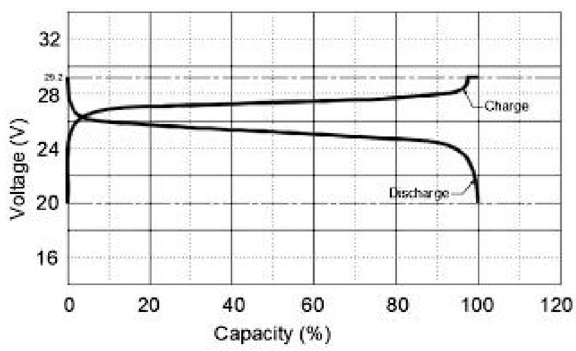
Model/Parameters	24100L
Rated Voltage	25.6V
Rated Capacity (0.2C，@25℃)	100Ah
Rated Energy	2560Wh
Cell & Pack	LiFePO4, Prismatic, Aluminum shell
Output voltage range	22.4V~28.8V
Charging voltage	28.0V~28.8V, CC-CV
Cut-off voltage	22.4V
Max. Constant Charging current	50A
Recommended charging current	<50A, best @ 50A
Recommended charging type	CC-CV until current <0.02C
Max. Constant Discharging current by B+ and C-/P-	100A
Max.Constant Discharging current by B+ and B-	100A
Capacity Efficiency	⩾99.5%
Built-in BMS	
Over-charge protection	Cell>3.75V
Over-discharge protection	Cell<2.2V
Over-current protection	Charging: >180A, delay 1000mS; Discharging: >900A, delay 10mS; Discharging: >1800A, delay 1000uS; Short circuit protection: Integrated
Cell balance	Passive,200mA
Over temperature protection	Charging: >-15∽75℃ Discharging: >75℃
Dimension L*W*H（mm）	483*170*240
Weight（kg）	21±0.5kg
Environment	
Humidity	5%~95% relative humidity
Charging temperature	0℃~50℃
Discharging temperature	-20℃~55℃
Storage temperature	-20℃~50℃
Service Life	
Cycle life	90%DOD>4000 times，@0.2C，25℃
Design life	>5 years

5. Performance curve

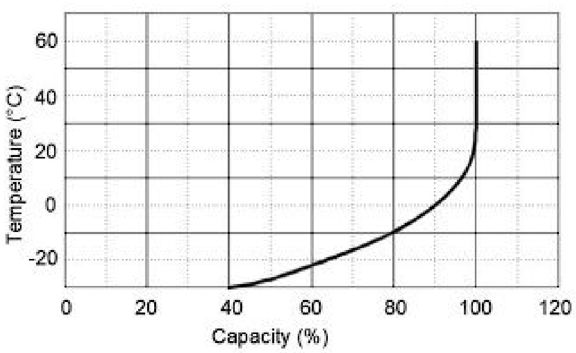
Discharge perfomance with different rate @ 25°C



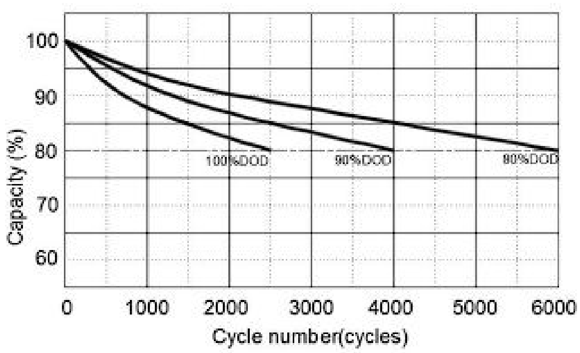
Charge & Discharge curve with 0.5C @ 25°C



Discharge capacity with different temperature @ 0.5C



Cycle life with DOD @ 0.2C，25°C



Self-discharge @ different temperature