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Decarbonization of Urban Road Infrastructure Using Solar Street Lighting in Kenya: Assessing Implementation and Impact

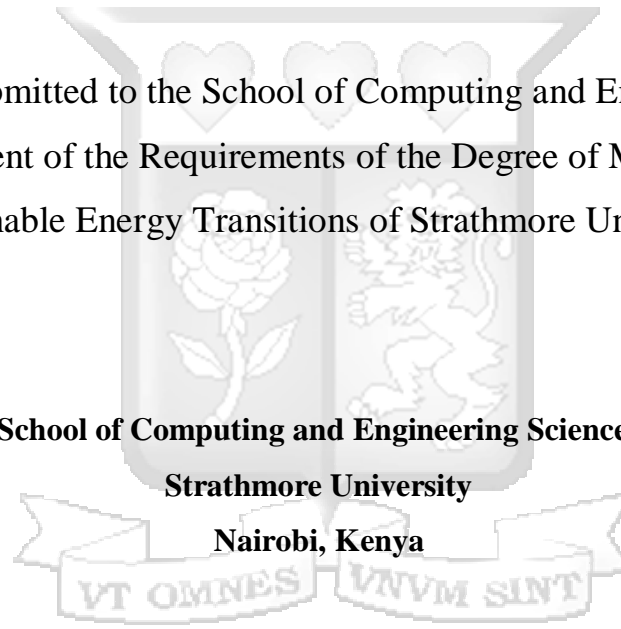
Paul Simiyu Mabonga

152990

A Dissertation Submitted to the School of Computing and Engineering Sciences
in Partial Fulfillment of the Requirements of the Degree of Master of Science in
Sustainable Energy Transitions of Strathmore University

**School of Computing and Engineering Sciences
Strathmore University**

Nairobi, Kenya




June 2025

Declaration

I, the undersigned, declare that this dissertation is my original work and has not been presented to any other institution or examination body.

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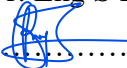
Signed..........

Date..... 25/03/2025

Declaration by the Supervisor

This dissertation has been submitted with my permission as the University Supervisor.

Name: Dr. Eng S Roy Orege

Signed..........

Date..... 25/03/2025



Dedication

I dedicate this dissertation to my family, whose unwavering support and encouragement are my driving force. Your belief in my abilities has fueled my passion for this endeavor. This work is a testament to the love and inspiration you have provided throughout my academic journey.



Acknowledgments

I express my sincere gratitude to my supervisor for his unwavering support and invaluable guidance throughout the development of this research project. His expertise, constructive feedback, and encouragement have been instrumental in shaping the direction of this study. Fortunately, I have a supervisor dedicated to fostering academic growth and excellence. I want to thank my family and friends for their unwavering encouragement and understanding during this research endeavor. Their support has been a source of strength, and I am truly fortunate to have such a dedicated support system. Thank you all for being an integral part of this journey towards sustainable and innovative solutions in solar street lighting.



Abstract

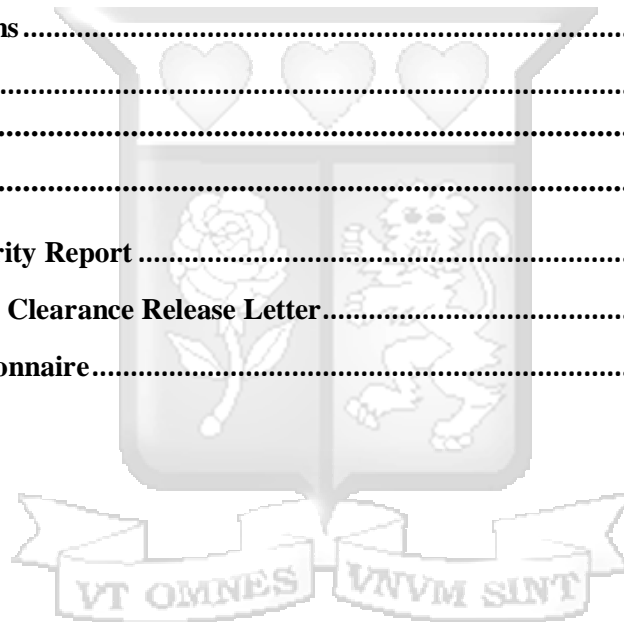
Decarbonizing urban road infrastructure using solar street lighting is a very promising perspective for the sustainable development of Kenya. This dissertation deals with a comprehensive study investigating the implementation and impacts of solar-powered lighting system adoption in urban areas, taking Mombasa City's southern bypass highway as a case study. The fact that warrants the transition is that the benefits are manifold, such as reduced greenhouse gas emissions, increased energy efficiency, better public safety, and economic savings in running and maintaining lighting systems. However, the potential of solar street lighting has several limitations and assumptions that require empirical research to evaluate its feasibility and effectiveness. The dissertation design is based on a comprehensive literature review to consolidate the current knowledge on solar street lighting, followed by a detailed methodology based on data collection, model development, and data analysis. The Mombasa Southern Bypass case study has helped us understand the local context, considering regulatory frameworks, technological requirements, and socioeconomic factors. The research, by running a qualitative and quantitative investigation about the main technical, economic, and regulatory issues arising from the implementation of solar street lighting, aimed to estimate the impacts that the sustainable infrastructure solution has on urban planning, energy consumption, and environmental quality to orient the definition of the potential advantages and disadvantages for policymakers, urban planners, and other stakeholders in implementing such solutions. The way forward is to gather findings from the outcomes of this research, which aided in developing evidence-based mechanisms to achieve decarbonization and sustainable urban development in Kenya and beyond. The study found that while street lighting infrastructure in Mombasa City is functional, significant improvements are needed, with a predominant reliance on conventional lighting technologies like incandescent and fluorescent lamps. In addition, the study found that solar street lighting is viable in Mombasa, and the irradiation level is sufficient to maintain reliable operation. The study identified several barriers to adopting solar street lighting in Kenya, including high initial costs, insufficient technical expertise, inadequate infrastructure, limited local solar technology availability, and logistical challenges. It also highlights the lack of government incentives, public resistance, and financing issues as significant obstacles to widespread adoption. Further, the study revealed that adopting solar street lighting in urban areas, including Mombasa City, is expected to reduce energy consumption and carbon emissions. The study recommends transitioning to solar-powered lighting technologies in Mombasa City and the rest of the country to reduce energy consumption and emissions. It suggests integrating sustainable lighting into urban planning, investing in local solar technology adoption, and developing financing mechanisms to overcome financial barriers. Additionally, it emphasizes strengthening local capacity through training, streamlining approval processes, and increasing awareness campaigns to address public resistance and ensure the successful implementation of solar street lighting projects.

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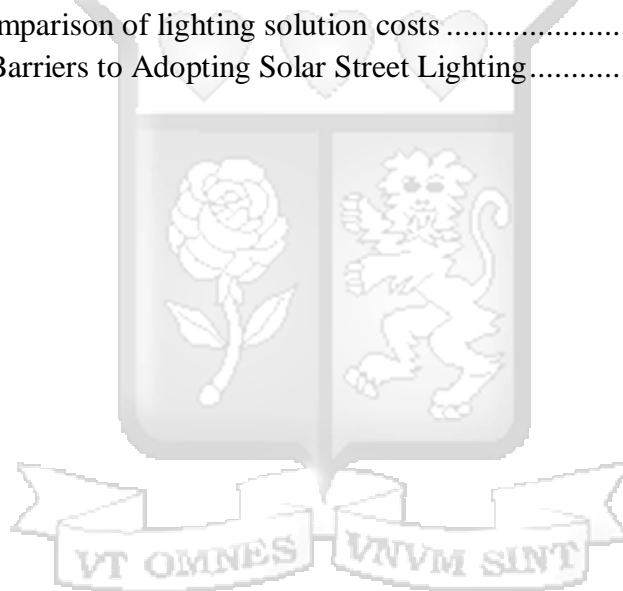
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Abbreviations/Acronyms

CDM- Clean Development Mechanism

CO₂ – Carbon Dioxide

EF – Emission Factor

EPRA: Energy & Petroleum Regulation Authority

GHG – Greenhouse Gas

GIS – Geographic Information System

IEA – International Energy Agency

IPCC – Intergovernmental Panel on Climate Change

KENHA- Kenya National Highways Authority

KPLC- Kenya Power and Lighting Company

LCPPD-Least Cost Power Development Plan.

LED- Light Emitting Diode

NACOSTI-National Commission for Science, Technology & Innovation

NDCs- Nationally Determined Contributions

PPPs- Public-Private Partnerships

PV- Photovoltaic

R&D- Research and Development

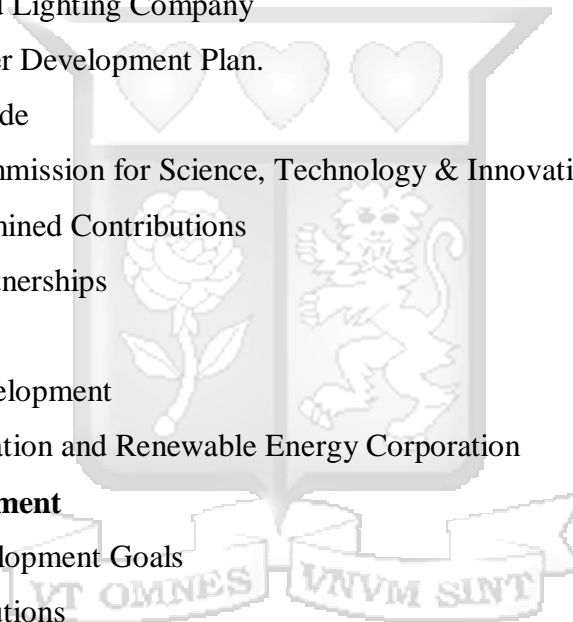
REREC-Rural Electrification and Renewable Energy Corporation

ROI – **Return on Investment**

SDGs - Sustainable Development Goals

SSL- Street Lighting Solutions

UNFCCC – United Nations Framework Convention on Climate Change



Definition of Terms

Carbon Emissions – Carbon dioxide (CO₂) and other GHGs are released into the atmosphere due to human activities, including burning fossil fuels, industrial processes, and urban infrastructure management (Wimbadi & Djalante, 2020).

Conventional street lighting solutions refer to traditional methods and technologies for illuminating public spaces, roadways, and urban areas, where the lighting source is mainly the national grid (Burgess2022).

Decarbonization – The elimination or reduction of carbon dioxide (CO₂) emissions from various sectors like transport, energy, and infrastructure to prevent climate change and promote sustainability (Bernstein & Hoffmann, 2015).

Energy Efficiency – The practice of reducing energy usage while delivering the same quality of service or manufacturing, usually accomplished by introducing innovative technologies like LED lights and intelligent control systems (BalaMurugan & Karuppiah, 2021).

Environmental benefits: This refers to the positive impacts and contributions of solar-powered lighting systems to the natural environment (Arent et al., 2022).

Greenhouse Gas (GHG) Emissions – The release of gases such as CO₂, methane (CH₄), and nitrous oxide (N₂O) that are trapped in the atmosphere and cause global warming (Amuyunzu & Kisimbii, 2021).

Light-Emitting Diode (LED) Lighting – An energy-efficient lighting technology that uses less energy and has a longer lifespan than traditional incandescent or fluorescent lamps (Welfle et al., 2020).

Lux: This refers to the quantity of light per square area (Wambui et al., 2022).

Lumens refers to the total quantity of light emitted from a light source (Terblanche, 2019).

Photovoltaic (PV) System – An array system that uses solar panels to produce electricity, most commonly used in solar streetlights (Sutopo et al., 2020).

Public-Private Partnership (PPP) – An arrangement partnership between public government and private institutions to invest in, construct, and operate infrastructure schemes like solar streetlights (Pulselli et al., 2021).

Return on Investment (ROI) measures an investment's profitability, defined as the ratio of net savings or returns to the implementation cost (Bernstein & Hoffmann, 2015).

Solar street lighting: This sustainable and energy-efficient solution harnesses solar energy to power outdoor lighting systems, particularly street lights (Ciriminna & Pagliaro, 2017).

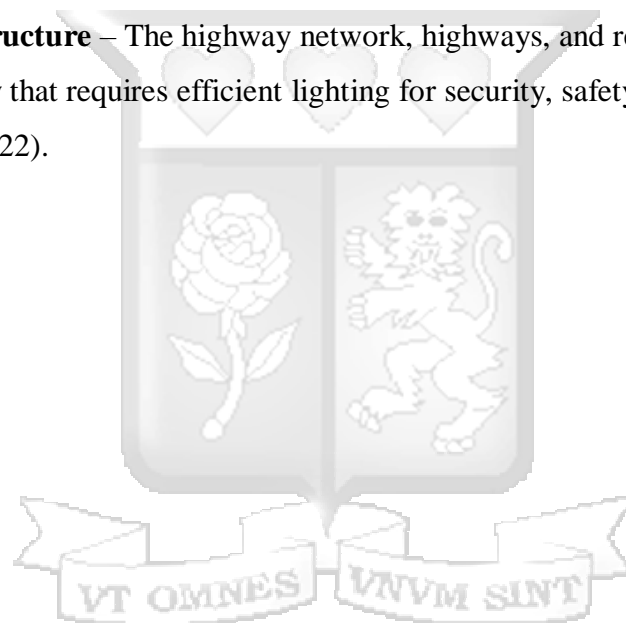
Solar Street Lighting (SSL) – A green light source that utilizes solar power to power LED streetlights, reducing the consumption of grid electricity and GHG emissions (Odak & Aila, 2023).

Social benefits refer to positive outcomes or advantages that directly or indirectly impact individuals, communities, or society (Stewart & Mele, 2018).

Sustainable Development Goals (SDGs) – A set of global goals accepted by the United Nations (UN) for the use of sustainability, including affordable and clean energy (SDG 7) and climate action (SDG 13) (Stewart & Mele, 2018).

Traditional Street Lighting – Conventional street lighting systems based on grid electricity, derived from fossil fuels, leading to high energy use and GHG emissions (Wimbadi & Djalante, 2020).

Urban Road Infrastructure – The highway network, highways, and related public infrastructure of a city that requires efficient lighting for security, safety, and energy efficiency (Burgess2022).



Chapter 1: Introduction

1.1 Background of the Study

Kenya has a high rate of urbanization, and its urban areas are growing at unprecedented levels. Energy consumption and greenhouse gas (GHG) emissions are increasing with this urban growth rate, attributed to the transport and urban infrastructure sectors. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) supports several initiatives by assessing and reducing GHG emissions in developing countries, including the "Advancing Transport Climate Strategies in Rapidly Motorizing Countries" (TrACS). In Kenya, GIZ partnered with the University of Nairobi to get firm road transport CO₂ emission factors, emphasizing that time is overdue to address emissions from all the urban infrastructures, including street lighting. Street lighting is part of urban infrastructure, ensuring urban dwellers' safety, security, and quality of life (Luusa, 2019). Most streetlights in Kenya are associated with high energy consumption and emissions since they run on electricity generated from fossil fuels from the grid by at least 17%. As Kenya continues to urbanize, the demand for street lighting will increase further, worsening the challenge of managing energy consumption and reducing emissions (Welfle et al., 2020). Kenya has one of the highest potentials for solar energy in the world, which provides the country with a vast opportunity to decarbonize urban road infrastructure using solar street lighting systems.

The "Transport Sector Climate Change Annual Report 2021/2022" highlights the progress and challenges in reducing greenhouse gases in Kenya's transport sector. Emissions from the road subsector dominate the total emission from Kenya's transport sector compared to the railway, aviation, and maritime subsectors, which stand at 98% and 2%, respectively. A report to fulfill the mandate of the Climate Change Act 2016 details the priority actions, the status of their implementation in mitigation, and activities to reduce emissions to 3.5 MtCO₂e by 2030. It documents steps taken in public transport optimization, construction of non-motorized transport, development of resilient infrastructures, and other capacity-building activities. However, the report identifies the need for sustained capacity building, regulatory strengthening, and enhanced financial and technical support to ensure more investments for increased emission reduction targets for the future.

Table 1. 1: Transport Sector prioritized actions and level of implementation as of June 2022 (based on sectoral expert consultations)

	Priority Actions	Objectives	Implementation Level (as of June 2022)
1	To develop a BRT for the Nairobi Metropolitan area and optimize public transport.	To reduce congestion and provide improved mobility services.	Line 2 is under construction. The process is being led by NAMATA line 3 & 5 design works complete.
2	Shift freight from/to Mombasa and Nairobi from road to rail.	To reduce congestion on the road and shorten the time limit for cargo transportation.	Continuous marketing and connecting to rail sidings consolidation of cargo at Nairobi Boma line, transit shed.
3	NMT construction across different urban areas	To enhance mobility for short trips	Ongoing developments: KURA is incorporating NMT in all upcoming roads and other strategic existing roads.
4	Climate-proofing transport infrastructure.	To increase the resilience of transport infrastructure against flooding and extreme temperature differences.	Continuous resilient infrastructure development by KERRA, KUNHA, KAA, KURA, KR.
5	Finalization of CORSIA regulations for the aviation sector.	To enhance compliance with international aviation with ICAO carbon offsetting standards.	Regulations awaiting ministerial approval
6	Finalizations of regulations on the prevention of air pollution from shipping	To give the complete effect of the international convention on the prevention of pollution from ships (Marpol 73)	Draft regulations being finalized by KMA

Solar street lighting is a sustainable and environmentally friendly approach to conventional street lighting. It reduces grid dependence, which is one way of reducing the use of fossil fuels and electricity charges. Solar streetlights are made of photovoltaic panels, batteries, and LED lamps (Wambui et al., 2022). During the day, the photovoltaic panels absorb solar energy and store it in batteries; the LED lamps light up at night. Technology reduces carbon footprints and contributes to energy security because it offers a point source of generation from a clean source with no fossil-based process. Electricity is generated from the solar module, stored in a battery, consumed at the same point, and loaded by the connected light. Despite the tremendous benefits likely to emanate from solar street lighting, the technology has not seen much use in Kenyan urban areas (Akomolafe, 2023). The reasons are the high capital costs, lack of awareness, and technical challenges concerning installing and maintaining solar street lighting systems. In addition, there is also a lack of proper and adequate studies that have been conducted to determine the feasibility, implementation challenges, and overall impact of solar street lighting on GHG emissions reduction in an urban area (Welfle et al., 2020). This research gap has been a significant disadvantage to policymakers and stakeholders in deciding which avenue to adopt to ensure solar street lighting is widely and rampantly used in urban areas as a decarbonization strategy.

The rise of climate change concerns and the urgency for sustainable energy have necessitated innovations and investments in alternative energy sources. Like other countries worldwide, Kenya has recently scaled up investments in renewable energies (Osano & Kingiri, 2021). Kenya's Vision 2030 long-term development vision underscored the importance of renewable energy in attaining sustainable development and reducing greenhouse gas emissions. Solar energy is one of the key resources tapped to meet the country's energy needs sustainably. Based on Wambui et al. (2022), Kenya has demonstrated its concern for renewable energy resources by setting ambitious targets for the rise in the proportion of renewable resources in the national energy balance. In a bid to attract investors into the renewable energy sub-sectors, the government has put in place many policies, including exemption of import duties for energy-related materials and equipment, reduction of customs duties on renewable energy equipment and materials and related accessories from 25% to 10%, VAT exemption for zero rating for renewable equipment, concessional corporate taxes, and VAT rate reduction from 20 to 0% on renewable energy equipment (Luusa, 2019). Tax holidays have been given to investors, and tariffs have been fed in for solar investors who sell power to the national grid. Following these initiatives, the level of solar systems use in Kenya has increased significantly.

However, most initiatives have focused on using solar power for residential and commercial use, with a minimal focus on solar street lighting.

The implementation of solar street lighting in urban areas will serve to make a significant contribution to Kenya's decarbonization. Such a move will reduce energy use and the emission of GHGs in cities by using solar streetlights. Social and economic benefits that come with solar street lighting include better public security, low energy costs, and an improved outlook for urbanization (Luusa, 2019). This is especially helpful in rural and peri-urban places that have little or no grid electricity access. It is helpful in these areas to provide a constant lighting source and support local economic activities. To successfully implement street lighting with solar power in urban centers, it is necessary to comprehensively analyze the existing situation with street lighting, the state of solar street lighting applications, and the difficulties and obstacles in its wide-scale adoption. It is also necessary to analyze the impact of solar street lighting on reducing energy use and GHGs in a specified area (Amuyunzu & Kisimbii, 2021). This paper focuses on these critical issues and conducts a detailed study of the implementation and impact of solar street lighting in Kenya's urban areas.

Based on Welfle et al. (2020), implementing solar street lighting in urban areas will significantly contribute to Kenya's decarbonization. Such a move will reduce energy use and the emission of GHGs in cities by using solar streetlights. Social and economic benefits that come with solar street lighting include better public security, low energy costs, and an improved outlook for urbanization. This is especially helpful in rural and peri-urban places that have little or no grid electricity access. It is helpful in these areas to provide a constant lighting source and support local economic activities (Akomolafe, 2023). To successfully implement street lighting with solar power in urban centers, it is necessary to comprehensively analyze the existing situation with street lighting, the state of solar street lighting applications, and the difficulties and obstacles in its wide-scale adoption. It is also necessary to analyze the impact of solar street lighting on reducing energy use and GHGs in a specified area (Wambui et al., 2022). This research focuses on these critical issues and studies the implementation and impact of solar street lighting in Kenya's urban areas.

Urbanization and its associated challenges have increased pressure on energy systems and the environment. This has resulted in an enormous increase in energy demand and GHG emissions, primarily in the transport and urban infrastructure sectors, as a result of this fast rate of urbanization. Street lighting is a key component of any urban infrastructure that contributes to this problem. Using fossil fuel-based grid electricity by at least 15% in traditionally designed

street lighting systems is a massive source of energy consumption and GHG emissions for any urban area. The demand for street lighting in Kenya will only increase in the coming years with the increase in urban population, further intensifying the energy consumption and emission reduction challenge (Luusa, 2019). Although solar street lighting is urgently required to occur in the urban settings of Kenya, such adoption remains low. Solar street lighting has great potential to emerge as a popular alternative to conventional street lighting, as it harnesses renewable solar energy and cuts down on fossil fuel dependency and the cost of electricity. These systems can operate independently of the grid, making them particularly advantageous in areas with limited or unreliable access to grid electricity. However, several barriers impede the widespread implementation of solar street lighting, including high initial capital costs, lack of awareness and technical expertise, and challenges related to installation and maintenance.

1.2 Problem Statement

The Transport Sector Climate Change Annual Report 2021/2022 reveals significant challenges in the Kenyan transport sector, with high greenhouse gases and the need for resilient infrastructure solutions. Even after establishing a target to reduce emissions by 3.5 MtCO₂e by 2030, the transport sector remains largely dependent on fossil fuel, while road transport alone accounts for approximately 98% of the sectoral emissions. This development involves the environmental costs of the existing conventional street lighting. The proposed interventions have become attractive with the urgent need for innovative approaches, such as solar street lighting, to decarbonize urban road infrastructures and support the transition to a safe and friendly low-carbon economy that improves urban mobility and resiliency. On the other hand, the limited adoption of solar street lighting in Kenya suggests an inadequacy of generalized findings assessing the feasibility, implementation challenges, and overall impact on reducing GHG emissions (Welfle et al., 2020). Correctly understanding these factors is important for decision-makers and stakeholders to decide on the momentum for the shift toward sustainable street lighting solutions.

In addition, there is the need to assess the social and economic benefits derived from solar street lighting, among them enhanced public safety, lowered energy costs, and improved aesthetics of the urban areas, which further support its adoption. Policies within the urban infrastructure sector that seek to harness the country's renewable energy potential seriously need sustainable energy solutions (Wambui et al., 2022). There is an urgent need in Kenya to understand and implement sustainable energy solutions for urban infrastructure, including road infrastructure, in line with the commitment to Vision 2030 for the reduction of GHG emissions.

In contrast, solar street lighting provides an important opportunity for the decarbonization of road infrastructures in urban areas and, therefore, should be exploited to realize an overall decrease in GHG emissions in the country. However, the lack of comprehensive data and analysis on the implementation and impact of solar street lighting hinders the development of effective strategies and interventions to promote its widespread adoption.

This project, therefore, addressed the following key gaps: a detailed study on the implementation and the impact of solar street lighting in Kenya's urban areas. The research will see a further evaluation of the existing street lighting infrastructure, an analysis of the technical, economic, and environmental benefits of solar street lighting, and the constraints and barriers to its massive adoption (Wambui et al., 2022). In this regard, the study in question will provide a comprehensive framework for understanding the feasibility and impact of solar street lighting, which informs the policymakers and stakeholders on the strategies and interventions necessary to realize sustainable urban development and the climate targets of Kenya (Osano & Kingiri, 2021). The high consumption of traditional energy and GHG emissions from the lighting systems and the fossil-powered vehicular traffic of the country's urban roads create the need to explore sustainable street lighting alternatives, such as solar street lighting as an alternative carbon sink. So, the outlined gaps need to be addressed to drive the change to sustainable urban infrastructure. This project sought to fill these gaps and provide valuable insights into the potential of solar street lighting as a key component in decarbonizing urban road infrastructure in Kenya.

1.3 Research Objectives

General Objective

This research aimed to assess the status of street lighting and the impact of solar street lighting on decarbonizing urban road infrastructure using the Mombasa Southern Bypass as a case study.

Specific Objectives

1. To assess the status of street lighting infrastructure and its implication for urban GHG emissions in Kenya.
2. Analyze the feasibility and potential benefits of solar street lighting in urban areas.
3. Identify the challenges and barriers to adopting solar street lighting in Kenya.

4. Estimate the impacts of solar street lighting on urban energy consumption and GHG emissions reduction in Kenya.

1.4 Research Questions

1. What is the status of street lighting infrastructure and its implication for urban GHG emissions in Kenya?
2. What are the technical, economic, and environmental benefits of implementing solar street lighting in urban areas?
3. What challenges and barriers are experienced in adopting solar street lighting in Kenya?
4. How does solar street lighting affect urban energy use and the associated GHG emissions?

1.5 Justification

Since the early 2000s, Kenya has recorded rapid urbanization and motorization, leading to a surge in energy consumption and greenhouse gas (GHG) emissions in the transport and urban infrastructure sectors. For example, as shown by the 2018 GIZ TraCS pilot study, Kenya's road transport sector has very significant CO₂ emission factors: 185.20 g CO₂/km for passenger cars, 216.48 g CO₂/km for LCVs, and 759.88 g CO₂/km for HGVs. Combined, this gives a very significant carbon footprint, which means that climate change is a real threat, and there is a need for action, urgently and innovatively, to contain the situation (Luusa, 2019). The most promising approach that has the potential to mitigate these emissions is the decarbonization of urban road infrastructure through the adoption of solar street lighting. By using renewable solar energy, solar street lighting reduces the use of fossil fuels and simultaneously reduces the carbon emissions from grid-powered street lighting to a considerable extent. It will thus sit very well with Kenya's mandate for sustainable development and climate action, as spelled out in Kenya's National Climate Change Action Plan and its Vision 2030.

The application of solar street lighting has several convincing advantages other than the sustainability aspect of the environment. First, it can drastically reduce operational expenditure on street lighting. Standard street lighting requirements usually involve high consumption of electricity and, therefore, incur high energy costs for urban local bodies (Wambui et al., 2022). The switch to solar streetlights could save many urban areas money on energy bills, which could be diverted to other important urban infrastructure projects. Second, public safety and security will be enhanced with solar street lighting. Illumination of streets is crucial in reducing criminal rates and road incidents, creating better urban environments for residents (Welfle et

al., 2020). Solar streetlights, with their capability to operate off-grid, are reliable and entail continuous lighting even during power outages, providing consistent and continuous safety. Third, this promotes energy independence and resiliency. Reliance on local and renewable energy resources reduces the dependency of urban areas on the national grid, which is often unreliable and inefficient (Akomolafe, 2023). This resiliency is, therefore, a great asset considering the increasing energy demand in Kenya and the urge for reliable infrastructure to support economic development.

Further, adopting solar street lighting will align with Kenya's socio-economic development agenda. Solar lighting system installation and maintenance can also create many job opportunities and stimulate economies at the local level. It also makes Kenya an important front-runner in adopting renewable energy, thus sending a signal to other developing countries (Welfle et al., 2020). Of course, these significant advantages come with careful planning and consideration of some factors, such as initial investment costs, technological constraints, and maintenance challenges. However, in the long run, the benefits are higher on the economic and environmental fronts, thus making it an extreme case for adopting solar street lighting in urban areas in Kenya (Luusa, 2019). Decarbonizing urban road infrastructure through solar street lighting is a key step toward achieving sustainable urban development in Kenya. It helps achieve immediate GHG emissions reductions, improve public safety and energy cost savings, and promote renewable energy consumption (Baburajan, 2021). This paper aims to evaluate the implementation and effect of solar street lighting to gain crucial insights and provide recommendations in line with Kenya's climate and development objectives.

1.6 Scope

This project focused on the proposed decarbonization of urban road infrastructure in Kenya using solar street lighting systems in a case study of the Mombasa southern bypass. The study involved many components to make it quite comprehensive regarding the feasibility, implementation, and implications of solar street lighting in urban cities.

Coverage

The study included only a segment of the Mombasa Southern Bypass highway, a 38km road connecting the port of Mombasa with the rest of the city. The objective is to use this case study for the rest of the country's roads. The road is currently installed with 2008 grid-powered lights rated at 150w at an efficiency of 120lumens/watt emitting 22lux light level of lighting

for a total electricity consumption of 3,615 Kwhr daily for a Kshs 13,041,000 annual billing to Kenya National Highways authority.

Key Aspects

- *Technological viability*: This will consider the technical requirements for implementing solar street lighting, including specifications for solar panels, battery storage, lighting technology, and the infrastructure required for their installation (Wambui et al., 2022). It will also investigate the available solar radiation data towards optimum harnessed energy.
- *Economic Analysis*: This is tantamount to a cost-benefit analysis of the initial investment, costs of operation, and maintenance compared with conventional grid-powered street lighting. This will further probe potential savings by bringing out quantifiable energy cost results and the large-scale implementation's economic viability.
- *Environmental and Greenhouse Impact Analysis*: The assessment includes establishing the reduction in greenhouse gas emissions associated with the transition to solar street lighting. This will be measured against the current emission data collected from conventional street lighting.
- *Social Impact Assessment*: A broader social assessment, including public safety enhancement and increased security, job creation, and community acceptability of solar street lighting technology (Luusa, 2019).
- *Implementation Challenges*: This section identifies and describes potential implementation barriers, ranging from financial to technical and maintenance problems, and further develops strategies for overcoming these barriers.

Time Frame

The research was conducted for 8 months to facilitate proper data collection, analysis, and evaluation. This period encompassed the installation of solar streetlights, pilot projects, and monitoring and evaluation phases.

Stakeholder Involvement

The study drew the participation of a wide range of stakeholders, including local governments, energy providers, community organizations, and international development partners, to ensure that the assessment and implementation of solar street lighting systems is comprehensive and inclusive. In this regard, this scope outlines the critical areas of focus for

the project in terms of assuring a detailed and holistic assessment of the potential for decarbonizing urban road infrastructure in Kenya through solar street lighting (Maina et al., 2022).

1.7 Limitations

While this project sought to conduct an overall decarbonization assessment of urban road infrastructure in Kenya through solar street lighting, the following limitations are identified and need to be stated for a realistic understanding of the study's constraints.

1. Technological Restrictions

The performance and efficiency of solar street lighting systems are susceptible to the availability of sunlight. Variations in the intensity of solar radiation for various reasons, such as variability in weather and seasonal changes, and shading effects from tall buildings associated with urban developments, may affect the reliability of these systems (Wambui et al., 2022). Moreover, with technologies associated with solar panels and battery storage evolving increasingly fast, systems put in place will be outdated in a short period.

2. Infrastructure Challenges

Urban areas, especially the cities that are densely populated, such as Nairobi and Mombasa, have numerous infrastructural challenges. Coupling solar street lighting with the existing urban road infrastructures can be particularly challenging and might require complex modifications (Akomolafe, 2023). Additionally, the question of the durability of solar equipment in urban conditions—where vandalism and accidental damage are possible—remains.

3. Data Availability and Accuracy

The accuracy of the current street lighting energy consumption, greenhouse gas emissions, and infrastructure is critical to this study. However, data inconsistency and missing data may affect the accuracy of the analysis. Adequate solar radiation data regarding consistency and accuracy for the chosen urban areas is also important for a reliable feasibility study.

4. Socio-Cultural Acceptance

The success of implementing solar street lighting also depends on how much the community accepts and supports it. The willingness to change from conventional street lighting

systems to solar systems can be limited by a lack of knowledge and misconceptions regarding whether solar systems can be reliable and the benefits of this technology (Welfle et al., 2020).



Chapter 2: Literature Review

2.0 Introduction

This chapter presents a literature review on decarbonizing urban road infrastructure for economic and social benefits and using solar street lighting in low-carbon cities. The literature review was done according to the study's objectives.

2.1 Statistics on Carbonization in Kenyan Urban Roads Infrastructure

It is no exception for Kenya, among the world's significant sources of GHG emissions. The urban road infrastructure, particularly those of fast-growing cities like Nairobi and Mombasa, has been the big carbon emitters (Rauland & Newman, 2019). The urgency of dealing with the carbon emissions issue in the transport sector on Kenya's roads is well caught under the GIZ pilot study in 2015. By volume, the transport sector in Kenya accounts for close to 12% of the total national GHG emissions, most of which come from the urban road infrastructure (Luusa, 2019). The GIZ study in 2015 showed that the average CO₂ emission factors in various vehicle categories operating in the Kenyan urban areas were: passenger cars, 185.20 g CO₂/km; light commercial vehicles, 216.48 g CO₂/km; heavy goods, 759.88 g CO₂/km; and coaches, 846.26 g CO₂/km; and motorcycles emit 68.46 g CO₂/km.

All these statistics point to the fact that urban road transport in Kenya results in high carbon emissions. The growth in urbanization and rising numbers of motor vehicles make it worse. Nairobi, for instance, has witnessed a massive increase in vehicle registration, with over 300,000 new vehicles registered per annum in recent years. With such a high increase, traffic jams increase with a propensity for long idling, further increasing GHG emissions (Wambui et al., 2022). Further research revealed that the country's fuel economy for vehicles is significantly lower than the rest of the world, attributed to importing older, inefficient vehicles. More than 90% of vehicles used in Kenya as passenger cars are second-hand imports, mainly from Japan, and the average delay in improving fuel efficiency between second-hand imports and new vehicles is eight years (Amuyunzu & Kisimbii, 2021). This results in higher emissions per kilometer.

Based on Akomolafe (2023), conventional street lighting is similarly an energy-intensive process in urban areas, and this also has a share in the carbonization scenario. Powered mainly by the national grid, traditional street lighting systems substantially depend on fossil fuels. Many streetlights are found in major urban cities, and their collective energy consumption translates to high carbon emissions. The carbonization of urban road infrastructure in Kenya will only be mitigated by multifaceted interventions focused on

improving vehicle fuel efficiency, traffic management, and integrating renewable energy solutions such as solar street lighting. The deployment of solar street lighting within urban centers would drastically reduce the use of fossil fuels, leading to GHG emissions that are not sustainable.

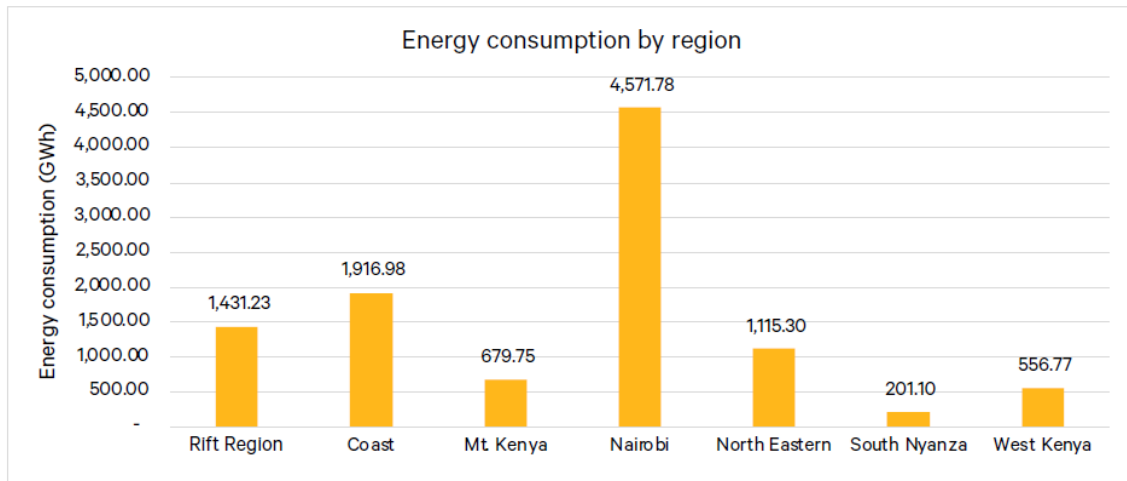


Figure 2.1: Energy Consumption based on KPLC region categorization for the year ending June 2024

As per EPRA statistics, the bar chart in Figure 2.1 illustrates energy consumption across regions in Kenya (in GWh). Nairobi peaks in energy consumption at 4,571.78 GWh, with other regions being way behind. Coast (1,916.98 GWh) and Rift Region (1,431.23 GWh) also have high consumption. Northeastern (1,115.30 GWh) is next, and South Nyanza (201.10 GWh) and West Kenya (556.77 GWh) use the lowest amount of energy. The statistics reflect regional disparities in electricity consumption.

2.2 Current Street Lighting Solutions across the Globe

The implementation of street lighting solutions worldwide is at very different levels due to the development of infrastructure, energy resources, environmental considerations, and technological development. A look at existing street lighting solutions worldwide offers us an opportunity to understand the feasibility and effectiveness of different approaches. In developed nations like the United States, Europe, and Asia, traditional street lighting systems use electricity from the grid to a certain extent. HPS and metal halide lamps have primarily been used because of the efficiency and dependability of this lighting technology (Luusa,

2019). That said, changing to LEDs has become a trend due to their significant energy savings, prolonged life, and quality of light.

On the other hand, with energy poverty and financial challenges, there is an excellent problem with adequate street lighting in developing countries, including the Horn of Africa. Solar street lighting is the other technology that has been very effective in these regions. Solar streetlights are just lighting that trap power from the sun using photovoltaic panels (Maina et al., 2022). The captured energy is then stored in batteries to be used at night. The off-grid method is low-cost and less dependent on fossil fuels in terms of infrastructure, thus very appropriate for rural and remote areas. Indian governments have aggressively ensured the large-scale adoption of solar street lighting in the country (Wambui et al., 2022). Under the Street Lighting National Programme and other schemes, efforts have been made to ensure that these energy-saving systems replace conventional street lighting. Not only does this save a considerable amount of energy and reduce the carbon footprint, but it also adds an element of safety and visibility to the roads.

It could be one way of bettering the infrastructure on the roads of the urban areas and, at the same time, reducing the number of challenges in line with sustainability in such regions as Kenya, which has a shortage of electricity (Amuyunzu & Kisimbii, 2021). Besides, the country's commitment to climate action, marked by its participation in the Paris Agreement and the policy framework on climate change, underscores the need to embrace low-carbon technologies. Despite these benefits, solar street lighting still has a challenge with initial costs, design, maintenance challenges, and concerns with technology. Therefore, the reliability and robustness of solar-powered systems under varying environmental conditions are considered the key conditions for their widespread adoption. Furthermore, effective policy frameworks, financing mechanisms, and capacity-building efforts are needed to implement and maintain solar street lighting projects (Welfle et al., 2020). The literature review was also important in understanding the state of street lighting solutions around the world, considering the use of solar technology in these areas, and this forms an integral part of the proposed study, which seeks to outline how urban road infrastructures could be decarbonized in Kenya using solar street lighting.

2.3 Jurisdiction and Administrative Responsibilities for Street Lighting Solutions

Based on Welfle et al. (2020), knowing where jurisdiction and administrative responsibilities fall for street lighting solutions is important for effectively delivering any smart-style initiative. These vary quite differently from country to country and, in some cases, even from region to region within countries, based on their policy frameworks, especially in local contexts. This section introduces how street lighting management and administrative roles work in different jurisdictions. In street lighting solutions, many countries usually assign responsibility to sub-national entities, such as municipalities or city councils, to plan, install, maintain, and upgrade street lighting infrastructure. For example, in most developed countries like the United States, municipalities usually collaborate with utility companies to provide electricity (Luusa, 2019). At the same time, local public works departments may manage and maintain street lights. Since many of these activities are conducted at the local level, the funds to finance the projects are usually drawn from local sources such as taxes, utility bills, or an investment budget, which is set up separately and allocated towards investment in infrastructure.

The case is similar in European countries, with municipalities at the center. However, the degree of coordination with the national or regional level is usually much higher, mainly regarding funding and standards. For instance, in Germany, street lighting is in the domain of the local government, but the country follows the energy and environment standards of the federal authorities (Akomolafe, 2023). The European Union also dictates policy through directives that mandate energy efficiency and sustainability, eventually driving the entire street lighting system to be someday composed mainly of LED and solar-powered lighting. In contrast, administrative landscapes are more complex in developing countries due to variable infrastructure development and governance capability levels. In India, street lighting is the responsibility of the central and state agencies and local municipal authorities. Central-level programs like the Street Lighting National Programme (SLNP) provide policy direction and financial support. Implementation is done by state and local governments across the country (Wambui et al., 2022). This multi-tier approach to the responsibility of street lighting actualizes a difference in dealing with both urban and rural needs but also causes problems in coordination.

In Africa, the administrative or governance structure for street lighting takes due cognizance of decentralization policies designed to improve local governance. In Kenya,

county governments are mainly responsible for urban infrastructure, including street lighting. However, street lighting projects often involve partnerships with national agencies, private-sector stakeholders, and international development organizations for their execution. For example, the Kenyan Urban Roads Authority (KURA) works with county governments to improve road infrastructure involving street lighting (Welfle et al., 2020). Private sector participation has also been substantial in many countries. Public-Private Partnerships (PPPs) are being used to attract private sector capabilities and financing for street lighting investments. Such PPPs relieve the local government's revenue-constrained budget and ensure more efficient project implementation (Amuyunzu & Kisimbii, 2021). For example, in several African countries, private companies have been contracted to install and maintain solar streetlights, often with financing support from international donors or climate funds.

The effectiveness of street lighting solutions depends heavily on clear lines of responsibility in administration and robust coordination mechanisms. The policy frameworks should thus pop up, indicating what various stakeholders are supposed to do and involving adequate financing besides promoting the cause of sustainability (Wambui et al., 2022). In Kenya, capacity development for county governments, collaboration with national and private agencies, and compatibility with best practices internationally are some of the avenues that guarantee the success of solar street lighting programs. Within this jurisdictional and administrative dynamics knowledge, the proposed study in the context of decarbonizing urban road infrastructure in Kenya becomes relevant.

2.4 Impact of Conventional Street Lighting Solutions to the Urban Planning and Infrastructure

Conventional street lighting solutions manifest significant impacts on urban planning and infrastructure. These impacts range from energy consumption, environmental sustainability, and economic costs to urban aesthetics and functionality (Osano & Kingiri, 2021). Most importantly, conventional street lighting is in high energy demand. The two traditional street lighting systems, high-pressure sodium (HPS) and metal halide lamps, require high energy. High energy requirements are very problematic for the urban power grid, adding much tension, which will increase operational costs for the municipality (Welfle et al., 2020). Sometimes, the energy consumed in street lighting may make up the bulk of electric power demand for a city, contributing to high greenhouse gas emissions that the city will bear as emissions from power generation.

On environmental levels, conventional street lighting leads to light pollution, which disturbs the ecosystem and affects the health of humans. Over-illumination from improperly directed sources harms many animals, often causing disorientation during their nocturnal migrations and breeding behavior. In humans, it can interfere with sleep patterns and diminish the quality of life by hiding the night sky. More so, the high energy consumption involved with traditional street lighting systems further exacerbates urban areas' carbon footprint, contributing to climate change. From an economic point of view, conventional street lighting incurs high installation, operation, and maintenance costs (Akomolafe, 2023). Bulb replacement and infrastructure maintenance costs related to outdated infrastructure accrue into long-term costs for any municipality. Such costs are attributed to municipal budgets that require investment in other inevitable and vital urban development projects. From a purely urban aesthetic and functionality viewpoint, conventional street lighting can make or mar an urban setting.

Well-designed lighting contributed to safety and security by ensuring visibility on the streets, sidewalks, and public places and discouraging criminal activities and accidents. However, Badly designed street lighting can cause uncomfortable light flashes and uneven lighting, leading to visibility and overall night appearance issues in urban areas. Consequently, urban planners must consider these effects when designing or modernizing street lighting systems (Wambui et al., 2022). This is where the transition to more sustainable and energy-efficient solutions, such as LED or energy-saving solar streetlights, can mitigate many of these problems. With energy-efficient sources, such as LED or solar, at relatively lower costs for installation and energy, they aid in saving on initial costs of purchase and installation, provide low energy usage, save on costs, and provide better lighting quality with low maintenance for better urban areas (Luusa, 2019). Cities can improve their infrastructure by improving on the shortfalls of conventional street lighting; this transition in the energy sector can improve the sustainability of cities in every way possible.

2.5 Local and International Regulatory Framework Towards Decarbonization

Decarbonization, especially of urban infrastructure and street lighting, is a constantly moving target under the umbrella, mainly consisting of a thicket of local and international regulatory frameworks that guide the reduction of greenhouse gas emissions and sustainable development (Osano & Kingiri, 2021). The frameworks are now important in guiding light from conventional to sustainable light.

2.5.1 International Regulatory Frameworks

United Nations Framework Convention on Climate Change (UNFCCC)

UNFCCC is one of the most vital international treaties to combat climate change. UNFCCC, through its offshoot, the Paris Agreement, entails a commitment by countries to effectively bring down global warming by reducing it to well below 2 degrees Celsius and doing their best to put it beneath 1.5 degrees Celsius. The treaty, in other words, encourages nations to implement measures currently by lowering the store or cutting down on carbon emissions through means like the transition to renewable energies and energy-efficient technologies like solar street lighting.

Sustainable Development Goals (SDGs)

The United Nations developed SDGs to push the world toward a better and sustainable future. Under this, Goal 7 works towards providing clean and affordable energy (Luusa, 2019). It further seeks to increase the use of renewable energy and improve energy efficiency. In this category falls solar street lighting, which provides a clean and sustainable use of lighting methods instead of traditional ones.

International Energy Agency (IEA)

The IEA advocates reliable, affordable, and clean energy policies. It gives guidance on integrating renewable energy into national energy policies. In particular, the IEA's Energy Efficiency policy recommendations underscore the need to use energy-efficient technologies in urban infrastructure.

European Union Directives

The EU has established stringent regulations about the Energy Efficiency Directive and the Renewable Energy Directive (Welfle et al., 2020). These regulations give binding targets on energy efficiency and renewable energy use and encourage member states to invest in sustainable infrastructural solutions, like solar street lighting.

2.5.2 Local Regulatory Environments

Kenya Vision 2030

Kenya Vision 2030 is the long-term national development blueprint seeking to make a newly industrializing, middle-income country Kenya. The program mainly focuses on the development of sustainable urban infrastructures. On the same note, it promotes the integration of renewable energy technologies like Solar Street Lighting—eliminating carbon emissions and increasing the general energy mix.

Kenya National Climate Change Action Plan (NCCAP)

This policy document provides the anchor for Kenya's climate change mitigation and adaptation roadmap. One of the key Intervention Areas in this strategic attention is embracing energy efficiency and using renewable energy. Solar Street Lighting is one of those visible steps in implementing NCCAP, which, in the spirit of a national campaign, seeks to cut down greenhouse gas emissions to a considerable level (Wambui et al., 2022).

Energy (Solar Photovoltaic Systems) Regulations 2012

Under the Energy and Petroleum Regulatory Authority, EPRA, these are the regulations that provide the standards and guidelines for implementing and operationalizing Solar PV systems within the nation. It aims to ensure quality and safety in installation works, promoting the mainstreaming of solar technologies in applications that include street lighting.

Kenya's Energy Act, 2019

The Energy Act provides a broad legal framework for developing energy and provisions for renewable energy and energy efficiency. The Act has further imposed an obligation to adopt sustainable energy practices that make it even easier for municipalities to implement solar street lighting projects (Welfle et al., 2020).

Challenges and Opportunities

The regulatory frameworks provide a solid basis for promoting decarbonization via sustainable street lighting, although enforcement and compliance issues remain problematic. There may be challenges in successful regulation implementation due to the lack of enough financial resources, technical capacity, and bureaucratic hurdles. There is an opportunity to leverage international funding mechanisms through the Green Climate Fund and partnerships with international agencies to support local action (Amuyunzu & Kisimbii, 2021). The second part of the opportunities is leveraging public-private collaboration to facilitate innovation and investment in sustainable urban infrastructure.

2.6 Technical and Technological Gaps in Solar Street Lighting Systems Solutions

Some technical and technological challenges must be addressed when switching to solar street lighting to garner maximum effectiveness and reliability. Some gaps remain even though there have been significant advancements in this field. Solar panels are the core component of solar street lighting systems since they convert sunlight directly into electrical energy. This is very important for the efficiency of the solar panels. Current commercial solar panels have an efficiency level of about 15–20%, which means that a significant portion of the sunlight is not

converted to usable energy (Akomolafe, 2023). Research and development should be ongoing to increase the efficiency of photovoltaic cells to make solar street lighting systems more effective when used in parts with poor sunlight reception.

The reliability of solar streetlights is significantly dependent on the storage capacity and lifespan of the battery. Many challenges face current battery technologies such as lead-acid and lithium-ion; these include a limited lifespan and problems with charging efficiency, especially at extreme temperatures (Luusa, 2019). Tremendous improvements in battery technology—like the envisioned solid-state batteries—are set to offer more durable and highly efficient energy storage solutions suitable for use with solar street lights. The solar street lighting systems are subjected to different kinds of weather, notably rain, dust, and extreme temperatures. The durability of the solar panel, battery, and other hardware components must also be enhanced to withstand harsh environmental conditions. Extended lifespan and more reliable systems can be ensured using improved materials and, sometimes, protective coatings (Osano & Kingiri, 2021).

Regular maintenance is important to get the best out of street solar lighting systems. However, most rural and urban areas still lack the technical personnel needed for proper maintenance. This could be addressed by simplifying the design and automatically providing self-diagnostic and maintenance features (Welfle et al., 2020). This can be achieved by implementing innovative technologies, such as sensors and IoT, which can help raise the efficiency and functionality of solar street lighting to a whole new level. Smart controls can effectively allow adaptive lighting so the light is bright when the presence of pedestrians or vehicles is detected. Their integration, however, requires dense communication networks and additional investments.

Although off-grid, when solar street lighting systems are grid-integrated, they will provide backup power and enhanced reliability (Arent et al., 2020). The hybridization of these systems will need compatible infrastructure and regulatory support for their failure-proof operation. Innovation and design improvements are the best techniques to help cover such technical and technological gaps for improved performance and adoption in solar street lighting systems (Wambui et al., 2022). Overcoming these challenges will allow solar street lighting to become a more viable and sustainable solution for urban and rural areas.

2.7 Street Lighting Engineering Standards

Engineering standards for street lighting are more important, together with ways to ensure the efficacy, safety, and reliability of lighting systems in the urban context. Such guidelines and specifications include lighting design, particularly installing, operating, and maintaining lighting systems (Rauland & Newman, 2019). They ensure adequate lighting for clear visibility and security while minimizing energy use and environmental impact.

- *International Standard:* Illuminating Engineering Society (IES) provides comprehensive guidelines for street lighting design, including recommended illumination levels, uniformity ratios, and glare control. IES RP-8-18 is a key publication that provides lodging light for the specification of different types of roadways and traffic conditions to meet the requirements of drivers, pedestrians, and cyclists (Gorham, 2017).
- *International Commission on Illumination (CIE):* CIE offers global lighting quality and performance guidelines. Standards like CIE 115:2010, Lighting of Roadways for Motor and Pedestrian Traffic, deal with illumination levels of luminance and uniformity and require the color rendering of street lights. All these standards help provide a safe and comfortable visual environment.
- *European Standards (EN):* EN 13201 is the European standard for road lighting. EN 13201 comprises several parts covering performance requirements, design criteria, and energy efficiency. The requirements shall ensure that compliant lighting systems subjected to different parameters guarantee a common and constant quality of lighting installation throughout Europe concerning performance in the main task areas of road users, thus enhancing safety and sustainability.
- *National Standard:* American National Standards Institute (ANSI) standards, in particular, ANSI/IES RP-8, describe the aspects of technical requirements for street lighting to be realized within the United States. These innovative roadway lighting designs must derive from standards ensuring feasible layouts that supplement adequate lighting for security while at the same time minimizing excessive energy use and light pollution (Amuyunzu & Kisimbii, 2021).
- *British Standards (BS):* BS 5489-1:2020 provides a code of practice for the design of road lighting in the U.K. BS 5489-1 includes guidelines for lighting classes, performance metrics, and energy efficiency (Luusa, 2019). This British standard

assures that street lighting in the U.K. meets safety requirements and is incorporated with various sustainability paths.

Key Features of Street Lighting Standards

- *Illumination Levels*: Standards set minimum carriageway illumination levels to ensure all road users have enough visibility. These levels vary depending on the type of road, density of traffic, and prevailing environmental conditions.
- *Uniformity and Glare Control*: The uniformity ratios ensure that the light distribution is even and prevent the creation of dark areas and unnecessary brightness. The control of glare is important to reduce discomfort and eventual accidents for vehicle drivers and pedestrians (Welfle et al., 2020).
- *Energy Efficiency*: New standards emphasize energy efficiency. Energy-conservation technologies such as LED lighting and solar-powered systems are preferred to reduce carbon footprint and operational costs.
- *Safety and Maintenance*: This standard provides guidelines for safe installation practices and contains all the requirements for installing and maintaining street lighting systems (Akomolafe, 2023).

2.8 Cost Benefit Analysis of Solar Street Lighting

Solarizing street lights becomes one bright spot towards achieving more accessible urban road infrastructure, eventually resulting in cost savings, environmental benefits, and energy security. A typical CBA of Solar street lighting will consider available quantitative and qualitative aspects of the impact compared to conventional lighting systems.

Initial Costs

- *Capital cost*: The cost of implementing solar street lighting will be higher than that of traditional streetlights, considering the cost of the photovoltaic panel, battery, and advanced control system (Amuyunzu & Kisimbii, 2021). However, solar prices have been reducing significantly in the last decade with increased mass production.
- *Installation cost*: The installation cost of a solar streetlight will be cheaper or competitive with conventional systems. Further, there is no complicated trenching and cabling for a solar streetlight unit. All the solar units are single units that only need pole placement and light mounting. This will minimize labor costs.

Operational Costs

- *Energy saving:* In the case of solar street lights, the electricity generated from sunlight becomes an enormous energy savings. Unlike grid-based electricity lighting, a solar light will not have electricity charges as all the operation is independent of the grid. Therefore, it will benefit a municipality or commercial business with a high electricity cost (Wambui et al., 2022).
- *Operation and Maintenance:* A solar streetlight's maintenance cost is cheaper than other conventional systems. Even if the batteries need replacement after 5-7 years, the lifespan of many solar lights is long due to the use of robust and long-life LED technology, minimizing the maintenance cost (Luusa, 2019). In addition, the system is decentralized, so there are no complexities; when one part fails, it does not interfere with other parts, saving time and money on repair.

Environmental Benefits

- *Carbon Emissions Reduction:* Solar street lighting systems significantly reduce greenhouse gas emissions by replacing conventional lighting systems that use fossil fuel energy (Rauland & Newman, 2019). Every solar street light helps mitigate the carbon footprint toward global climate goals and local environmental policies.
- *Little or no Light Pollution:* Solar street lights, most often fitted with LEDs, have a higher capability to control the distribution of light, thereby reducing light pollution. They are designed with intelligent lighting controls, such as motion and dimming sensors, so they have improved energy efficiency and reduced excess illumination.

Social and Economic Benefits

- *Improved Public Safety:* Adequately illuminated streets guarantee public safety and reduce crime and accidents. Solar streetlights provide reliable lighting in areas where grid electricity is undefined or unavailable, improving the quality of life and offering security to those living in such areas (Welfle et al., 2020).
- *Energy Independence:* Solar-based streetlights help improve energy independence. They do this by harnessing locally available solar energy, reducing dependence on foreign energy sources, and, therefore, eliminating the details of energy security solutions, especially in remote or underdeveloped regions.
- *Job creation:* Exploiting solar street lighting in developing regions can be a source of job creation—jobs concerning manufacturing, installation, and maintenance. This, in turn, creates economic development and enhances skills acclaimed.

The Long-Term Financial Savings

- *Return on Investment (ROI)*: Though the installation cost is high, the ROI for solar street lights is positive because, throughout their life, a considerable amount is saved on energy and maintenance expenses. Usually, payback is between 3 and 5 years, after which the benefits will continue accruing with minimal ongoing expenses (Maina et al., 2022).
- *Funding and Incentives*: Municipalities can reduce their part-financing through grants, subsidies, and other financial incentives barely availed by governments and international agencies; they speed up the dynamics of getting into solar street lighting.

2.10 Social, Economic, and Environmental Benefits of Solar Street Lighting

Solar street lighting has many social, economic, and environmental benefits, and it is becoming a sound and sustainable solution for urban infrastructure.

Social Benefits

- I. Solar streetlights offer reliable and constant lighting in urban regions to improve visual conditions and, in the process, mitigate the roots of accidents and crime (Sutopo et al., 2020). Enhanced street lighting means the residents always feel safe and secure, encouraging outdoor activities and interactions with other community members.
- II. Consistent lighting increases the duration of safe traveling and various activities. This is particularly helpful for students who can study after nightfall and businesses that can operate longer, thus improving the quality of life (Wambui et al., 2022).

Economic Benefits

- I. Although the initial installation cost of solar streetlights is high, the long-term savings are enormous. The cost of electricity is eliminated, and maintenance costs are minimized due to the long life of LED technology and independence from power grids. Ultimately, such economies will soon pay for themselves and give back in terms of ROI (Gorham, 2017).
- II. The application of solar street lighting systems creates employment at the local level, specifically in the assembly, erection, and even maintenance processes. This will help boost a community's economy and skill levels.
- III. Solar street lighting stimulates the local economy through job creation in the assembly, installation, and maintenance sectors. This fosters economic growth and boosts skills in that society (Welfle et al., 2020).

- IV. Solar street lighting caps the use of fossil fuels and grid electricity, ultimately leading to energy sovereignty. This is assured for areas with erratic power supplies and those interested in controlling energy imports.

Environmental Benefits

- I. Solar streetlights harness renewable energy, eliminating greenhouse gas emissions tied to classical, fossil fuel-based electricity generation. This aligns with the global goals of mitigating climate change and national and local environmental policy.
- II. Solar streetlights usually use LED techniques, which allow better control over light distribution and intensity (Baburajan, 2021). Thus, they reduce light pollution, protecting the natural nocturnal environment and the well-being of nocturnal wildlife.
- III. solar street lighting observes the use of energy from resources that can be renewed, thus reducing the dependence on non-renewable energy sources (Luusa, 2019). This sustainable approach stays in harmony with conserving limited resources and promoting green technology use.

2.11 Concept Mapping on Decarbonization of Urban Road Infrastructure

Concept mapping provides a visual diagram of the main elements and their relationships in decarbonizing urban road infrastructure by implementing solar street lighting. It systematically organizes and represents the various elements and their connections, allowing one to understand every aspect of the project properly.

Key Components

Technology for Solar Street Lighting

- Solar Panels: Collect solar energy and convert it into electrical energy.
- Batteries: Energy storage for use at night and during cloudy periods.
- LED Lights: High-efficiency and long-life lighting.
- Smart Controllers: Energy usage regulation and performance optimization.

Environmental Impact

- CO2 Emission Reduction: There is less dependence on fossil fuels, which reduces greenhouse gas emissions.
- Control of Light Pollution: Better lighting that reduces light spill and glare is advantageous for the no-light environment.

Economic Aspects

- Return on Initial Investment: The cost of installation is high.

- Savings in the Long Term: Reduced electricity bills and maintenance costs in the long term (Wambui et al., 2022).
- New Spin-offs of Employment: In manufacturing, implementing, and maintaining solar streetlights.

Social Benefits

- Public Safety: Reduction in accidents and crime due to better visibility
- Quality of Life: It encourages evening activities, improving quality of life.

Regulatory Framework

- Local Regulations: Compliance with local and national standards, especially at the municipal level, for street lighting.
- International Guidelines: Alignment with global standards on environmental sustainability and energy efficiency.

Technical Issues

- System Integration: Ensuring solar panels, batteries, and lights interact smoothly.
- Maintenance: Resolving technical problems and securing the longevity of the systems (Rauland & Newman, 2019).

Implementation strategies

- Pilot Projects: Implementing and adjusting solar street lighting solutions in a few demonstrations locations
- Stakeholder Integration: Embracing community members, local government authorities, and private sector partners
- Funding Mechanisms: Attracting investments and grants to roll out the project interlinkages (Luusa, 2019).
- Technology and Environment: The technology area of solar street lighting directly impacts the environmental aspect by reducing emissions and energy conservation.
- Economics and Society: Reducing energy costs results in savings that can easily be used for more critical social needs (Amuyunzu & Kisimbii, 2021).
- Regulations and Implementation: A supportive environment for implementing technology projects through favorable regulation to enhance technology application and operational principles.
- Technical and Economics: Some technical issues have cost implications on the final system, and solving the technical problems through creativity can further bring down

the cost and improve the system's reliability, hence increasing the economic viability of the solution (Welfle et al., 2020).

These interrelations will allow the stakeholders to visually perceive the multi-dimensionality of the process of decarbonization of urban road infrastructure and locate the most sensitive areas for action. This holistic view guarantees that every factor is appropriately considered in planning and executing the transition toward solar street lighting, ultimately ensuring sustainable urban development.

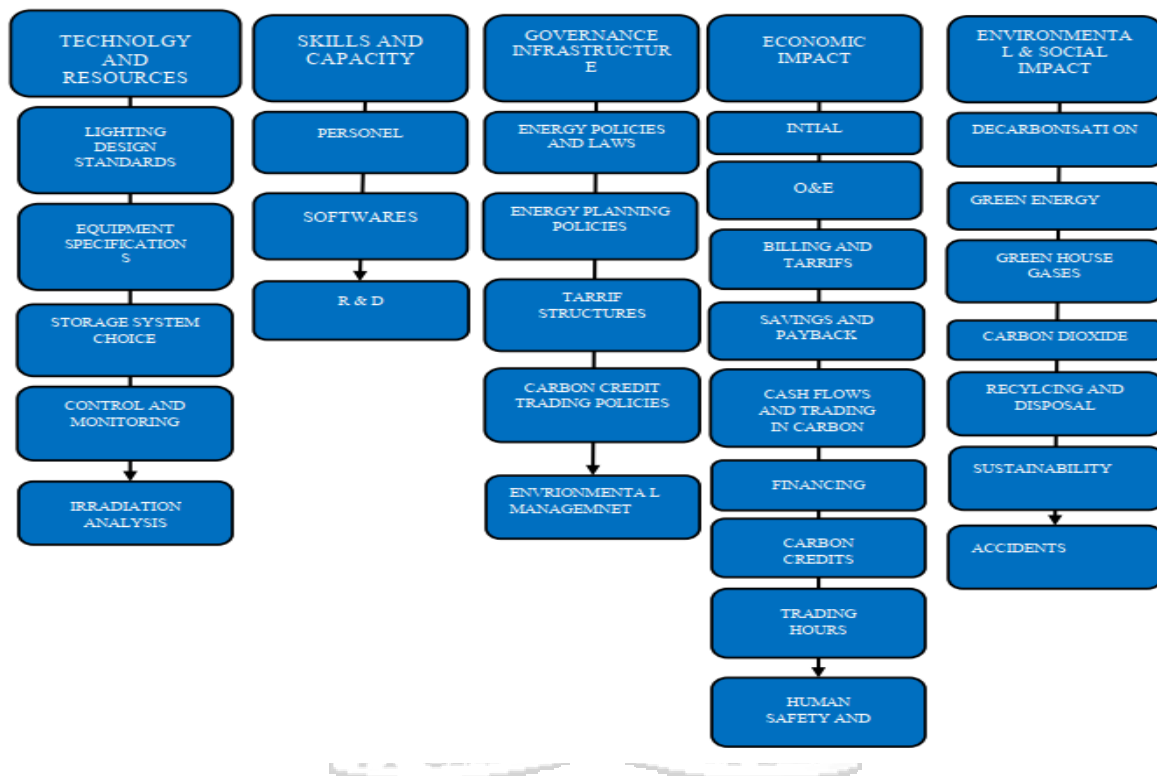


Figure 2. 2: Concept Mapping on Decarbonization of Urban Road Infrastructure

2.12 Research Gaps in Literature

Various research has been conducted on solar street lighting and its possible benefits. However, several gaps exist that obstruct the real meaning and, in turn, efficient provision of decarbonized urban road infrastructure in Kenya (Luusa, 2019). The solution to these research gaps is imperative for robust and scalable solutions that can generally adapt to different urban settings.

1. Site-Specific Environmental Impact Assessment

While there are established environmental benefits from solar street lighting in various cities across the globe, there is an absence of site-specific assessments in Kenyan urban setups.

Rigorous studies have to quantify and isolate the exact amount of CO₂ emissions reduction and other such co-benefits in Kenya's unique climatic, urban density, and energy infrastructure.

2. Economic Viability and Cost Analysis

While cost-benefit analysis has been drawn for solar street lighting, such analysis often depends on generic or outdated data. There is a need for regional levels of analysis to consider this factor, in addition to the current prevailing market prices, local labor costs, and potential funding mechanisms in Kenya (Maina et al., 2022). This includes long-term financial modeling to assess returns on investment and economic sustainability of large-scale solar street lighting projects.

3. Social Acceptance and Community Impact

Research on the social implications of solar street lighting is scant. Levels of community perception and acceptance and social aspects when transitioning from conventional to solar streetlights need to be understood (Wambui et al., 2022). Specifically, it is unclear how improved lighting affects local businesses, pedestrian activities, and public safety in urban areas.

4. Adaptation and innovative technology

There is a gap in research focusing on how solar street lighting technology can be adapted for its use under local and rural conditions. This includes the durability of solar panels and batteries in Kenya's diverse climatic conditions, the potential for integrating innovative technology, and innovations in storage solutions to ensure consistent lighting during cloudy periods.

5. Policy and Regulatory Frameworks

Although there are international standards and local policies regarding renewable energy, specific regulatory frameworks addressing the deployment of solar street lighting in urban areas are very few (Welfle et al., 2020). Research is needed to develop and tailor relevant policies that will make it easier and possible to integrate solar lighting into already existing infrastructure within the urban set-up in a manner that includes environmental and standard safety assurance.

6. Long-term Maintenance and Sustainability

Most studies look at solar street lighting systems' long-term maintenance requirements and sustainability. Important research issues should focus on developing efficient maintenance protocols, the lifespan of components in local conditions, and strategies for end-of-life disposal and recycling of both solar panels and batteries.

2.13 Conceptual Framework

The conceptual framework of decarbonizing urban road infrastructure through implementing solar street lighting in Kenya is set at the intersection of several key pillars geared towards sustainable, low-carbon urban development (Osano & Kingiri, 2021). The framework integrates technological, environmental, social, economic, and policy dimensions to ensure holism in the approach toward achieving the desired outcomes. The conceptual framework imputes adopting solar street lighting as a clean and renewable energy solution to reduce carbon emissions from conventional street lighting systems (Luusa, 2019). Solar street lighting systems store solar energy in batteries collected during the day using photoelectric panels for use during the night. Significant emissions of greenhouse gases can be reduced by replacing the traditional, on-grid streetlights with solar ones, helping Kenya honor her climate commitments.

The framework recognizes the necessity of grounding solar street lighting solutions within the local urban context. City and town conditions, such as density, traffic, pedestrian activity, and security features, shall influence the lighting design to meet the peculiarities of Kenyan cities and towns (Welfle et al., 2020). The durability of the solar components also has to be factored in the variable climatic conditions experienced in Kenya, as well as the availability of the skills of maintenance personnel to take care of the artifacts. The conceptual framework provides many other benefits from solar street lighting and carbon reduction. Improved lighting increases public security, activity within public areas, and social inclusion similarly, especially in the informal areas of a town or urban zones (Amuyunzu & Kisimbii, 2021). Through solar street lighting, public lighting from street to street and in other public spaces will therefore contribute to breathing life into various townships and urban areas, increasing the quality of life for individuals, residents, and tourists.

Policy and regulatory frameworks are significant vehicles for facilitating the large-scale adoption of solar street lighting (Welfle et al., 2020). The need for supportive policies that will provide investment incentives to deploy renewable infrastructure and harmonize regulatory procedures to meet environmental and safety specifications is envisaged in the conceptual framework. However, the role of the policy framework is to create an enabling environment for deploying solar street lighting, catalyze private-sector engagement, and unlock funding avenues for this and other sustainable urban development initiatives. The conceptual framework defines roadmaps for transitioning towards decarbonized urban road infrastructures in Kenya through the strategic deployment of solar street lighting (Luusa, 2019). The

realization of synergies between technological innovation, stewardship of the environment, social equity and well-being, and policy coherence offers enormous potential for developing resilient and sustainable cities that will thrive in the future's low-carbon economy.



Chapter 3: Research Methodology

3.1 Introduction

The same methodology was employed for assessing the deployment and decarbonization impact of solar street lighting in Kenya, with Mombasa City forming the epicenter of my study. The research design, description of the case study, methods of data collection, stages of model development, choice of simulation software, and evaluation of results are explained in this chapter. This study, through adopting a mixed-method approach and using SPSS version 28 for data analysis, distilled a thorough understanding of how solar street lighting abates carbon emissions and ensures improvement in urban sustainability variables for Mombasa.

3.2 Research Design

This mixed-method design utilizes qualitative and quantitative techniques to comprehensively analyze the implementation and impact of solar street lighting in Mombasa City. The study has several phases: exploratory research, data collection, model development, simulation, and evaluation. Preliminary exploratory research involves a review of available literature and consultations with experts about the existing street lighting solutions and their carbon-emission impacts (Amuyunzu & Kisimbii, 2021). This approach identifies the significant variables and helps in developing data collection instruments. Quantitative data was collected through surveys and existing databases with information on the existing street lighting infrastructure, energy utilization data, and information about carbon emissions (Baburajan, 2021). This would constitute baseline metrics to understand the magnitude of the problem.

The qualitative data was gathered through interviews with stakeholders such as city planners, environmental experts, and local government officials. These interviews gave insights into the challenges and opportunities of making solar street lighting a reality. Data collected was used to develop a simulation model using SPSS version 28. This model analyzed the potential transition to solar street lighting and its impact on carbon emissions and urban infrastructure (Akomolafe, 2023). It equally examined economic justification and social benefits accrued from such a transition. Finally, the simulation results were evaluated so that the effectiveness of the solar street lighting method in reducing carbon emissions can be determined. Moreover, the evaluation was based on a cost-benefit analysis and considerations

concerning social, economic, and environmental impacts, providing a broad view of the potential benefit of this technology.

3.3 Case Study Description

The case study concentrated on Mombasa's southern Bypass. The road is a 38km dual carriage highway owned and operated by the Kenya National Highway Authority (KeNHA). The road is the main entry and exit to the strategic port, a key gateway for trade in East Africa. Additionally, it links the central city of Mombasa Island to the key strategic transport infrastructure of Moi International Airport, the Kenya Navy and United Nations (UN) Forward Air Force operating base, and the Mombasa Standard Gauge Railway (SGR) station. It is, therefore, the main road that feeds traffic and cargo to the Mombasa city and acts as the new connecting route to the tourism-rich southern Coast through the Mwache interchange, decongesting the Likoni ferry crossing by 90% of vehicular traffic.

This road, like the rest of the road network, the city has a conventional, grid-powered streetlights network. Totaled to 2008 units and rated at 150w per unit at an efficiency of 120lumens/watt, the lights are installed in double arm and single arm distribution powered by 11 control pillars interspaced at 4km distances on two substations rates 150kva located at Gate A and mwache interchange consuming a daily power demand of 3,615 Kwhr at a kshs 13.2M annual billing to KeNHA.

The coastal region, in general, to which this road is found primarily consumes about 9.2GWH of electricity for lighting up the streets. Street lighting happens at night. The region's base load is anchored daily by two thermal power plants, Kipevu II and Rabai, which combined supply a cumulative 33MW of electricity for 16 hours, data rising to 9.6GWH of electricity annually, a 55% mix ratio to the overall consumption demand, of the region.

The study area, therefore, provides a sample study of assessment about the level of potential benefits that the solar street lighting system brought in terms of a reduction in GHG, improvements in energy efficiency, and enhancement in public safety (Maina et al., 2022) against an overall average supply of 17% thermal energy supply against 103GWH of electricity consumed on street lighting countrywide. This specifies a general scope in which missed opportunities can be uncovered by other researchers studying other urban settings of Kenya or abroad.

Table 3. 1: Distribution of the Respondents

ORGANIZATION	POSITION OF RESPONDENTS	INTERVIEW POPULATION	QUESTIONNAIRE POPULATION
KENYA POWER AND LIGHTING	Regional Managers	0	8
	Head of Safety and Sustainability	1	0
COUNTY GOVERNMENTS	Department of Energy and Environment	3	5
	Department of Roads and Infrastructure	0	15
KENYA URBAN ROADS AUTHORITY (KURA)	Electrical Engineering Department	1	0
	Climate Proofing and Sustainability Department	1	2
KENYA NATIONAL HIGHWAYS AUTHORITY (KUNHA)	Special Projects Department	1	0
	Climate Proofing and Sustainability Department	1	0
MINISTRY OF TRANSPORT AND INFRASTRUCTURE (MTI)	Head of Public Works	0	1
MINISTRY OF ENERGY AND PETROLEUM (MOEP)	Head of Public Safety and Lighting	1	1
TOTAL		9	32

3.4 Data Collection

This embraced data collection from primary and secondary sources to ensure comprehensive and precise information. Primary data was sourced from the field through surveys, interviews, and direct observations in Mombasa City. Surveys targeted residents, road agency officials, the Ministry of Energy, and city officials to tap their experiences considering current street lighting, energy consumption, and environmental concerns. The information from interviews provided detailed information on the existing infrastructure, operational challenges, and opportunities for solar street lighting implementation. Secondary data was sourced from official reports, academic studies, and relevant databases. It follows that this featured statistical data on energy uptake, greenhouse gas emissions, and urban infrastructure in Mombasa. The solar street lighting systems' general technical specifications and performance data were also reviewed to support the model development and analysis. Combining these data sources would create a strong foundation for evaluating the feasibility and impact of solar street lighting in Mombasa.

3.5 Data collection methods

Surveys: Conducting a primary survey involving various residents of Mombasa City, both the business community and city officials. The survey was structured to collect quantitative data on street lighting, the level of energy consumption, and residents' views on safety and allowance. Questions targeted issues around the frequency and reliability of street lighting, the extent of coverage in various estates, and respondents' perceptions of potential benefits from the adoption of solar street lighting. It has close-ended questions for quantitative measurement and open questions for qualitative presentation.

The interviews were semi-structured and targeted specific key stakeholders, including municipal authorities, energy providers, and urban planners, to gather detailed qualitative data that describes the current infrastructure status, identifies operational challenges, and considers the feasibility of implementing solar street lighting. Interview guides were developed according to the needs of each key stakeholder target group and centered on questions about the technical, financial, policy and regulatory, and potential perceived barriers to adoption and implementation (Akomolafe, 2023). All the interviews were recorded, transcribed, and analyzed for comprehensive information.

Direct Observation: The researcher also directly observed street lighting infrastructure in several neighborhoods around Mombasa City to establish its current condition and

availability (Rauland & Newman, 2019). Observations shall determine the numbers, types, and status of the lights in place, whether functional, out of order, or non-working, and whether some work inconsistently. The method provided first-hand data on streetlights' distribution and functionality and helped substantiate survey and interview responses.

Data Collection from Secondary Sources

Data from secondary sources were collected from government reports, academic studies, industry publications, and databases. This data offered support to the analysis and provided a contextual background. The most notable secondary data sources include:

- *Government reports*: Reports by the Mombasa County government and national agencies were reviewed to collect official statistics on energy usage, greenhouse gas emissions, and urban infrastructure development. The reports also included the government's existing policies and initiatives regarding street lighting and the utilization of renewable energy.
- *Academic studies*: Relevant academic literature was reviewed. This included works on Solar Street lighting, urban infrastructure, and decarbonization (Rauland & Newman, 2019). This offered insights into best practices and technical specifications and previously made case studies in similar contexts.
- *Industry publications*: Publications of the renewable energy industry and street lighting providers were reviewed. The study was conducted to gather technical specifications, performance data, and cost estimates of solar street lighting systems. Such data was essential in modeling the economic and technical models used in the study (Luusa, 2019).
- *Databases*: This category included web-based databases, e.g., databases of the International Energy Agency and the World Bank, from which global and regional data on energy utilization, adoption of renewable energy, and carbon emissions are collected. The last data source was used to compare the data and provide benchmarks on the Mombasa Street lighting infrastructure.

Data Analysis

This collected data underwent quantitative and qualitative analysis. The trend, correlation between variables, and most influential factors on street lighting and energy consumption were statistically determined for quantitative data from surveys and secondary

sources and analyzed through SPSS version 28. Qualitative data from the interviews and open-ended responses to the survey were analyzed thematically to bring out common themes, insights, and stakeholders' perspectives.

Humanitarian Considerations

Ethical considerations were taken during the data collection. The survey and interview participants were thoroughly informed of the purpose of the study and their rights before data collection. In addition, the confidentiality and anonymity of the respondents were ensured when storing the research data and methods of accessing them.

3.6 Model Development

The model development phase aims to create a comprehensive and robust framework to assess the impact and feasibility of implementing solar street lighting in Mombasa City. This involves several key steps:

Defining the Model Objectives

The primary purposes of this model are to estimate the capability of GHG emissions reduction, investigate the cost-effectiveness of conventional street lighting systems, and analyze social, economic, and environmental benefits. Among other objectives of the model is locating potential installations of solar streetlights considering the current infrastructure, population density, and energy consumption patterns in the different settings.

Messaging Data Integration

The model captured several data sources, including primary data to be realized through surveys and interviews and secondary data to be retrieved from documentary reports from governmental institutions, academic studies, and industry publications. The integrated approach provided an overview of the current state of street lighting and energy use in its totality in Mombasa City.

Simulation and Analytical Tools

The model used simulation tools embedded in SPSS version 28 to analyze and interpret the collected data. These tools were important in running several hypothetical scenarios, including differing penetration levels of solar street lighting, policy interventions, and changes in solar technology costs (Welfle et al., 2020). In this context, simulation facilitates the prediction of outcomes, including emission reductions, improved public safety, and urban aesthetics, alongside potential savings.

Cost–Benefit Analysis

An essential part of the model, the CBA, evaluated the costs of installing, operating, and maintaining a solar street lighting system compared to the benefits obtained from the reduction in energy use, GHG savings, and public safety improvements. The CBA brought in data on the initial capital expenditure, operational expenditure, and maintenance expenditure for the lifespan expected from the solar systems.

Smartening

The model included an optimization algorithm to determine the most efficient allocation of solar streetlights across different areas of Mombasa City. It is considered the area with the most excellent pedestrian density, high crime rates, and low current lighting availability (Amuyunzu & Kisimbii, 2021). Parameters used in the optimization aimed to maximize the benefits while minimizing costs and ensuring that the benefits are spread evenly throughout urban and suburban areas.

This work, therefore, is geared towards providing proper knowledge and recommendations for responsible commissioning of planning and management of decarbonized urban road infrastructure, in which various policymakers, urban planners, and other stakeholders are essential players.

3.7 Data analysis methods

The research instruments generated both qualitative and quantitative data. Thematic analysis, a widely used method for analyzing qualitative data, was used to analyze qualitative data from open-ended questions and key informant interviews. It involves systematically identifying, analyzing, and reporting patterns or themes within qualitative data to better understand the research topic (Uwe, 2020). Thematic analysis provides a structured and flexible approach to making sense of complex and rich qualitative data. Quantitative data from the questionnaires was edited, coded, and entered into statistical Software known as the Statistical Package for Social Sciences (SPSS version 28).

Quantitative data was analyzed by using both descriptive and inferential statistics. Descriptive statistics include frequency distribution, percentages, measures of central tendencies (mean), and measures of dispersion (standard deviation). This is then followed by inferential statistics such as Pearson correlation analysis. The study used a 95% confidence level; hence, the p-value was 0.05. Therefore, associations and relationships with a p-value of 0.05 and below were considered statistically significant, but associations with a p-value above

0.05 were considered statistically insignificant. The results are then presented in tables and figures such as bar charts and pie charts.

3.8 Ethical Considerations

There are a couple of key ethical considerations for research involving human participants and topics with sensitives, like urban infrastructure development. The study considers some ethical principles as follows:

- *Informed consent*: All participants must freely participate in the study, knowing its purpose, risks, and benefits.
- *Confidentiality*: The data concerning participants must be confidential throughout the research period, and single responses should be anonymous and not disclosed without consent from the party.
- *Respect of participants*: The rights and well-being of the participants shall be respected, and their autonomy and privacy shall be well considered in the study.
- *Minimization of harm*: Possible risks associated with the collection of data, as well as the results, must be minimized to avoid harm and risks.
- *Transparency*: Openness and honesty in every aspect of the research, from the intentions and possible conflict of interest to the methods used, while maintaining openness and honesty in all transactions with the participants and stakeholders.

These ethical principles guide and protect integrity, credibility, and the trustworthiness of the research process and ensure the rights and well-being of all parties involved.

3.9 Summary

The project assessed the implementation and effects of decarbonizing urban roads within the infrastructural setting in Kenya. More so, this research justified the need for transition based on justified and concrete environmental, social, and economic imperatives in light of the prevailing and current constraints and assumptions. A thorough literature review was conducted as part of the study, and a detailed methodology adopted in this research included the research design, case study description about Mombasa Southern Bypass, data collection, model development, and data analysis using SPSS version 28. Therefore, the research regards the analysis of the technical, economic, and regulatory aspects primarily involved in implementing the policy in the street lighting sector, and it paves the way for making informed choices about sustainable urban development.

Chapter Four: Results

4.1 Introduction

This chapter presents the study's results on adopting solar street lighting in urban areas in Kenya, specifically focusing on its potential to reduce energy consumption and greenhouse gas (GHG) emissions. This chapter is divided into several key sections that detail the research findings. It begins with an overview of the response rate and the demographic profile of the participants. The subsequent sections delve into the status of current street lighting infrastructure and its contribution to urban GHG emissions, the feasibility and potential benefits of transitioning to solar street lighting, the challenges and barriers faced in adopting solar solutions, and finally, the impacts of solar street lighting on urban energy consumption and GHG emissions reduction.

4.2 Response Rate

The target population of the study consisted of 41 respondents, including regional managers and heads of street lighting projects from Kenya Power and Lighting Company, county governments, Kenya Urban Roads Authority, Kenya National Highways Authority (KeNHA), and relevant officials from the Ministry of Transport and Ministry of Energy. Out of 32 distributed questionnaires, 28 were filled and returned. Seven interviews were conducted with the Head of the Street Lighting Project in Kenya Power, the Head of the state Department of Public Works in the Ministry of Transport, the Head of the Public/street lighting Project in the Ministry of Energy, and three county governments officials in charge of public works and environment of Mombasa. The response rate was, therefore, 82.86%. Bhattacharjee (2018) states that a 75 percent response rate is generally sufficient for data analysis, drawing conclusions, and making recommendations.

4.3 Status of Street Lighting Infrastructure and Urban GHG Emissions

The study's first objective was to assess the status of street lighting infrastructure and its implication for urban GHG emissions in Kenya, using the Mombasa Southern Bypass as a case study.

4.3.1 Assessment of the Current status and types of Street Lighting Infrastructure

Mombasa City County has approximately 14,000 streetlights and 800 public lighting masts. These streetlights and public lighting masts cover about 30% of the city. However, about 40% of these lights are not in operation. The lights are powered by the grid to 90% by numbers representing 12,600 streetlights in total and 726 high masts for area lighting. The new lighting infrastructure is planned to cover the remaining 70% of the city, consisting of about 959 public lighting masts and 40,029 street lighting points at a capital investment estimated to cost Kshs. 9.841 billion. 2008 streetlights are installed on Mombasa southern bypass, the case study area.

4.3.2 Types of Street Lighting fixtures in use.

Conventional streetlight fixtures power the Mombasa southern bypass. The lights are made of high-pressure sodium lamps (HPS) mounted at a pole height of 12 m and interspaced between 40m. The lights consist of a single pole (with a mounting of 2 light fixtures) and double arms with a mounting of 4 light fixtures per pole. The light fixtures are rated as having a 150w effective wattage with a light efficiency of 120 lumens/watt and a lighting hour of 15,000 hours, effectively putting them in commission for 3 years before replacement. The entire road runs 162km of 1.5mm twin with earth electrical cabling powered by two substations rated at 150kva located at the entry port gate A and mwache junction interface and supported by 10 electrical control pillars for effective electricity supply and control.

The records from Kenya national highways authority shows that this road alone consumes a daily load demand of 301kw for 12 hours daily.

This data is taken from the relationship below:

$$\begin{aligned} \text{Load Demand} &= \text{Appliances Rating} \times \text{Quantity} \dots\dots\dots 1 \\ &= (150w \times 2008) \div 1000 = 301.2kw \end{aligned}$$

This load demand is subjected to a daily operation time of 12 hours. This is the time available to light up the road from dusk to dawn.

Therefore, the electricity demand for the Mombasa southern bypass is calculated as below:

$$\begin{aligned} \text{Electricity demand} &= \text{load demand} \times \text{load hours} \dots\dots\dots 2 \\ &= 301.2 \times 12 = 3,614.4 \text{ Kwhr daily.} \end{aligned}$$

Annual electricity demand for the Mombasa southern bypass is given as below:

$$\begin{aligned} \text{Annual electricity demand} &= \text{daily demand} \times 365 \text{ (number of days in a year)} \dots\dots\dots 3 \\ &= 3614.4 \times 365 = 1,319,256 \text{ Kwhr.} \end{aligned}$$

This shift towards LED technology reflects efforts to reduce energy consumption and operational costs. However, challenges remain, particularly in transitioning away from older systems, including HPS lamps, in some urban regions, such as Mombasa, where solar street lighting and LED adoption are still in the early stages. Table 4.2, which is Kenya Power data, shows that Mombasa used 9.2 gigawatt hours (GWh) to light up its streets in the year to June 2023.

Table 4. 1: Regional Sale of Electricity for Street Lighting in GWh (KPLC Economic Analysis Report)

REGION	2018/19	2019/20	2020/21	2021/22	2022/23
Nairobi	31.0	34.9	37.6	40.5	41.6
Coast	7.4	10.4	11.0	11.9	9.2
Central Rift	7.7	7.7	9.0	13.7	18.5
West Kenya	5.1	5.3	5.9	6.4	6.8
North Rift	3.0	4.5	6.5	7.4	8.0
South Nyanza	0.8	1.4	1.0	1.8	2.6
Mt Kenya	7.3	7.3	10.1	10.6	9.6
Northeastern	5.8	6.0	4.3	4.6	4.7
TOTAL	68.1	77.4	85.4	96.8	101.0
% Increase P.A.	1.9%	13.7%	10.3%	13.4%	4.3%

Countrywide Kenya power supplies 101GWH of electricity for street lighting usage, accounting for 165,000 streetlights installed. This number represents 98% of the total streetlights installed, with the remaining 2% on solar. Expected expanded lighting programs in place for major cities of Nairobi (110,000 lights), Mombasa city (40,100 lights), Nakuru city (22,000 lights) and Kisumu City (18,000 lights) will drive this energy consumption to 151GWH annually, increasing the energy demand on the current installed capacity to 3% with triple percentage the carbon emissions, especially in regions that run purely on thermal power supply during peak demand and night time loads such as western Kenya and coastal region.

Through its mandate, the Kenya National Highways Authority strives to provide safe National Trunk Roads by constructing and maintaining road lighting. The Directorate currently maintains 132.9 Km of road lighting through Performance Contracts, and an additional 25 Km was procured in the third and fourth quarters of FY 2023/2024. The lighting inventory under this body is as follows.

Table 4. 2: KENHA Construction and Maintenance of Road Lighting

S. No.	Project Name	Double Arm Poles	Single Arm Poles	High mast	Footbridge Lighting	Underpass Lighting	Average Monthly Electricity Bill
1.	Thika Superhighway	1,202	1,320	24	219	165	3,500,000.00
2.	Nairobi Southern Bypass	721	249	9	69	28	2,800,000.00
3.	James Gichuru – Athi River (A8)	190	1231	22	505	23	1,800,000.00
4.	Athi River – Bisil (Kitengela)	91	345	3	0	20	100,000.00
5.	Moi International Airport Access and Port Reitz Road	160	124	0	0	0	1,290,560.30
6.	Western Bypass	366	0	2	0	0	1,902,096.00
7.	Lamu Link Road	276	0	0	0	0	506,736.00
8.	MPARD PK 3	76	175	1	0	12	617,446.80
9.	MPARD PK 2	24	447	0	0	0	735,000.00
10.	MPARD PK 1	305	336	15	0	0	3,335,600.00
Total		3,933	3,269	76	793	248	16,587,409.70

The table displays street lighting infrastructure and electricity costs on ten priority road projects in Kenya. It presents the number of double-arm poles, single-arm poles, high masts, footbridges, and underpass lights used. Thika Superhighway has the most significant

infrastructure and electricity bill, and the smallest is that of Athi River – Bisil. The combined monthly electricity bill is KES 16.59 million.

A total of 2,764 streetlights and 16 high masts are operated and maintained by KENHA, with an annual billing budget of Ksh 77,824,104.00 for the coastal region alone and a total of Ksh 199,048,909.20 overall electricity bills on trunk road lighting countrywide. This shows that 95% of the road lighting infrastructure is powered by the grid in the coastal region.

4.3.3 Contribution of Street Lighting to Urban GHG Emissions

Greenhouse gases are gases in the earth’s atmosphere that trap heat and prevent it from escaping into space. This process, known as the greenhouse effect, helps regulate the earth’s temperature by promoting ideal living conditions. The dominant gas is carbon dioxide (CO₂). Others are methane (CH₄), Nitrous Oxide (N₂O), water vapor (H₂O), and fluorinated gases. Excessive GHG emissions (increased global temperatures, heat waves, storms, cyclones, droughts and wildfires, heavier than normal rainfall, rising sea levels, and flooding) significantly affect the environment. Economic activities (change of weather patterns affecting agriculture, damage to infrastructure, loss of production, and high costs of disaster recovery and adaptation) and human, animal, and plant health (increased pests and diseases, ocean and land acidification, poor air quality, and heat-related deaths). It must be controlled.

Greenhouse gas emissions are measured in the carbon dioxide (CO₂e) equivalents, also known as carbon footprint. These emissions are calculated based on the country’s energy mix with the model below:

$$CapGHG = 0.001 * fuel\ usage * high\ heat\ equivalent\ value * emission\ factor$$

..... (4)

Table 4.4 the data on electricity generation in Kenya from 2000 to 2023. Oil-based generation peaked in 2009 at 2,997 GWh but declined, reaching 1,305 GWh in 2024, indicating a move away from fossil fuels. Hydropower fluctuated over the years, peaking at 4,386 GWh in 2013 but declining to 2,666 GWh in 2023, possibly due to climate variability. Geothermal energy has seen remarkable growth, rising steadily from 429 GWh in 2000 to 6,032 GWh in 2023, making it Kenya’s dominant energy source. Wind and solar PV have also emerged as significant contributors, particularly in recent years, with wind reaching 2,008 GWh and solar PV increasing to 491 GWh in 2023.

Table 4. 3: Electricity Generation in Kenya

Year	Electricity Generation in Kenya (GWh)					
	Oil	Hydro	Biofuels	Wind	Solar PV	Geothermal
2000	2124	1325	133			429
2001	1508	2403	115			480
2002	1022	3119	145			386
2003	920	3433	135			498
2004	1038	3169	150			987
2005	1506	3039	163			1002
2006	1819	3025	162			1046
2007	1736	3592	176			989
2008	2145	3267	168			1039
2009	2997	2160	279	7		1293
2010	2586	3224	270	17	3	1057
2011	2801	3183	270	18	6	1444
2012	2200	3977	258	14	12	1516
2013	2162	4386	271	15	27	1781
2014	2585	3411	220	17	49	2917
2015	1412	3464	230	60	50	4521
2016	1470	3960	229	56	60	4484
2017	2534	2776	156	61	73	4756
2018	1545	3986	169	374	89	5127
2019	1313	3205	148	1562	92	5234
2020	754	4232	218	1331	88	5059
2021	1262	3675	250	1984	167	5037
2022	1584	3039	264	2143	383	5517
2023	1305	2666	199	2008	491	6032

4.3.4 Installed, Effective, and Captive Power Capacity

Table 4.5 outlines the installed, effective, and captive power capacities across various energy technologies as of June 30, 2024, showcasing their contribution to the overall energy mix. The table includes details on interconnected, captive (self-generated), and off-grid capacities, highlighting the diversity of energy sources. Hydropower, geothermal, and thermal

technologies play significant roles, with hydropower contributing 24.38% and geothermal making up 26.37% of the total installed capacity. Solar and wind energy also contribute notably, with solar accounting for 12.38% and wind contributing 12.19%, while bioenergy, imports, and WHRC play more specialized roles in the system. Overall, the total installed capacity is 3,778.5 MW, with an adequate capacity of 3,051.7 MW. This distribution reflects a firm reliance on renewable sources, particularly geothermal, hydro, and solar while highlighting the role of thermal generation and imports.

Table 4. 4: Installed, effective, and captive power capacity as of 30th June 2024

Technology	Interconnected Capacity (MW)	Captive Capacity (MW)	Off Grid Capacity (MW)	Total Installed Capacity (MW)	% of Total Installed Capacity
Hydro	839.3 (Effective: 810.4)	33	0.1	872.4	24.38%
Geothermal	940.0 (Effective: 841.1)	3.7	-	943.7	26.37%
Thermal	572.8 (Effective: 562.4)	21.3	-	636.1	17.78%
Wind	435.5 (Effective: 425.5)	-	42	436.1	12.19%
Solar	210.3 (Effective: 210.3)	229.2	0.6	442.9	12.38%
Bioenergy	2.0 (Effective: 2.0)	161.8	3.4	163.8	4.58%
Imports	200	-	-	200	2.33%
WHRC	-	83.5	-	83.5	-
Total	3,199.9 (Effective: 3,051.7)	532.6	46	3,778.50	100.00%

4.3.5 Energy Consumption by Region

Nairobi region emerged as the leading consumer of electrical energy, utilizing 4,571.78 GWh, marking the highest consumption nationwide, as per EPRA statistics, the bar chart in Figure 2.1. This constituted 43.7% of the country's total energy consumption. The Coast region ranked second in energy consumption, utilizing 1,916.68 GWh, constituting 18.3% of the country's total energy consumption. The Rift region accounted for 13.67% of the total consumption, utilizing 1,431.23 GWh, followed by North-Eastern and Mt. Kenya regions, contributing 10.7% and 6.5% to the overall consumption, respectively. In this case, the Northeastern region covers Garissa, Wajir, Mandera, Marsabit, Kitui, Thika, and parts of Machakos. West Kenya and South Nyanza regions reported the lowest consumption percentages, representing 5.31% and 1.92% of the total consumption, respectively.

4.3.6 Green House Gas Emissions

As a signatory to the Paris Agreement, Kenya has committed to reducing its greenhouse gas emissions by 32% by 2030 compared to a business-as-usual scenario. This commitment is part of its updated Nationally Determined Contributions (NDCs) and includes a range of adaptation and mitigation strategies. In the energy sector, Kenya has pledged to achieve 100% renewable energy generation by 2030 and to double the rate of energy efficiency improvements, as outlined during the 28th United Nations Conference of the Parties (COP 28). These efforts have contributed to a reduction in emissions from electricity generation. According to the Energy & Petroleum Statistics Report for the Financial Year 2023/2024, carbon dioxide emissions from electricity generation decreased by 29.6%, from 845,256.51 tCO₂ to 652,285.12 tCO₂. The grid emission factor dropped by 34%, from 0.06397 tCO₂/MWh to 0.04789 tCO₂/MWh. This decrease in CO₂ emissions can largely be attributed to a 21% reduction in grid thermal generation, which fell from 1,320,000 MWh to 1,042,031 MWh. This declining emission trend has continued since the 2021/2022 financial year, as illustrated in Figure 4.2.

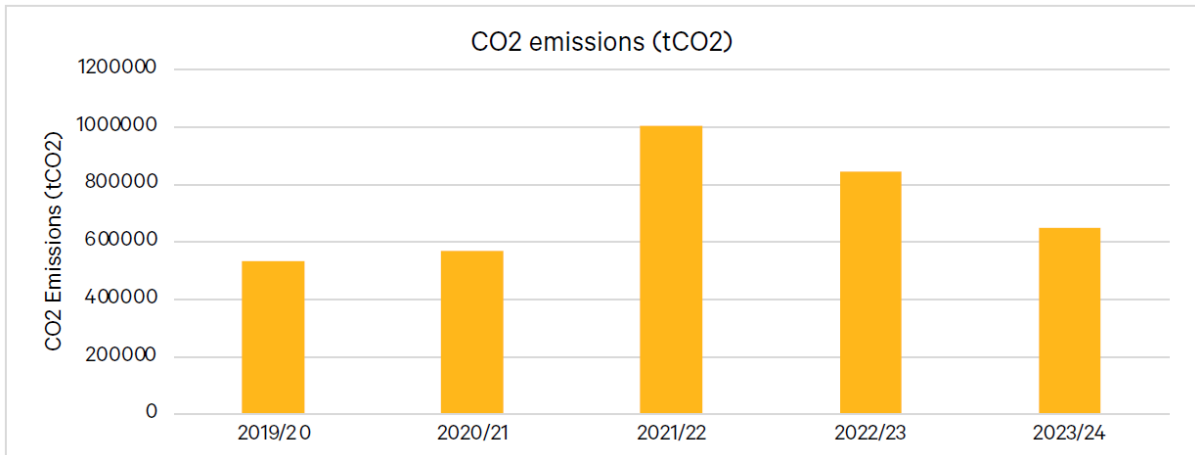


Figure 4. 2: A Trend in CO2 Emissions from Electricity Generation

4.3.7 Thermal electricity supply Data

Kenya has an installed thermal capacity of 636.1 MW, comprising 512.8 MW from medium-speed diesel and 60 MW from gas turbines, 21.3 MW of captive capacity, and 42 MW of off-grid capacity. These thermal energy resources are used to meet peak demand, support voltage stability, and address the intermittency of variable renewable energy sources. For the 2023/24 review period, 1,127.11 GWh of energy was generated from thermal sources, accounting for 8.24% of Kenya’s total energy demand. As shown in Figure 4.3, the highest thermal energy generation occurred in October 2023, at 140.57 GWh.

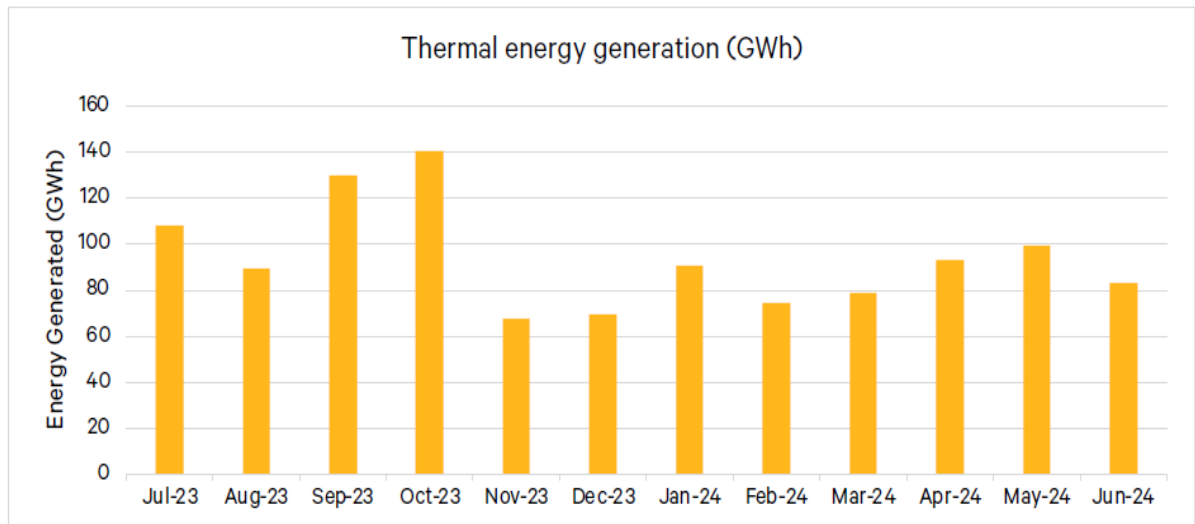


Figure 4. 3: Monthly Thermal Energy Generation during the Financial Year 2023/2024

Mombasa County is currently served by two major thermal power plants, Kipevu II and Rabai Plants. These plants provide electricity to this region exclusively. The generation data below highlights electricity generation figures across different months (June to September) in

terms of daytime and nighttime totals in the coastal region, focusing on contributions from Rabai Power Limited (132 MW), Kipevu P3 (Kengen), and other sources. It shows significant variations in generation, with total outputs ranging from approximately 33,000 MW to over 39,000 MW during the day and night. Additionally, the total kilowatt-hours (Kwhr) consistently exceeded 800 million, emphasizing high energy demand and production from thermal power sources in this region.

Using Table 4.6, the total average thermal power generation and supply for nighttime consumption in the coastal region from Kipevu, Rabai, and other sources is calculated by taking the average from June to September and multiplying by 12 to estimate the annual supply.

$$Total\ Average\ night\ time\ Thermal\ Power = \left(\frac{Sum(June:September)}{4} \right) \times 12 \dots\dots\dots 5$$

$$Total\ Average\ Thermal\ Power = 5,101.5\ MWh\ annually$$

To calculate the percentage of electricity consumed from thermal sources supplied at night against the overall nighttime street lighting demand in the coastal region, we divide the thermal power supply by the total street lighting demand and multiply by 100.

$$Percentage\ from\ Thermal\ Sources = \frac{Night\ Thermal\ Power\ Supply}{Overall\ Street\ Lighting\ Demand} \times 100 \dots\dots\dots 6$$

$$Percentage\ from\ Thermal\ Sources = \frac{5.1}{9.2} \times 100 = 55.4\%$$

Table 4. 5: Thermal Data

					TOTAL
		RABA Power	KDP3	TOTALS	MONTHLY
Month		Limited	MW (Kengen) MW	MW	KWHR
Day time		20,960	12,404	33,363	400,357,803
Totals	June			-	-
Nighttime		16,703	15,384	32,087	385,047,539
e Totals				-	-
Day time	July	23,958	14,455	38,414	460,963,012
Totals					-
Nighttime		18,958	20,464	39,422	473,067,165
e Totals				-	-
Day time	August	20,312	18,820	39,132	469,580,938
Totals					-
Nighttime		16,795	19,183	35,978	431,735,774
e Totals				-	-
Day time	September	19,782	16,119	35,901	430,812,873
Totals					-
Nighttime		16,219	18,001	34,220	410,644,022
e Totals				-	-

Table 4.7 analyzes electricity consumption across various roads and areas, detailing the number of street lighting poles, lamp wattage, lighting hours, and resulting annual electricity consumption (in kilowatt-hours, kWh). From the table, the road with the highest electricity consumption is Mombasa Island, with 6,000 poles and an annual consumption of 3,679,200 kWh. Other areas, such as Nyali Mtwapa Road and Mtwapa Kilifi Malindi Road, also demonstrate considerable consumption, with annual values of 451,315.2 kWh and 502,824 kWh, respectively. In contrast, regions like Likoni Diani Road and Lamu Township show much lower electricity usage, with annual consumption of 115,281.6 kWh and 257,544 kWh, respectively. The total annual electricity consumption for all the listed roads and areas is 9,256,254 kWh, indicating a significant overall demand for street lighting in the coastal region.

Table 4. 6: Selected Roads and Areas for Electricity Consumption Analysis

	Road identity	No of Lamp poles	Lamp wattage (w)	Lighting hours	Annual consumption (Kwhr)
1	Moi International Airport Access and Port Reitz Road	444	150	12	272260.8
2	Nyali Mtwapa road	736	150	12	451315.2
3	Lamu Link Road	552	150	12	338486.4
4	Mombasa island	6,000	150	12	3679200
5	Kibundani Likoni interchange	450	150	12	275940
6	Mtwapa Kilifi Malindi road	820	150	12	502824
7	Dongo Kundu road	495	150	12	303534
8	Likoni Diani road	188	150	12	115281.6
9	Kilifi township	800	150	12	490560
10	Malindi township	1560	150	12	956592
11	Lamu township	420	150	12	257544
12	Port Ritz Miritini Interchange Road	2008	150	12	1319256
13	Diani township	460	150	12	282072
14	Makupa Changamwe Miritini township	1125	150	12	689850
	Total	15095			9256254

Emission factors per region are calculated mostly annually based on the country’s energy mix. Based on the Adame Base Carbone emission factor database v.11.0, 1 for Kenya, Kwh emits 0.278kg of CO2.

Considering the subsector for street lighting alone, the GHG emission is modeled as below:

$$GHG\ lighting = E \times EF \dots\dots\dots 7$$

Where:

E = Electricity consumption by street lighting (kWh)

EF = Emission factor of the electricity grid (kg CO₂e/kWh)

The annual electricity consumption for street lighting in the selected project is taken from equation 6 as **1,319,256 Kwhr**.

Therefore, carbon emissions due to Lighting for the Mombasa southern bypass will be annually calculated as:

$$GHG_{lighting} = 1,319,256 \times 0.275 = 362,795 \text{ kg CO}_2\text{e/year} (= 395.8 \text{ metric tonnes CO}_2\text{e/year})$$

Annual Electricity consumption data from Kenya Power and Lighting places the entire coastal region at 9.2 GWH for street lighting alone.

Using the same model, therefore GHG emissions due to lighting in the coastal region will be:

$$GHG = 9.2 \times 1000000 \times 0.275 = 2,530,000 \text{ kg CO}_2\text{e/year} (2,530 \text{ metric tonnes CO}_2\text{e/year}).$$

Street lighting in Kenya consumes 103GWH for the period ending 2023/24.

Using the same model, the GHG emissions due from street lighting countrywide will be:

$$GHG = 103 \times 1000000 \times 0.275 = 28,840,000 \text{ kg CO}_2\text{e/year} (28,840 \text{ metric tonnes of CO}_2\text{e/year}).$$

Kenya's overall carbon emissions values are **652,857 TCO₂e/year** per the EPRA report ending 2023/24.

The percentage of street lighting emissions due on the Mombasa southern bypass will be given as:

$$GHG \text{ emissions-MPARD 1} = \text{emissions on MPARD 1} \div \text{total country emissions} \dots \dots \dots 8$$

$$= 2530 \div 652857 = 0.4\%.$$

$$GHG \text{ emissions due to street lighting countrywide} = 28,840 \div 652,857$$

$$= 4.4\%.$$

Future street lighting expansion plans will increase consumption by up to **155GWH**.

$$\text{The Emissions due to this expansion} = 43,400 \text{ Tco}_2\text{e/year}.$$

Overall emissions growth = 6.6%.

The Mombasa southern bypass emits 2475 metric tonnes of CO₂e, contributing 0.4% of the country's overall carbon emissions. On a national scale, streetlights' annual consumption of 103,00,000 Kwhr emits an equivalent amount of carbon of 28,840 T of CO₂e. This represents 4.4% of the overall carbon emissions due to electricity consumption in the country, which stands at 652,285.2 C02 in the consumption period of 2023/24. When the current mix is maintained, with the expected streetlighting expansion to 195,000 units and 155GWHS annual consumption, the CO₂ emissions will increase by 50% to 43,400, with an overall national contribution rising to 6.6% due to street lighting.

4.4 Feasibility and Potential Benefits of Solar Street Lighting

The study's second objective was to analyze the feasibility and potential benefits of solar street lighting in urban areas.

4.4.1 Solar Energy Potential

The weather data for the last 10 years at the coastal area location has been analyzed to determine the energy generation from the sun. This was done using the simulation software PVSYST (photovoltaic (PV) system SYST) and HOMER (Hybrid Optimization of Multiple Electric Renewables). The analysis includes both the irradiation and night length by month. The average annual irradiation at the location is 5.5 kWh/m² daily. The night length varies, around 11.7 to 12 hours throughout the year. This data ensures sufficient sunlight during the day to generate the required energy for consistent lighting, accounting for the varying night lengths and irradiation levels across different months. Generally, the country's average annual irradiation data is calculated at 4.2kWh/m².day affirming the solar energy potential for street lighting powering countrywide.

Case study location: Latitude Longitude (-4.00263; 39.57015)

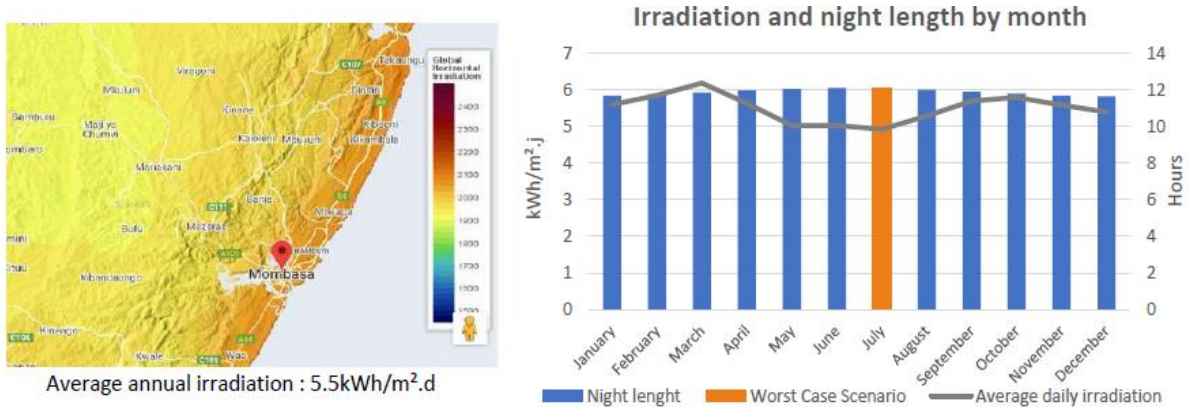


Figure 4. 4: Solar Energy Potential

4.4.2 Quality of the Lighting

The photometric analysis of the lighting system covers various road sections categorized based on their functional requirements and design standards. These include road category, width and median specifications, widths, and lengths tailored to ensure safe and efficient lighting. The installation features pole types and layouts optimized for uniform light distribution, with specified inter-distances between poles. Lux levels are designed to ensure adequate illumination, while uniformity values confirm consistent lighting across the road surface, adhering to regulatory and safety standards.

The models below have been used to calculate the lux levels and uniformity per road section, determining the width and length of the same with customized sections for interchanges,

$$E=F/A.....8$$

where:

E= lux or illumination defined as light quantity per square area

F=luminous flux

A= surface area of illumination.

Similarly, pole spacing formulae are given as:

$$Spacing =(F \times Q \times CU \times M \times U) \div (E \times W)9$$

Where:

F =luminous flux

Q =number of lamps

CU =coefficient of illumination

M =maintenance factor of illumination

U =uniformity index of light distribution

E =lux

W = Road width.

Uniformity U_0 is the ratio of maximum to minimum illumination on the road surface and measures how evenly light is distributed in an area.

Employing the EN13201 standards and using dialux and radiance modeling software on CAD-based drawings that employ the above models, the entire 38km Mombasa Southern Bypass lighting parameters were calculated, and the photometric analysis carried out to determine the equivalent solar street lighting equipment that can suitably replace the conventional lighting fixtures. Below are the results in Table 4.8.

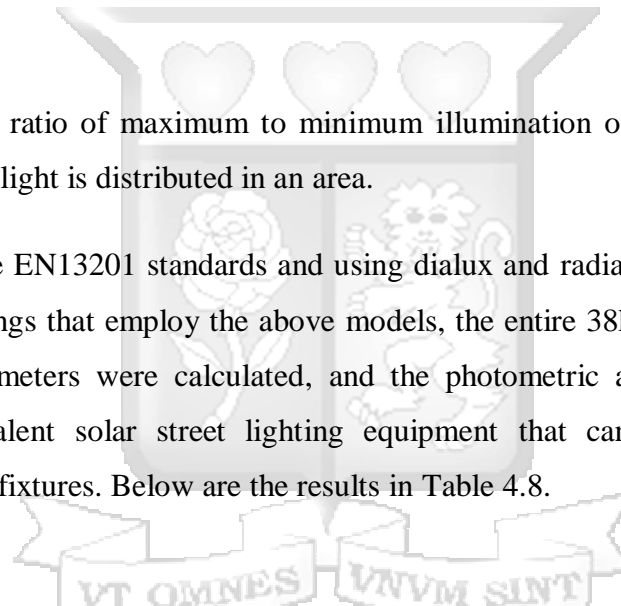


Table 4. 7: Photometric Calculation for Mombasa Southern bypass (Port Ritz Miritini).

Road sections	Road category	Road width	Median	Road width	Road length (m)	Layout	Interdistance	Lux level	Uniformity
(-0+300 to -0+100)	A	2x3,5	2	2x3,5	200	On the median	40	16.8 5	0.41
-0+100 to 0+82	B	3x3,5	2	3x3,5	182	On the median	40	18.9 2	0.4
Loop - let	C	3.5	4.5	3.5	500	Both sides, opposite	40	16.5 6	0.4
Loop - right	C	3.5	4.5	3.5	600	Both sides, opposite	40	16.5 6	0.4
1+300 right to 1+200	A	2x3,5	2	2x3,5	100	On the median	40	16.8 5	0.41
1+200 to 1+100	B	3x3,5	2	3x3,5	100	On the median	40	18.9 2	0.4
1+100 to 0+900	D	2x3,5	2	3x3,5	200	On the median	40	18.9 2	0.4
0+900 to 0+800	B	3x3,5	2	3x3,5	100	On the median	40	18.9 2	0.4
0+800 to 0+700	D	2x3,5	2	3x3,5	100	On the median	40	18.9 2	0.4
				2x3,5 - 0,5 -			40		
0+700 to 0+600	E	3x3,5	2	2x3,5	100	On the median	40	20.1 1	0.4
0+600 to 0+500	D	2x3,5	2	3x3,5	100	On the median	40	18.9 2	0.4

							40		
0+500 to 0+300	B	3x3,5	2	3x3,5	200	On the median	40	18.9 2	0.4
							40		
				2x3,5 - 0,5 -			40		
0+300 to 0+100	F	3x3,5	2	3x3,5	200	On the median	40	13.1 1	0.4
							40		
0+100 to 0+00	G	3x3,5	2	4x3,5	100	On the median	40	14.1 7	0.42
0+000 to 0+400 right	H	4x2,5			400	One side	40	13.1 9	0.44
0+000 to 0+400 left	H	4x2,5			400	One side	40	13.1 9	0.44
0+000 to 1+100	I	2x4			100	One side	40	13.1 3	0.57
0+000 to 0+400 right	C	3.5	4.5	3.5	400	Both sides, opposite	40	16.5 6	0.4
						e	40		
0+500 to 0+000 right	C	3.5	4.5	3.5	500	Both sides, opposite	40	16.5 6	0.4
						e	40		
0+000 to 0+400 left	C	3.5	4.5	3.5	400	Both sides, opposite	40	16.5 6	0.4
						e	40		
0+500 to 0+000 left	C	3.5	4.5	3.5	500	Both sides, opposite	40	16.5 6	0.4
						e	40		
0+700 o 0+400	J	4x3,5			300	Both sides, stagger	40	15.1 2	0.4
						ed	40		
0+500 to 0+400	J	4x3,5			100	Both sides, stagger	40	15.1 2	0.4
						ed	40		
0+400 to 0+250	D	2x3,5	2	3x3,5	150	On the median	40	18.9 2	0.4
							40		

0+250 to 0+000	K	3,5 - 0,5 - 3,5	2	3x3,5	250	On the median	40	16.8 3	0.72
							40		
3+700 to 3+800	A	2x3,5	2	2x3,5	100	On the median	40	16.8 5	0.41
							40		
3+800 to 3+900	L	3.5	2	2x3,5	100	On the median	40	16.8 5	0.41
							40		
				2x3,5 - 0,5 -			40		
3+900 to 4+000	E	3x3,5	2	2x3,5	100	On the median	40	20.1 1	0.4
4+000 to 4+050	B	3x3,5	2	3x3,5	50	On the median	40	18.9 2	0.4
							40		
0+000 to 0+400	A	2x3,5	2	2x3,5	400	On the median	40	16.8 5	0.41
0+000 to 0+500	A	2x3,5	2	2x3,5	500	On the median	40	16.8 5	0.41
0+000 to0+400	M	2x3,5			400	One side	40	13.2 2	0.53
0+82 to 0+192	A	2x3,5	2	2x3,5	110	On the median	40	16.8 5	0.41
				2x3,5 - 0,5 -			40		
0+192 to 0+400	N	2x3,5 - 0,5 -	2	2x3,5	208	On the median	40	14.9 3	0.4
		2x3,5							
0+400 to 0+500	B	3x3,5	2	3x3,5	100	On the median	40	18.9 2	0.4
0+500 to 0+800	A	2x3,5	2	2x3,5	300	On the median	40	16.8 5	0.41
0+800 to 1+300	B	3x3,5	2	3x3,5	500	On the median	40	18.9 2	0.4
							40		
1+300 to	A	2x3,5	2	2x3,5	100	On the	40	16.8	0.41

1+400						median		5	
				2x3,5 - 0,5 -			40		
1+400 to 1+500	O	2x3,5	2	2x3,5	100	On the median	40	15.2 8	0.48
		2x3,5 - 0,5 -		2x3,5 - 0,5 -			40		
1+500 to 1+600	N	2x3,5	2	2x3,5	100	On the median		14.9 3	0.4
		1x3,5 - 0,5 -					40		
1+600 to 1+800	Q	1x3,5 - 0,5 -	2	3x3,5	200	On the median	40	14.4 5	0.44
		2x3,5							
		2x3,5 - 0,5 -					40		
1+800 to 2+700	E	2x3,5	2	3x3,5	900	On the median		20.1 1	0.4
2+700 to 3+050	B	3x3,5	2	3x3,5	350	On the median	40	18.9 2	0.4
							40		
3+050 to 3+100	G	3x3,5	2	4x3,5	50	On the median		14.1 7	0.42
							40		
3+100 to 3+200	R	3x3,5	2	5x3,5	100	On the median		17.5 6	0.42
3+200 to 3+250	D	3x3,5	2	2x3,5	50	On the median	40	18.9 2	0.4
							40		
3+250 to 3+300	P	4x3,5	2	2x3,5	50	On the median		16.0 2	0.43
							40		
3+300 to 3+400	R	5x3,5	2	3x3,5	100	On the median		17.5 6	0.42
		3x3,5 - 0,5 -					40		

3+400 to 3+500	F	2x3,5	2	3x3,5	100	On the median		15.1 8	0.54
3+500 to 3+600	A	2x3,5	2	2x3,5	100	On the median	40	16.8 5	0.41
		2x3,5 - 0,5 -					40		
3+600 to 3+800	E	2x3,5	2	3x3,5	200	On the median		20.1 1	0.4
3+800 to 4+000	B	3x3,5	2	3x3,5	200	On the median	40	18.9 2	0.4
4+000 to 4+200	D	3x3,5	2	2x3,5	200	On the median	40	18.9 2	0.4
4+200 to 4+400	B	3x3,5	2	3x3,5	200	On the median	40	18.9 2	0.4
4+400 to 4+700	A	2x3,5	2	2x3,5	300	On the median	40	16.8 5	0.41
4+700 to 5+350	B	3x3,5	2	3x3,5	650	On the median	40	18.9 2	0.4
0+000 to 0+400	S	3.5	2	3.5	400	On the median	40	19.6	0.4
							40		
0+400 to 0+000	S		2	3.5	400	On the median	40	19.6	0.4
		3.5					40		
0+000 to 0+400	S		2	3.5	400	On the median	40	19.6	0.4
		3.5							
0+400 to 0+000	S		2	3.5	400	On the median	42	19.6	0.4
		3.5							
Bridge 1	T	2x3,5			80	One side	33	15.1	0.67
Bridge 2	T	2x3,5			80	One side	33	15.1	0.67
		2x3,5 - 0,5 -							
5+350 to	O	2x3,5	2	2x3,5	50	On the	40	15.2	0.48

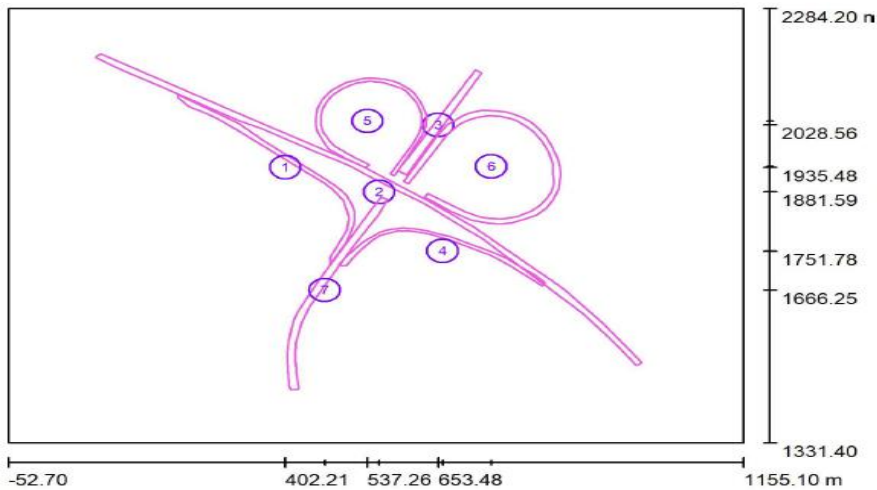
5+400						median		8	
		2x3,5 - 0,5 -		2x3,5 - 0,5 -					
5+400 to 5+500	N	2x3,5	2	2x3,5	100	On the median	46	14.9 3	0.4
5+500 to 5+650	U	2x3,5	3	2x3,5	150	On the median	40	15.8 6	0.41
5+650 to 5+700	U	2x3,5	3	3x3,5	50	On the median	40	15.8 6	0.41
5+700 to 5+750	D	2x3,5	2	3x3,5	50	On the median	40	18.9 2	0.4
5+750 to 7+200	B	3x3,5	3	3x3,5	1450	On the median	40	18.9 2	0.4
8+200 to 8+500	B	3x3,5	2	3x3,5	300	On the median	40	18.9 2	0.4
				2x3,5 - 0,5 -					
8+500 to 8+600	E	3x3,5	2	2x3,5	100	On the median	40	20.1 1	0.4
8+600 to 8+700	A	2x3,5	2	2x3,5	100	On the median	40	16.8 5	0.41
8+700 to 9+100	B	3x3,5	2	3x3,5	400	On the median	40	18.9 2	0.4
0+000 to 0+300	S		2	3.5	300	On the median	40	19.6	0.4
		3.5							
0+000 to 0+450	T	2x3,5			450	One side	40	15.1	0.67
Bridge 3	T	2x3,5			80	One side	40	15.1	0.67
1+300 to 0+000	T	2x3,5			700	One side	40	15.1	0.67
-0+173 to 0+500	U	2x3,5	3	2x3,5	673	On the median	40	15.8 6	0.41

0+000 to 0+300	W	4.5			300	One side	40	13.1 7	0.45
0+500 to 0+000	W	4.5			500	One side	40	13.1 7	0.45
0+100 to 0+300 drop	V	2x5			200	Both sides,	40	15.1 1	0.59
0+500 to 0+600	U	2x3,5	3	2x3,5	100	On the median	40	15.8 6	0.41
9+100 to 9+200	A	2x3,5	2	2x3,5	100	On the median	40	16.8 5	0.41
				2x3,5 - 0,5 -					
9+200 to 9+400	O	2x3,5	2	2x3,5	200	On the median	40	15.2 8	0.48
9+400 to 10+000	A	2x3,5	2	2x3,5	600	On the median	40	16.8 5	0.41
				2x3,5 - 0,5 -					
10+000 to 10+050	E	3x3,5	2	2x3,5	50	On the median	40	20.1 1	0.4
10+050 to 10+200	B	3x3,5	2	3x3,5	150	On the median	40	18.9 2	0.4

Miritini Interchange / Planning data Luminaire Parts List

This table provides the total luminaire power and luminous flux of the street lighting setup.

No.	Pieces	Designation (Correction Factor)	LED Street (Luminaire) [lm]	Lamps [lm]	Power (P) [W]
1	166	Lights 1107 implantation (Type 1)× (1.000)	10,980	10,980	61
Total			1,822,680	1,822,680	10,126.00



Scale 1 : 10842

Miritini Interchange / Calculation surfaces

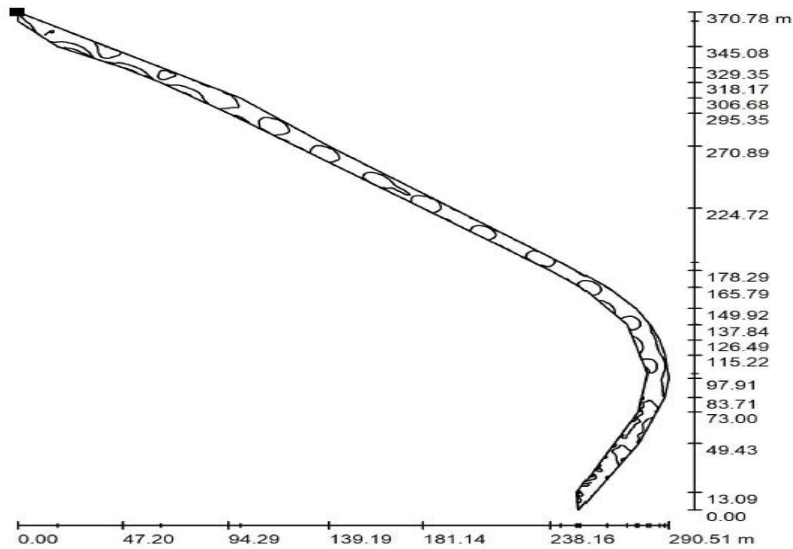
Calculation Surface List

This table presents the average illuminance (Eav), minimum illuminance (Emin), maximum illuminance (Emax), and uniformity (u0) values for each specified road section.

No.	Designation	Type Grid	Eav [lx]	Emin [lx]	Emax [lx]	u0 (Uniformity)	Emin / Emax
1	Entry at 0+200 from bridge perpendicular	128 x 128	15	6.86	24	0.455	0.289
2	Bridge perpendicular	128 x 128	20	8.06	40	0.412	0.202
3	0+000 to -0+300 perpendicular	128 x 128	20	8.09	41	0.404	0.198
4	Exit at 0+200 towards bridge perpendicular	128 x 128	169.07	32	0.566	0.286	
5	Exit from bridge at -0+100 perpendicular	128 x 128	158.59	24	0.557	0.359	
6	Entry from bridge at -0+100 perpendicular	128 x 128	156.24	22	0.428	0.289	
7	0+000 to 0+500 perpendicular	128 x 128	187.57	39	0.409	0.193	

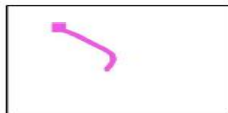
Summary of Results

Type	Quantity	Average [lx]	Min [lx]	Max [lx]	u0	Emin / Emax
perpendicular	7	17	6.24	41	0.36	0.15



Values in Lux, Scale 1 : 2900

Position of surface in external scene:
Marked point:
(225.939 m, 2095.291 m, 0.000 m)

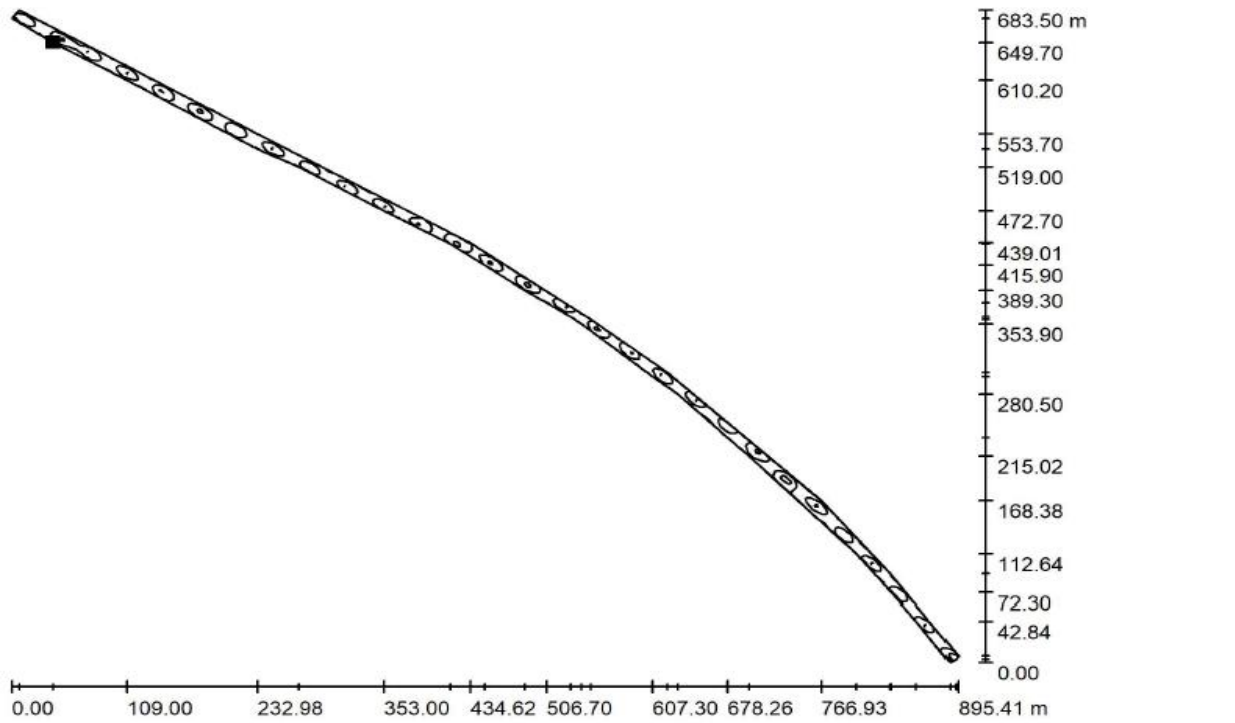


Miritini Interchange / Entry at 0+200 from bridge / Isolines (E, Perpendicular)

This table represents the average illuminance (E_{av}), minimum illuminance (E_{min}), maximum illuminance (E_{max}), uniformity (u_0), and the ratio of E_{min} / E_{max} .

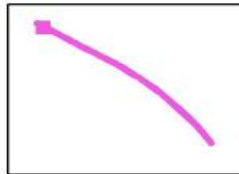
E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u_0	E_{min} / E_{max}
15	6.86	24	0.455	0.289

Miritini Interchange / Bridge / Isolines (E, Perpendicular)



Values in Lux, Scale 1 : 6402

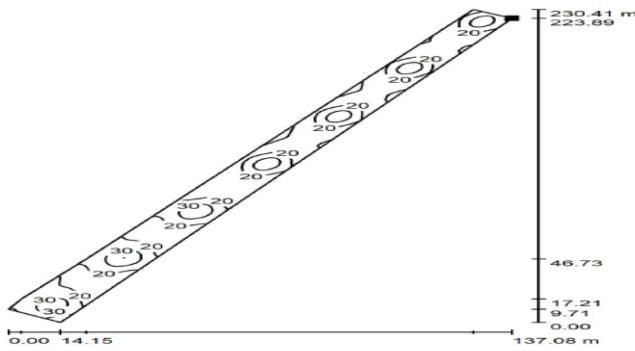
Position of surface in external scene:
Marked point:
(130.700 m, 2151.000 m, 0.000 m)



Grid: 128 x 128 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
20	8.06	40	0.412	0.202

Miritini Interchange / 0+000 to -0+300 / Isolines (E, Perpendicular)



Position of surface in external scene:
Marked point:
(724.698 m, 2142.684 m, 0.000 m)

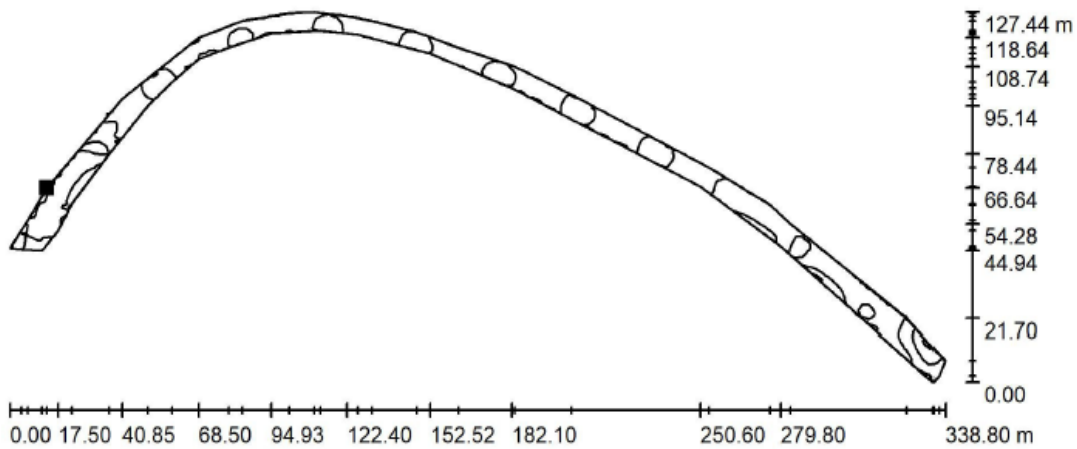


Values in Lux, Scale 1 : 1802

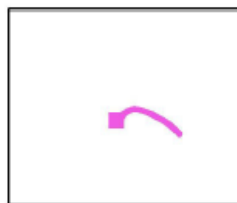
Grid: 128 x 128 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	$u0$	E_{min} / E_{max}
20	8.09	41	0.404	0.198

Miritini Interchange / Exit at 0+200 towards bridge / Isolines (E, Perpendicular)



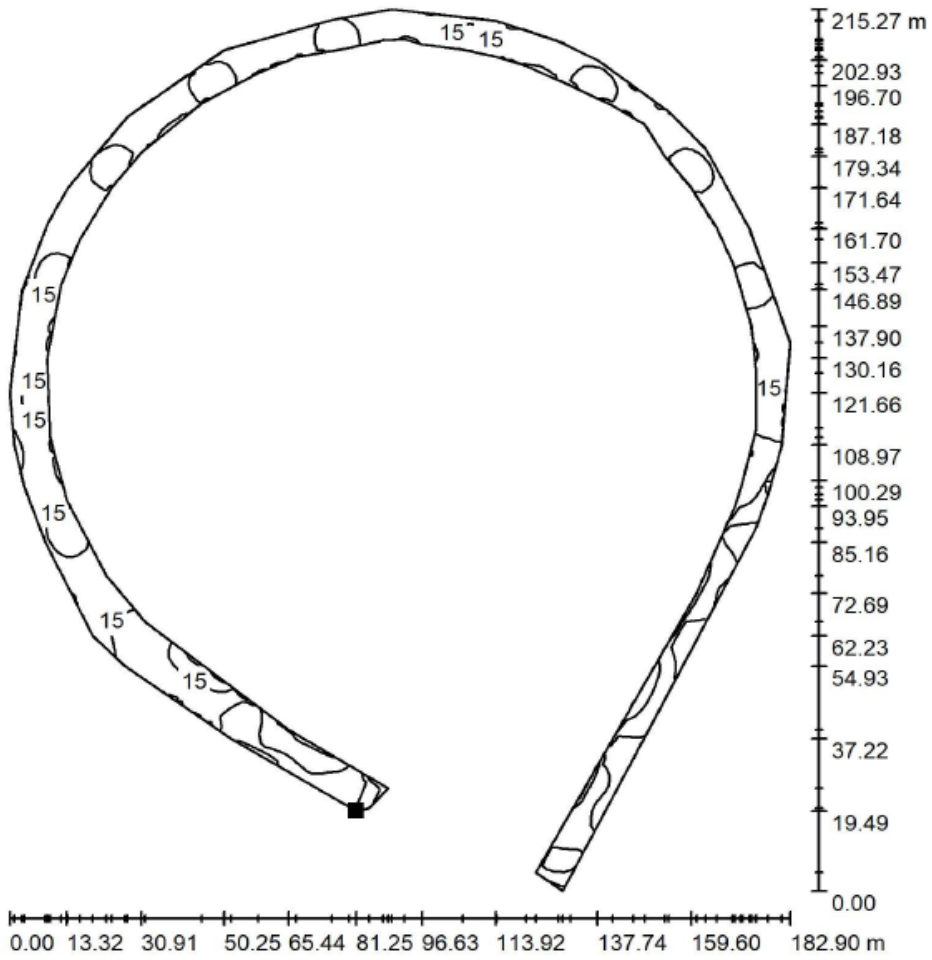
Position of surface in external scene:
Marked point:
(503.100 m, 1741.700 m, 0.000 m)



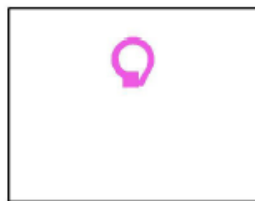
Values in Lux, Scale 1 : 2423

Grid: 128 x 128 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	$u0$	E_{min} / E_{max}
16	9.07	32	0.566	0.286



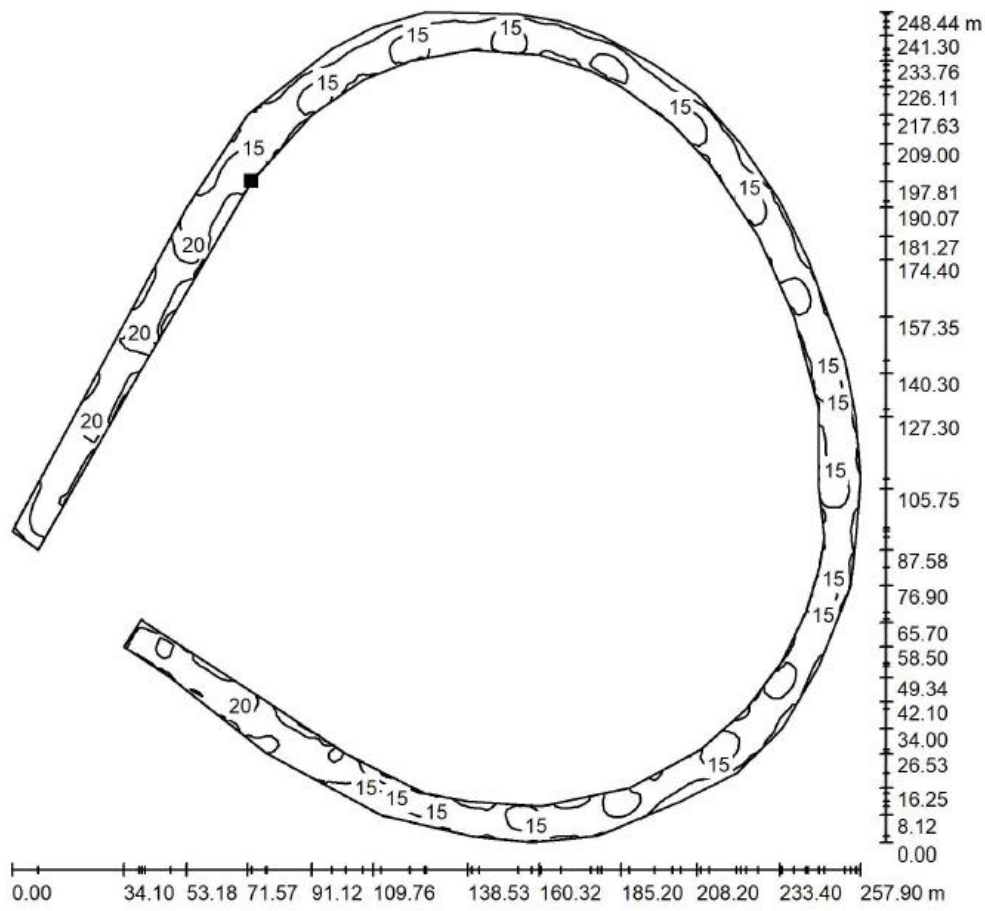
Position of surface in external scene:
 Marked point:
 (532.774 m, 1936.116 m, 0.000 m)



Grid: 128 x 128 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u_0	E_{min} / E_{max}
15	8.59	24	0.557	0.359

Miritini Interchange / Entry from bridge at -0+100 / Isolines (E, Perpendicular)



Values in Lux, Scale 1 : 1943

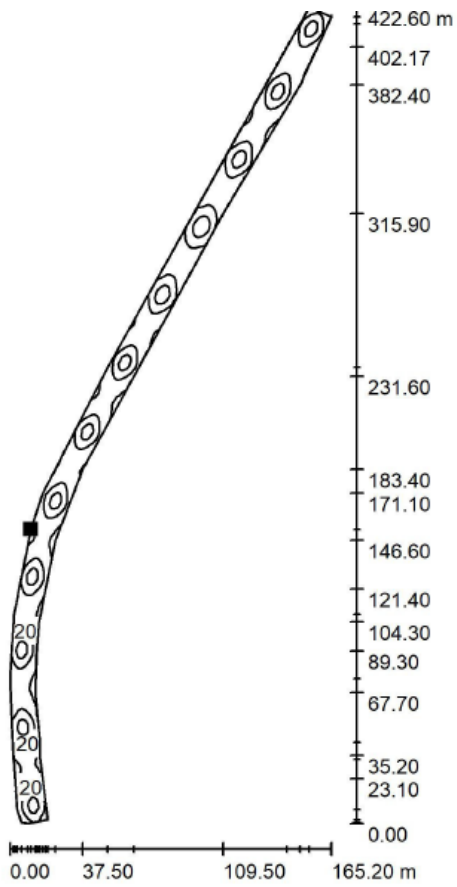
Position of surface in external scene:
 Marked point:
 (669.362 m, 2009.514 m, 0.000 m)



Grid: 128 x 128 Points

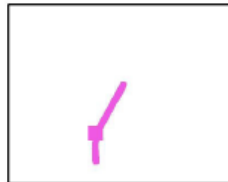
E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
15	6.24	22	0.428	0.289

Miritini Interchange / 0+000 to 0+500 / Isolines (E, Perpendicular)



Values in Lux, Scale 1 : 3305

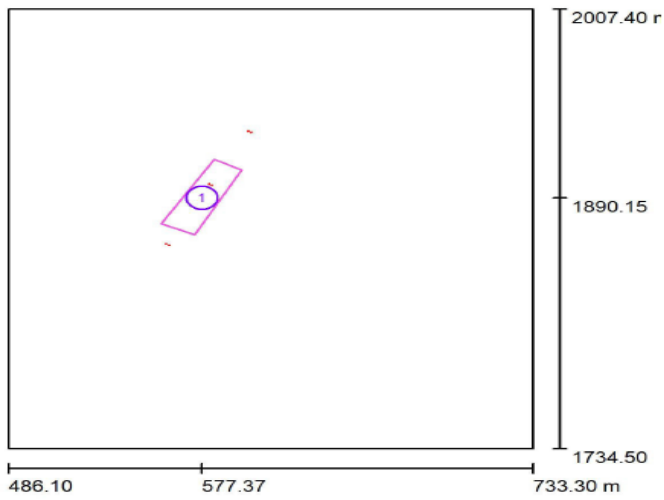
Position of surface in external scene:
Marked point:
(415.900 m, 1600.100 m, 0.000 m)



Grid: 128 x 128 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
18	7.57	39	0.409	0.193

Below The Bridge / Calculation surfaces (results overview)

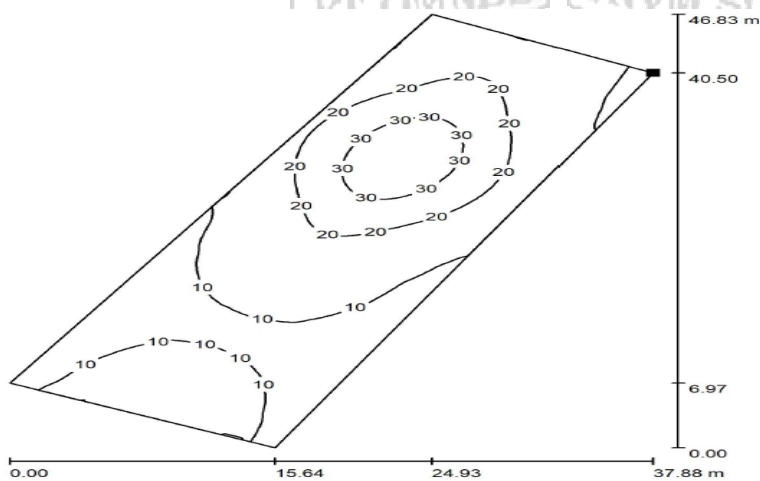


Scale 1 : 3106

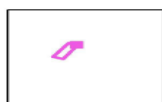
Calculation Surface List

No.	Designation	Type	Grid	Eav [lx]	Emin [lx]	Emax [lx]	u0	Emin / Emax
1	0+000 below the bridge	perpendicular	128 x 128	16	6.25	37	0.399	0.17

Below The Bridge / 0+000 below the bridge / Isolines (E, Perpendicular)



Position of surface in external scene:
Marked point:
(595.982 m, 1907.631 m, 0.000 m)

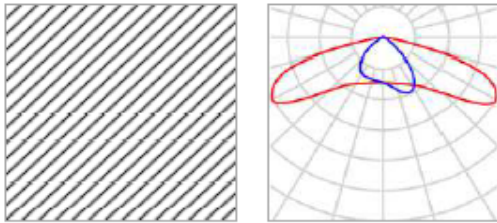


Values in Lux, Scale 1 : 367

Grid: 128 x 128 Points

E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	$u0$	E_{min} / E_{max}
16	6.25	37	0.399	0.170

Summary.

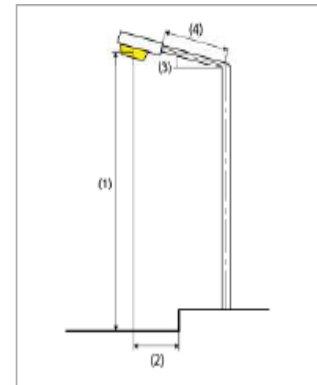


Article name	LED Street Lights 1107 route	P	61.0 W
Fitting	user-defined	Φ_{Lamp}	10980lm
		$\Phi_{Luminaire}$	10980 lm
		η	99.96 %



LED Street Lights 1107 route (Median, 2 per pole)

Pole distance	40.000 m
(1) Light spot height	11.0 m
(2) Light point overhang	-0.233 m
(3) Boom inclination	15.0°
(4) Boom length	0.781 m
Annual operating hours	4000 h: 100.0 %, 122.0 W
Consumption	2400.0 W/km
ULR / ULOR	0.02 / 0.01
Max. luminous intensities Any direction forming the specified angle from the downward vertical, with the luminaire installed for use.	$\geq 70^\circ$: 548 cd/klm $\geq 80^\circ$: 177 cd/klm $\geq 90^\circ$: 11.5 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.	G*1
Glare index class	D.4



Results for Valuation Fields

Symbol	Calculated Value	Target Value	Check
Carriage way2 (C4)	Eav: 16.85 lx	≥ 10.00 lx	✓
	Uo: 0.41	≥ 0.40	✓
Carriageway 1 (C4)	Eav: 16.85 lx	≥ 10.00 lx	✓
	Uo: 0.41	≥ 0.40	✓

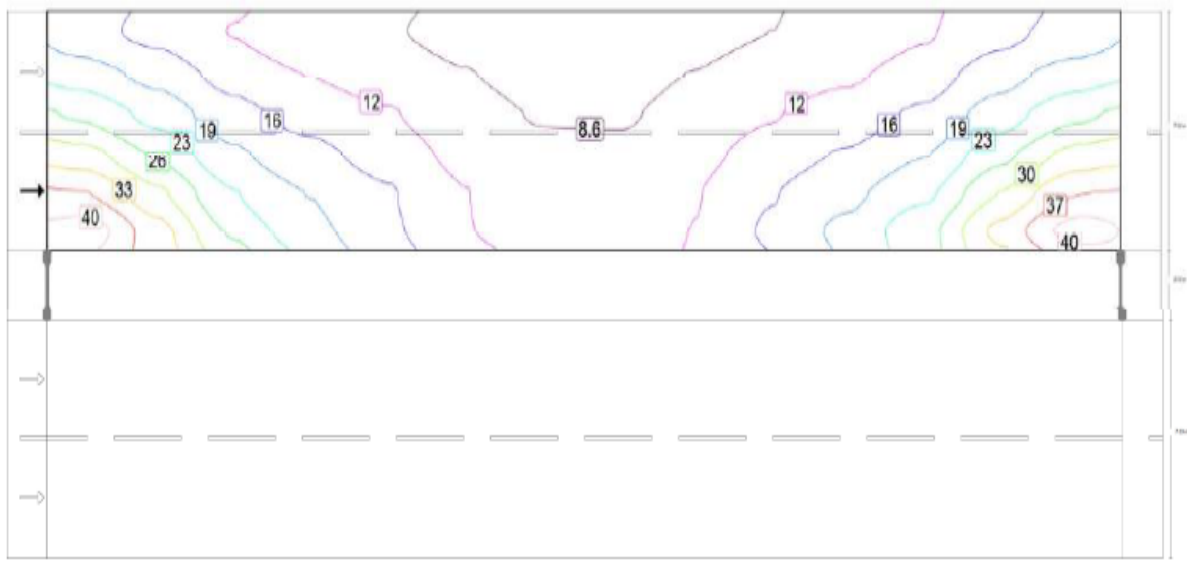
Results for Energy Efficiency Indicators

	Symbol	Calculated	Consumption
A	D _p	0.010 W/lx*m ²	-
LED Street Lights 1107 route (Median)			
	D _e	0.7 kWh/m ² yr,	384.0 kWh/yr

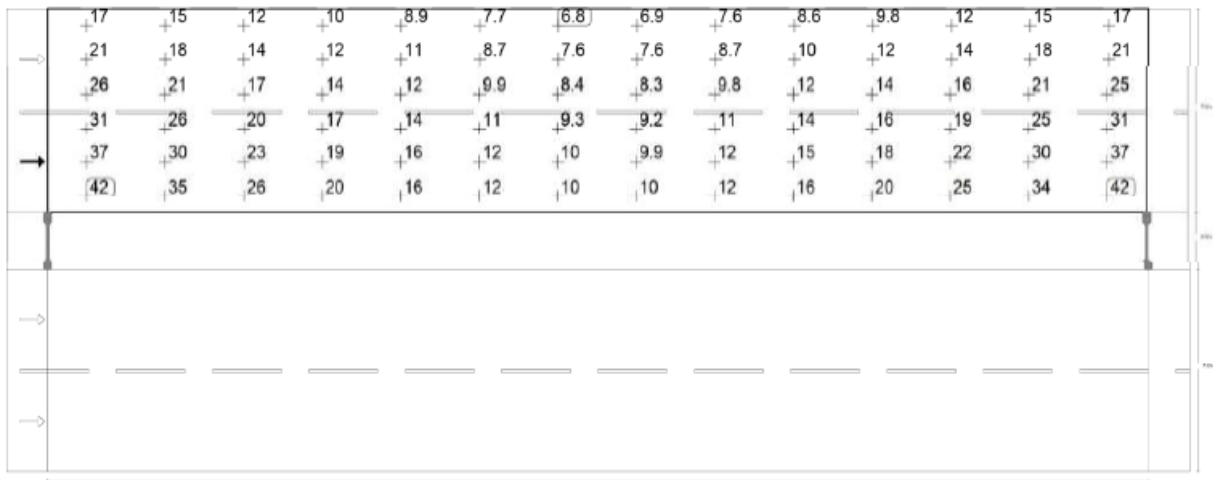
Carriageway 2 (C4)

Results for valuation field

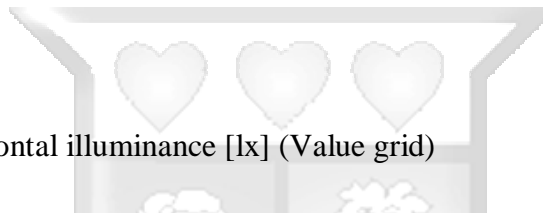
	Symbol	Calculated	Target	Check
Chaussée 2 (C4)	E _{av}	16.85 lx	≥ 10.00 lx	✓
	U ₀	0.41	≥ 0.40	✓



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



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



m	1.429	4.286	7.143	10.000	12.857	15.714	18.571	21.429	24.286	27.143	30.000	32.857	35.714	38.571	
	15.417	16.99	14.75	11.96	10.08	8.87	7.67	6.83	6.85	7.60	8.61	9.78	11.80	14.68	16.97

Carriageway 2 (C4)



m	1.429	4.286	7.143	10.000	12.857	15.714	18.571	21.429	24.286	27.143	30.000	32.857	35.714	38.571	
	14.250	20.98	17.92	14.20	11.97	10.51	8.74	7.63	7.62	8.68	10.13	11.52	13.85	17.74	20.89
	13.083	25.53	21.42	16.81	14.35	12.35	9.94	8.37	8.32	9.84	11.87	13.71	16.21	20.98	25.35
	11.917	31.02	25.55	19.75	16.72	14.12	11.12	9.27	9.19	10.97	13.61	15.95	18.97	25.12	30.91
	10.750	36.78	30.23	22.70	19.00	15.87	12.14	10.02	9.94	11.96	15.43	18.24	21.98	29.81	36.58
	9.583	41.95	34.54	25.55	20.49	16.43	12.36	10.17	10.12	12.22	16.15	20.00	25.02	34.25	41.92

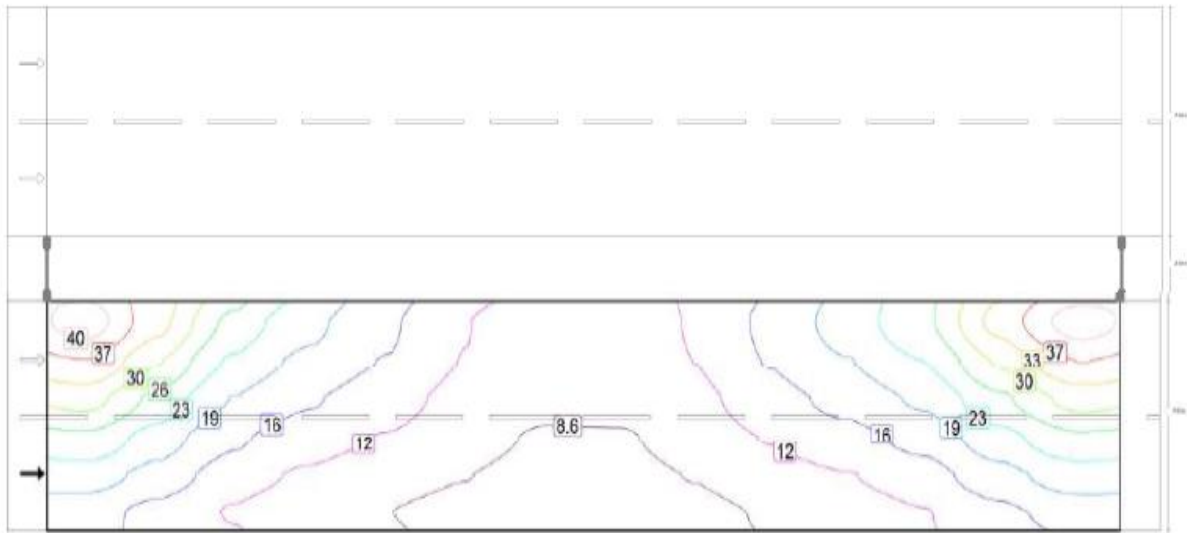
Maintenance value, horizontal illuminance [lx] (Value chart)

	E_{av}	E_{min}	E_{max}	g_1	g_2
Maintenance value, horizontal illuminance	16.8 lx	6.83 lx	42.0 lx	0.406	0.163

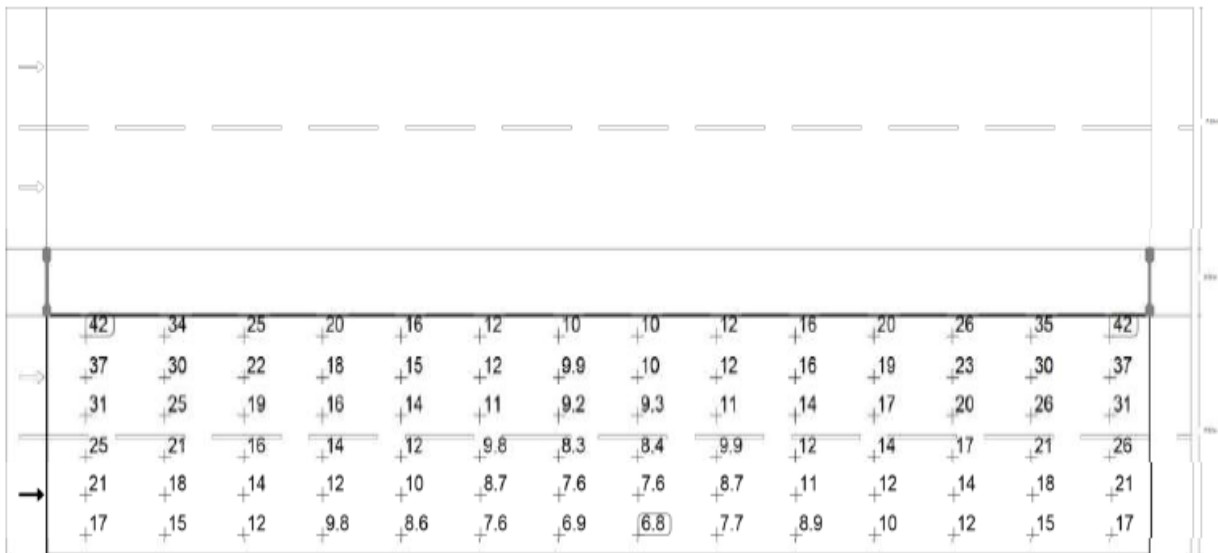
Carriageway 1 (C4)

Results for valuation field

	Symbol	Calculated	Target	Check
Chaussée 1 (C4)	E_{av}	16.85 lx	≥ 10.00 lx	✓
	U_0	0.41	≥ 0.40	✓



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



Summary of the calculations:

Based on EN 13201 lighting standards and using the below solar design parameters:

- I. 5.5 kWh/m² per day
- II. 15-20 lux lighting levels
- III. 40m interpole lighting distance
- IV. 11m lighting pole height
- V. 100% lighting levels throughout the night

The solar lighting equipment below is sufficient to replace the conventional lighting fixtures

- i. 270wp solar panel
- ii. 61w effective luminaire wattage
- iii. 1220-watt hour storage battery at 24VDC and 60% depth of discharge (DOD).

This is calculated as:

$$\text{Targeted standard lux} = 15 \text{ L/M}^2$$

$$\text{Area of lighting} = \text{road length} \times \text{road width} = L \times W \dots\dots\dots 10$$

$$40\text{m} \times 18\text{m} = 720\text{m}^2$$

The luminous flux for the area of study is expected between two lighting poles: therefore

$$\text{Area of lighting} \times \text{lux} \dots\dots\dots 11$$

$$720 \times 15 = 10,800 \text{ Lumens.}$$

For an LED specification of 192 lumens/watt

$$\text{The LED effective wattage} = \text{total lumens} / \text{efficiency} \dots\dots\dots 12$$

$$= (10,800/192) \times 10\% \text{ losses}$$

$$= 61\text{w.}$$

The 61 W LED lighting the whole night for 12 hours will consume electricity as per Equation

$$=61 \times 12$$

$$=732 \text{whrs.}$$

The depth of discharge required for such a system is up to 60%.

Therefore, for the battery size,

$$\text{The daily energy required for storage /DOD13}$$

$$=732 \div 0.6$$

$$=1220 \text{whr.}$$

The site receives a daily average irradiation of 5.27kwhrs/m².day

For solar panel sizing, the relationship factor is given below

$$\text{Solar panel sizing} = (\text{total energy required per day} / \text{daily average irradiation}) \times \text{efficiency factor14}$$

$$= (732 \div 5.5) \times 1.4$$

$$=200 \text{wp.}$$

Lowest irradiation values are recorded as 3.8kwh.m². d.

The ideal solar panel therefore will be given as per equation 14 as

$$= (732 \div 3.8) \times 1.4$$

$$=270 \text{wp}$$

4.4.3 Viability of the Investment

4.4.3.1 Solar Lighting vs Conventional Lighting

Solar lighting offers a cost-effective and efficient alternative to conventional lighting, being 25% less expensive overall. It significantly reduces installation time by up to 80%, eliminating the need for cables, trenching, and electrical cabinets. Moreover, solar streetlights are operational on the same day they are installed, providing immediate illumination and emphasizing their convenience and efficiency compared to traditional lighting systems. Below is the summary of the cost-benefits analysis table for the Mombasa southern bypass.

Table 4. 8: Costs Benefits Analysis

Description	Vote
Number of single light poles	336
Number of double-arm poles	305
Number of bridge and lighting fixtures	136
Number of light fixtures per single pole	1
Number of light fixtures per double arm poles	2
Luminaire power ratings	61w
No of substations	0
No of light fixtures	1086
Total power demand	66kw
Total monthly power consumption	23,760kwhrs
Total monthly bill costs	0
Power demand savings on the grid	100%
Power bills savings	100 %
Carbon emissions reduction	100%

The comparison between conventional and solar lighting investments over 1km of road lighting requirements reveals a significant cost difference, with solar lighting offering substantial savings in this case study. For conventional lighting, the total investment amounts to 10,285,000 KES, which includes expenses for power cables (6,800,000 KES), streetlight poles (2,030,000 KES), LED lights (870,000 KES), installation (435,000 KES), and an electrical cabinet (150,000 KES) and substations.

Investment conventional lighting			
Description	Qty	Price/U	TT
Power cable supply and installation	1 000	6 800 KES	6 800 000 KES
Pole streetlight supply	29	70 000 KES	2 030 000 KES
LED Light supply	29	30 000 KES	870 000 KES
Installation of conventional street lamps	29	15 000 KES	435 000 KES
Electrical cabinet supply and installation	1	150 000 KES	150 000 KES
Total			10 285 000 KES

Investment solar lighting			
Description	Qty	Price/U	TT
Power cable supply and installation	0	6 800 KES	0 KES
Pole solar streetlight supply	22	70 000 KES	1 540 000 KES
Solar lighting kit 275Wp 936Wh - supply	22	229 000 KES	5, 038 000 KES
Installation of solar street lamps	22	25 000 KES	550 000 KES
Electrical cabinet supply and installation	0	150 000 KES	0 KES
Total			7 128 000 KES

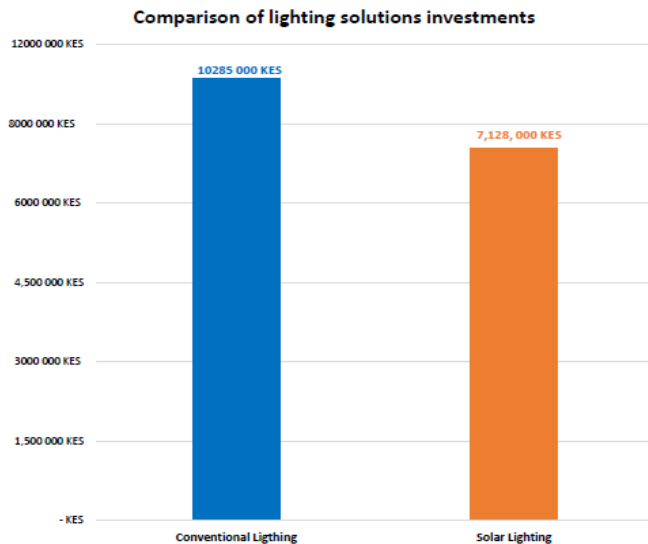


Figure 4. 5: Solar Lighting vs Conventional Lighting

In contrast, solar lighting requires no power cable installation and totals **7,128,000 KES**, covering costs for streetlight poles (1,540,000 KES), solar lighting kits (5,038,000 KES), and installation (550,000 KES). The solar lighting approach eliminates the need for an electrical cabinet, further reducing costs and presenting an environmentally friendly and economically advantageous solution.

Conventional Lighting

Solar lighting

Operating data		Operating data	
Power 29 LED lights – 150W	4350 W	Power 22 solar LED lights	0 W
Operating hours	1800 h	Operating hours	1800 h
Price per kWh	10.09 KES/KWh	Annual Consumption	0 kWh
Cost of annual consumption	192,245 KES/year	Price per kWh	10.09 KES/year
Cost of annual maintenance	2,407,755 KES/year	Cost of annual consumption	0 KES/year

Figure 4. 6: Annual comparison between Conventional and Solar Lighting ownership costs

Annually per km, the conventional street lighting for the Mombasa southern bypass requires an annual operation and maintenance cost of **kshs 2,407,755** compared to kshs 0 for annual operation and maintenance costs for solar over the same period. This trend is maintained for 10 years before the first operation and maintenance of solar street lighting. The significant costs for operation and maintenance are due to power bill payments (35%) and 65% on electrical and fixture replacements such as cables, drivers, and luminaires.

Comparison data from Kenya National Highways Authority (KeNHA) for similar roads shows the same trend of cost per km as below. The Authority introduced Performance-Based Contracts for road lighting in 2015 to enhance visibility to road users during inadequate natural lighting. The GoK funds the projects through the Road Maintenance Fuel Levy Fund (RMLF).

Table 4. 9: Cost of Road Lighting Maintenance

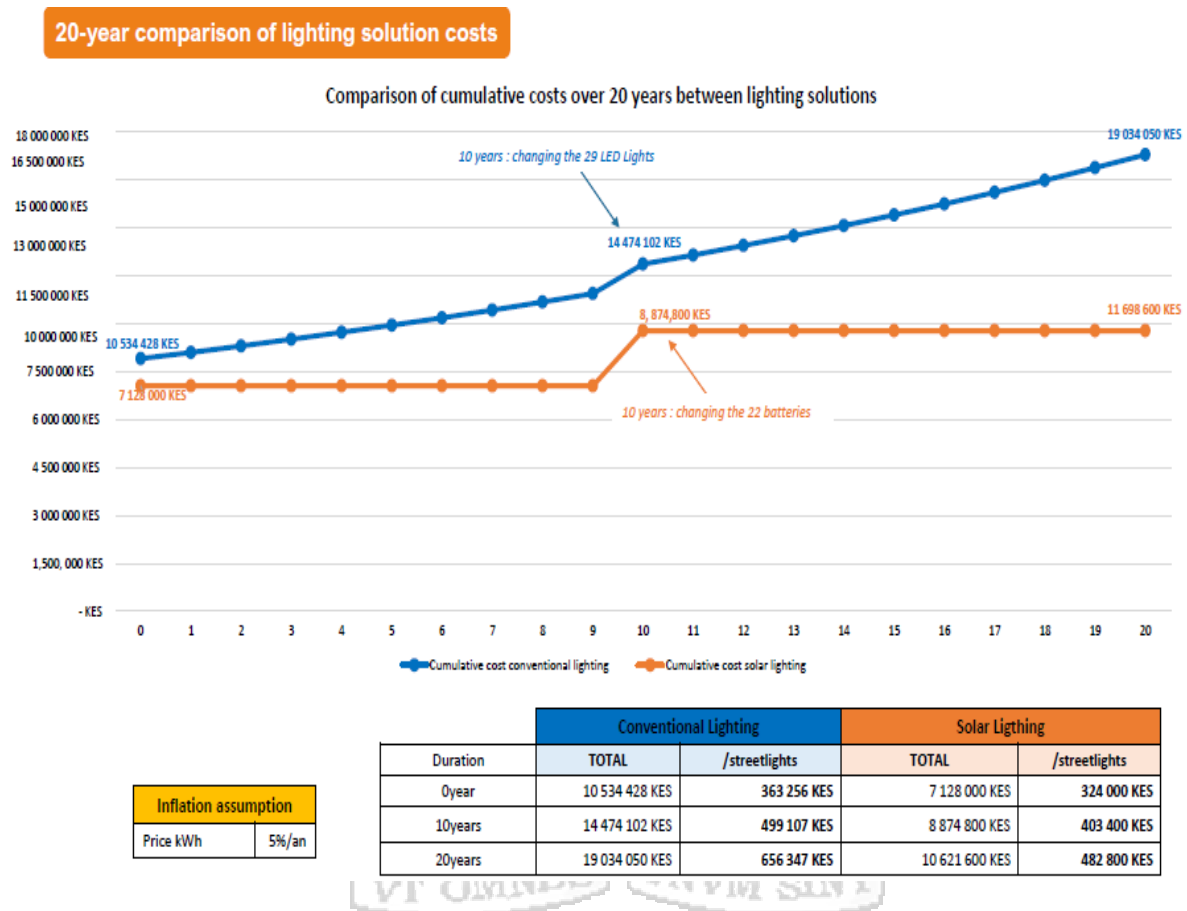
S. No.	Project Name	Contract Sum	Region	KM	COST PER KM
1	Thika Superhighway	598,101,809.20	Corridor C	45.10	13261680.91
2	Nairobi Southern Bypass	377,080,181.97	Corridor A	30.00	12569339.4
3	James Gichuru – Athi River (A8)	385,646,598.09	Corridor A	58.50	6592249.54
4	Athi River – Bisil (Kitengela)	168,761,599.53	Corridor A	29.80	5663140.924
5	Moi International Airport Access and Port Reitz Road	85,941,300.48	Coast	14.00	6138664.32
Total Cost of Road Lighting Maintenance		1,615,531,489.27			

Electricity bills payment constitutes 54% of the cost of the instructed works for Nairobi Southern Bypass, 40% of the instructed works for Thika superhighway, and 38% of the instructed works for James Gichuru – Athi River Interchange Road lighting projects. The current retail tariff for street lighting is Kshs. 9.24 per kWh according to the EPRA approved tariff 2023/2024, and the end user tariff amounts to Kshs. 17.56 per kWh. Road lighting is

metered for 12 hours every day. Similarly, the sustainability of the exact costs over 20 years for operation and maintenance of the two technologies are compared in Table 4.9 below.

4.4.3.2 20-year comparison of lighting solution costs

Table 4. 8: 20-year comparison of lighting solution costs



Overall, the chart shows that solar lighting has a significantly lower cumulative cost over 20 years than conventional lighting. The blue line represents the cumulative cost of conventional lighting. It starts at a higher initial cost and steadily increases over the years. This is due to ongoing energy consumption and maintenance costs associated with conventional lighting systems. The orange line represents the cumulative cost of solar lighting. It starts with a higher initial investment but remains relatively flat over the years. This suggests that the long-term operating and maintenance costs of solar lighting are much lower than conventional lighting. The chart demonstrates that while solar lighting may have a higher upfront cost, its long-term energy consumption and maintenance savings make it a more cost-effective solution over 20 years compared to conventional lighting.

4.4.4 Economic Benefits of Adopting Solar Street Lighting

The results highlight several potential economic benefits of adopting solar street on the Mombasa southern bypass. Costs of new installations are reduced by 25%, and the cost of operation is saved by 100% for the first 10 years. The solution frees over 3614kwhrs of grid power, enough to power 250 households daily, potentially increasing electricity access to Kenyans and revenue to Kenya power to kshs 45m, 300% more than lighting up the streets. Street lighting can free over 103GWH of electricity, potentially powering over 24,000 households or 600 light and medium industries, creating a better economy while tripling the earnings to Kenya power and lighting by kshs 3.2B.

4.4.5 Environmental Benefits of Adopting Solar Street Lighting

The key data indicates that solar street lighting offers significant environmental benefits by helping to reduce greenhouse gas emissions. 55.5 % of nighttime electricity is sourced from Kipevu and Rabai power plants for the southern bypass's coastal region. Street lighting by solar reduces the country's overall carbon footprint by 4.4%, significantly edging the country towards meeting the 2030 carbon footprint goals. Calculated from equation 8 where $\text{GHG emissions-MPARD 1} = \text{emissions on MPARD 1} \div \text{total country emission} = 0.4\%$. $\text{GHG emissions due to street lighting countrywide} = 28,840 \div 652,857 = 4.4\%$. Greenhouse effects related to challenges such as heat waves, prolonged drought, and floods, among others, will be minimized by this technology.

4.4.6 Social Benefits of Adopting Solar Street Lighting

The social benefits of solar street lighting regarding public safety and security are particularly evident. Solar street lighting improves safety by providing reliable illumination in urban spaces, significantly enhancing pedestrian and driver security at night through minimized power outages arising from unpaid bills or demand-related/system-enforced blackouts.

Similarly, natural calamities caused by greenhouse gas effects, such as plant and animal poisoning, respiratory-related diseases, destruction from prolonged droughts and flooding, fatigue and sudden deaths arising from heat waves, are minimized

4.5 Challenges and Barriers to Adopting Solar Street Lighting

The third objective of the study was to identify the challenges and barriers to adopting solar street lighting in Kenya.

4.5.1 Primary Barriers to Adopting Solar Street Lighting

The results reveal several significant barriers to adopting solar street lighting in Mombasa's Southern Bypass. High initial installation costs are the most prominent challenge, indicating that the upfront investment required for solar street lighting is a significant deterrent despite the long-term cost savings. The lack of technical expertise or training is a critical barrier, indicating that insufficient local knowledge and skilled labor could hinder the successful implementation and maintenance of solar systems. Another key obstacle recorded is inadequate infrastructure support, such as limited availability of solar technology locally, which could create logistical challenges and delay implementation.

Furthermore, Insufficient financing incentives or subsidies are a barrier, indicating that financial support to make solar street lighting more affordable is lacking. Public resistance or lack of awareness is a challenge, indicating that social or cultural factors may also affect the acceptance of solar technology in some communities.

The key informants support the findings and indicate that one of the primary challenges highlighted is the high initial capital cost of solar street lighting systems. County heads of the Department of Public Works emphasize that municipalities often struggle to secure the required financing for such capital-intensive projects. They also identified a gap in financial mechanisms that could help local governments manage the upfront costs based on the research outcomes; the chapter delivers concrete suggestions regarding the transition process to policymakers, urban planners, and stakeholders that the lack of tailored financial instruments for solar energy projects exacerbates the issue. In addition to funding constraints, technical barriers, such as the lack of skilled personnel for installation and maintenance, as indicated by the Head of Street Lighting Project at KENHA & KURA, hinder the widespread implementation of solar street lighting. Municipalities face difficulties securing financial resources and developing the technical capacity required to integrate solar lighting into urban infrastructure successfully.

Table 4. 9: Primary Barriers to Adopting Solar Street Lighting

	Frequency	Percent
High initial installation costs	91	95.8
Lack of technical expertise or training	85	89.5
Insufficient government incentives or subsidies	69	72.6
Public lack of awareness	41	43.2
Limited availability of solar technology locally	72	75.8
Inadequate infrastructure support (e.g., grid connections)	84	88.4

4.6 Impacts of Solar Street Lighting on Urban Energy Consumption and GHG Emissions Reduction

The fourth objective of the study was to estimate the impacts of solar street lighting on urban energy consumption and GHG emissions reduction in Kenya.

4.6.2 Estimated GHG Emissions Reduction from Solar Street Lighting

From equation 7, the coastal region receives up to 100MW of thermal power supply for 16 hours daily with a full nighttime of 12 hours supplied by the thermal from Kipevu III and Rabai diesel plants. This constitutes about 40% of the power demand in this region. Part of this supply powers the conventional streetlights, resulting in over 365 tonnes of carbon emissions for operating a 301KW power plant for a stretch of 38.km daily. This is in addition to further emissions from vehicular and maritime traffic.

As indicated by the KPLC Economic analysis report in Table 4.2, the total analysis of 9.2GWH of street lighting consumption at the coastal region for the year ending 2023/24 with over 5.2GWH supplied from the thermal power plants of Rabai and Kipevu, representing 55.5% of the overall energy mix at the coast. From GHG calculations on equation 7 and the analysis of tables 4.2, 4.6 and 4.7, installing solar streetlights in the coastal region saves over 2475T of CO₂e at the coastal region with a projected 6,679.8TCO₂e when the planned expansion is implemented. This is 15% of the carbon emissions in the coastal region. The contribution to environmental degradation is massive from this source of demand only.

Based on the Adame Base Carbone emission factor database v.11.0, countrywide, with an average emission factor of 0.278KgCoe/Kwhr at a current consumption of 103MWHrs for streetlighting and thermal energy mix supply at 17%, the streetlights contribute an annual carbon emission of 28,840TCO₂. This can be reduced to zero by installing solar streetlights,

reducing the overall emissions rate by a further 6.6% in the national emissions factor due to electricity generation.

4.6.3 Overall Impact of Solar Street Lighting on Energy Consumption

The country consumes an annual bill of 103GWH of electricity on street lighting, set to increase to 155GWH annually, should the planned expansion of coverage in major urban centres be implemented. From equation 8, Future Street lighting expansion plans will increase consumption by up to **155GWH**.

This power can be freed to power over 24,000 households, bringing electricity access to the population by another 3%. The same power can be used to power over 600 medium-scale hospitals, schools, and even hospitality centres, ensuring access to vital healthcare, education, and recreation for the community.

KENHA has recently implemented a street lighting solarization program on key roads of Mombasa Southern Bypass, Dongo Kundu Road, and Mombasa Airport Link Road, with overall results of zero bills for the last year compared to the rest of the roads under the grid.

Table 4.17: Estimated grid supply Reduction by Solar Street Lighting

S. No.	Project Name	Double Arm Poles	Single Arm Poles	High mast	Footbridge Lighting	Underpass Lighting	Average Monthly Electricity Bill
1.	Thika Superhighway	1,202	1,320	24	219	165	3,500,000.00
2.	Nairobi Southern Bypass	721	249	9	69	28	2,800,000.00
3.	James Gichuru – Athi River (A8)	190	1231	22	505	23	1,800,000.00
4.	Athi River – Bisil (Kitengela)	91	345	3	0	20	100,000.00
5.	Moi International Airport Access and Port Reitz Road	160	124	0	0	0	0
6.	Western Bypass	366	0	2	0	0	1,902,096.00
7.	Lamu Link Road	276	0	0	0	0	506,736.00

8.	MPARD PK 3	76	175	1	0	12	617,446.80
9.	MPARD PK 2	24	447	0	0	0	0
10.	MPARD PK 1	305	336	15	0	0	0
Total		3,933	3,269	76	793	248	11,226,278.80



Chapter Five: Discussions

The chapter discusses the findings of the study's aim of assessing the implementation and impact of solar street lighting on the decarbonization of urban road infrastructure in Kenya. Specifically, the study aimed to assess the status of street lighting infrastructure and its implication for urban GHG emissions in Kenya, analyze the feasibility and potential benefits of solar street lighting in urban areas, identify the challenges and barriers to adopting solar street lighting in Kenya as well as to estimate the impacts of solar street lighting on urban energy consumption and GHG emissions reduction in Kenya.

5.1 Status of Street Lighting Infrastructure and Urban GHG Emissions

The study found that between 2022 and 2023, there has been an increase in street lighting in Mombasa in terms of the number of streetlights and unit sales. In addition, there has been a steady increase in electricity usage for streetlights over the years, indicating an expanding coverage of street lighting infrastructure. This growth in lighting infrastructure is reflected in the increased electricity consumption across various roads and areas in Mombasa. For example, areas like Mombasa Island and Nyali-Mtwapa Road demonstrate significantly high electricity consumption, underscoring the substantial energy requirements for street lighting. This increase in electricity demand reflects the expanding street lighting infrastructure and the reliance on conventional energy sources to meet the growing needs.

Additionally, the study revealed that conventional street lighting, such as incandescent or fluorescent lights, is the most commonly used type in Mombasa City. This aligns with findings from Maina et al. (2022), who also pointed out the widespread use of conventional street lighting. However, the study shifted towards more energy-efficient and sustainable lighting solutions, including solar and LED lights. While the shift to solar and LED technologies is evident, it is still in its early stages, with conventional lights like High-Pressure Sodium (HPS) lamps being more prevalent in urban areas like Mombasa. This trend indicates a transition towards cleaner energy solutions, though challenges remain, particularly in replacing older lighting systems with more energy-efficient alternatives.

The study also highlighted the significant contribution of street lighting to urban greenhouse gas (GHG) emissions. Given the increasing reliance on conventional thermal power sources, transitioning to solar or LED lights could substantially reduce carbon emissions

and make urban infrastructure more sustainable. Solar street lighting was identified as a viable solution, especially in areas where lights are left on overnight, as seen in Mombasa's street lighting network. The study concluded that the high energy consumption of traditional street lighting systems, especially those powered by grid electricity, contributes significantly to GHG emissions and light pollution in Mombasa. This observation aligns with findings from Welfle et al. (2020) and Rauland and Newman (2019), who highlighted energy consumption and environmental impacts as pressing issues in urban lighting systems.

Furthermore, despite the expansion of street lighting infrastructure, significant areas in Mombasa City remain insufficiently lit, impacting safety and energy efficiency. The study found that while some areas have relatively adequate lighting, they still have room for improvement, and few areas meet the highest energy efficiency, reliability, and functionality standards. This is consistent with Wambui et al. (2022), who observed that many urban areas in Kenya still face challenges in maintaining high-quality street lighting infrastructure. Maintenance and replacement of existing street lighting infrastructure were found to be infrequent, a concern echoed by Amuyunzu and Kisimbii (2021), who stated that such maintenance rarely takes place.

5.2 Feasibility and Potential Benefits of Solar Street Lighting

The study analyzed the feasibility and potential benefits of transitioning from conventional street lighting to solar street lighting in Mombasa. The weather data over the past decade confirms the viability of solar street lighting, with an average annual solar irradiation of 5.27 kWh/m² per day providing sufficient energy for consistent operation. This ensures reliable lighting throughout the year, even with night lengths varying between 11.7 and 12 hours. These findings align with Akomolafe (2023), who observed that such irradiation levels are adequate to support reliable solar street lighting, even with seasonal variations in night lengths. Welfle et al. (2020) similarly concluded that solar energy systems with efficient battery storage could accommodate day and night duration variations in comparable climates.

Regarding the transition's feasibility, the study found that most respondents (45.3%) believe that transitioning to solar street lighting in Mombasa is very feasible, with another 50.5% agreeing that it is feasible but challenging. The primary concerns include the initial cost, infrastructure limitations, and logistical issues. Only 4.2% of respondents deemed the transition infeasible. These results indicate broad support for solar street lighting while highlighting the

challenges for successful implementation. This mirrors the sentiments of key informants, such as the Head of Safety and Projects at Kenya National Highways Authority (KeNHA), who highlighted high initial costs and lack of financing mechanisms as significant barriers. The consensus is that although scaling solar street lighting in Kenya is technically feasible, it requires structured financing and clear policy support.

Financially, solar street lighting presents a highly cost-effective alternative to conventional lighting. It is 25% less expensive overall and offers up to 80% faster installation, eliminating the need for cables, trenching, and electrical cabinets. Solar lights are operational immediately upon installation, unlike traditional systems that require a lengthy setup. A study by Luusa (2019) found that solar lighting systems while requiring a higher initial investment, offer substantial long-term savings due to lower maintenance costs and the elimination of monthly electricity bills. Similarly, Osano and Kingiri (2021) emphasized that solar-powered lights efficiently convert sunlight into usable energy, often yielding similar or superior energy outputs to traditional grid-based lighting while significantly reducing carbon emissions.

The financial comparison between conventional and solar lighting systems further demonstrates the economic advantages of solar technology. Conventional lighting requires an investment of approximately 10,285,000 KES, which includes costs for power cables, streetlight poles, LED lights, installation, and electrical cabinets. In contrast, solar lighting requires a total investment of 7,128,000 KES, which covers the costs for poles, solar lighting kits, and installation without needing an electrical cabinet. Over 20 years, solar lighting has emerged as the more cost-effective solution due to its significantly lower maintenance and operational expenses. The cumulative costs of conventional lighting rise steadily over time due to ongoing energy consumption and maintenance, while solar lighting's costs remain relatively flat after the initial investment.

The study found that transitioning to solar street lighting in Mombasa could reduce energy costs, lessen reliance on the national grid, and lead to substantial long-term savings. The operational and maintenance costs of solar street lighting are considerably lower than those of conventional systems, resulting in significant savings in government expenditure on electricity bills. Additionally, enhanced street lighting could improve Mombasa's appeal to tourists and businesses, boosting investment and economic activity, as observed by Osano and Kingiri (2021). The potential for increased investment in renewable energy technologies and

job creation in solar lighting installation and maintenance were also highlighted, creating more opportunities for local employment and economic growth.

Socially, solar street lighting offers several key benefits, including enhanced safety and well-being for pedestrians and drivers. Improved public safety is critical in poorly lit areas, where better lighting significantly enhances nighttime visibility. As a result, residents in these areas experience a higher quality of life due to the increased sense of security and health. Solar lighting also enhances the aesthetic appeal of urban spaces, making them more attractive to tourists. Furthermore, solar street lighting fosters greater community engagement and awareness of renewable energy, aligning with Sutopo et al. (2020), who emphasized the role of solar lighting in promoting public safety and enhancing the quality of life.

On the environmental front, solar street lighting offers notable benefits, particularly in reducing the carbon footprint of urban infrastructure. By replacing conventional, grid-powered streetlights with solar alternatives, cities can contribute significantly to sustainability goals. Renewable solar energy helps reduce reliance on fossil fuels, mitigating urban greenhouse gas emissions and supporting long-term sustainable development. Challenges associated with greenhouse gas effects, especially flooding, heat waves, drought, and respiratory health conditions, among others, are highly minimized.

Battery technology also plays a crucial role in the viability of solar street lighting. Various battery types—Lead Acid, Nickel-Metal Hydride (NiMH), Lithium-Ion (Li-ion), and Lithium Iron Phosphate (LiFePO₄)—each offer distinct advantages and limitations. The choice of battery is influenced by factors such as energy needs, environmental impact, and safety. While lithium-based batteries are more efficient, they pose challenges in terms of safety and recycling, whereas Lead Acid and NiMH batteries, though less efficient, are more environmentally sustainable. The comparison of these battery technologies highlights the trade-offs between efficiency, cost, and environmental impact when selecting the most suitable technology for solar street lighting.

The study confirms that transitioning to solar street lighting in Mombasa is technically feasible and holds numerous advantages. Solar lighting provides economic benefits through reduced installation, maintenance, and operational costs and contributes to social improvements by enhancing public safety and urban aesthetics. Additionally, the environmental impact of solar street lighting supports sustainability goals by reducing urban

carbon footprints. However, addressing the financial and policy challenges, including securing appropriate financing mechanisms and strengthening policy frameworks, is essential for successfully scaling solar street lighting in Mombasa and beyond.

5.3 Challenges and Barriers to Adopting Solar Street Lighting

The study identified high initial installation costs as the most prominent challenge to adopting solar street lighting. It also highlighted the lack of technical expertise and training as a critical barrier. Additionally, inadequate infrastructure support hindered implementation, such as insufficient grid connections or the lack of suitable sites for solar panel installations. The limited local availability of solar technology was indicated as creating logistical challenges and delays. Furthermore, insufficient government incentives or subsidies were identified as significant obstacles, aligning with Sutopo et al. (2020), who emphasized the role of government support in overcoming such barriers. Public resistance and lack of awareness were also highlighted as key challenges. Lastly, the study revealed that municipalities often face difficulties securing financing for these capital-intensive projects.

In addition, the findings indicated that the current level of technical knowledge about solar street lighting among Mombasa's infrastructure planners and decision-makers is moderate. The findings agree with Akomolafe's (2023) observations that the current level of technical knowledge about solar street lighting among Mombasa's infrastructure planners and decision-makers is moderate. The study found the technical knowledge high, indicating that some planners and decision-makers are well-versed in solar street lighting. Further, the study found low technical knowledge, indicating that a few stakeholders may lack the expertise to manage or oversee solar street lighting projects effectively.

The study found that financial incentives, such as tax breaks or subsidies, are the most effective policy changes for promoting solar street lighting adoption. These findings align with Baburajan (2021), who highlighted financial incentives as crucial for driving such initiatives. Additionally, the study revealed that streamlined approval and procurement processes significantly facilitate the faster implementation of solar lighting projects. Furthermore, public-private partnerships that combine financing with technical expertise effectively overcame financial and technical barriers. Also, the study emphasized the importance of awareness campaigns to educate the public and stakeholders about the environmental, economic, and social benefits of solar lighting.

5.4 Impacts of Solar Street Lighting on Urban Energy Consumption and GHG Emissions Reduction

The study established that energy consumption decreases by 100% when solar energy is substituted with the grid, creating potential savings and noticeable yet moderate savings. The findings are consistent with Arent et al. (2020) observations that energy consumption could decrease, resulting in a widespread belief in the potential for noticeable yet moderate savings. In addition, the study established a reduction, reflecting a more optimistic outlook regarding the impact of solar street lighting on energy consumption. Further, the study established substantial energy savings as unlikely, indicating mixed expectations regarding the overall impact of solar street lighting on energy efficiency.

The study also found a reduction in greenhouse gas (GHG) emissions in Mombasa City if solar street lighting were adopted on a large scale. The study also found that switching to solar street lighting would reduce emissions. The findings align with Luusa's (2019) observations that the switch to solar street lighting would positively impact emissions reduction. In addition, the study found that a moderate reduction in emissions was also seen as a plausible outcome. Further, the study established that solar street lighting is a potential tool for substantial emissions reduction. The study found that a decrease in emissions would reflect a more cautious outlook on the scale of the impact.

In addition, the study revealed that solar street lighting significantly reduces energy consumption, aligning with Maina et al. (2022), who observed its potential to decrease energy usage significantly. The findings highlighted that solar street lighting would substantially impact urban energy consumption by reducing reliance on the national grid. Furthermore, integrating solar street lighting with energy-efficient LED technology enhances its potential to cut energy use compared to traditional grid-powered systems. The study also found that renewable solar energy lowers grid strain during peak demand, improving urban energy management. Notably, transitioning to solar lighting could drastically reduce electricity demand from the national grid, alleviating pressure on urban power infrastructure in high-demand cities like Mombasa and Nairobi.

The study found that the impacts of solar street lighting on energy consumption and GHG emissions are evident over varying timeframes. While some effects become noticeable within 3–5 years, a significant portion is expected to materialize within 1–2 years. Additionally,

specific impacts may become visible in less than a year, particularly in areas with high solar potential and effective implementation. These findings align with Rauland and Newman (2019), who observed that the impact of solar street lighting on energy consumption and GHG emissions can be anticipated within less than a year in optimal conditions.



Chapter Six: Conclusion and Recommendation

6.1 Introduction

The research presents significant results and conclusions and proposed solutions for investigating solar street lighting for decarbonizing urban road infrastructure in Kenya. This research evaluated both the practicality and the implementation obstacles alongside the effects of changing street lighting from traditional grid systems to solar networks through the Mombasa Southern Bypass as its example. The study's significant results are introduced at the start of this chapter while also outlining the advantageous cost-effectiveness, environmental sustainability, and social advantages of solar street illumination. This dissertation examines the hurdles that prevent large-scale implementation, including policies, financial structure, and technological limitations. The chapter delivers concrete suggestions regarding the transition process to policymakers, urban planners, and stakeholders based on the research outcomes. The conclusion includes recommendations for research interests that focus on policy improvement, innovative lighting advancement, and long-term performance evaluation. The chapter is a research summary providing Kenya with essential guidance for achieving sustainable and low-carbon urban development.

6.2 Conclusion

The study concludes that while the street lighting infrastructure is functional to some extent, significant areas need improvement. Street lighting in Mombasa City predominantly relies on conventional technologies like incandescent and fluorescent lamps, though there is an emerging shift towards sustainable solutions such as LED and solar lighting. Despite some progress, gaps in coverage and quality persist, with some areas experiencing high electricity consumption, especially in Mombasa Island and Nyali Mtwapa Road. The study also found that infrequent maintenance exacerbates energy inefficiency and increases greenhouse gas (GHG) emissions. With the growing demand for lighting infrastructure, transitioning to solar and energy-efficient lighting presents a viable solution to reduce emissions, energy use, and light pollution. The study concludes that adopting sustainable lighting technologies can enhance urban sustainability, reduce environmental impacts, and improve overall functionality and safety in Mombasa's street lighting network.

In addition, the study concludes that solar street lighting is viable in Mombasa City, and the irradiation levels are sufficient to maintain reliable operation, even with seasonal variations in night lengths. The study further confirms that transitioning from conventional to solar street lighting in Mombasa is technically feasible due to abundant solar resources. With an average annual solar irradiation of 5.27 kWh/m² daily, Mombasa can ensure consistent solar street lighting throughout the year. The study also highlights that high initial costs and limited financing mechanisms are significant barriers to widespread adoption, although financial benefits and long-term savings are substantial. Moreover, the study found strong support for solar street lighting, with most respondents acknowledging its feasibility, though concerns over the high upfront costs remain. The study concludes that robust policy frameworks and structured financing models are crucial to scaling solar street lighting in urban areas. Solar street lighting can decrease government electricity expenditures, attract tourism and businesses, and create job opportunities in renewable energy sectors. The study also emphasizes that solar street lighting significantly reduces greenhouse gas emissions, contributing to sustainability goals. It enhances public safety, improves quality of life, and increases urban appeal. Finally, transitioning to solar street lighting offers substantial technical, economic, environmental, and social benefits, making it a comprehensive solution for Mombasa's urban infrastructure needs.

The study concludes that adopting solar street lighting in Kenya faces significant barriers, with high initial installation costs being the most prominent obstacle. The study concludes that inadequate technical expertise and training limit the proper installation and maintenance of solar lighting systems. The study concludes that insufficient infrastructure support, such as grid connections and suitable sites for solar panels, further complicates adoption. Additionally, the study concludes that limited local availability of solar technology and logistical challenges delay implementation. The study concludes that the lack of government incentives and subsidies discourages investment, while public resistance and low awareness of solar lighting benefits present additional challenges. Further, the study concludes that municipalities often struggle to secure necessary financing for these projects.

The study concludes that adopting solar street lighting in urban areas, including Mombasa City, is expected to reduce energy consumption, though the extent of the reduction varies. The study also concludes that while moderate energy savings are widely anticipated, expectations for substantial savings are mixed, indicating cautious optimism about its efficiency benefits. The study concludes that solar street lighting will reduce reliance on the

national grid when combined with energy-efficient LED technology. In addition, the study concludes that transitioning to solar energy would reduce strain on the grid during peak hours, improving energy management in high-demand cities like Mombasa and Nairobi. The study concludes that solar street lighting also holds significant potential to lower greenhouse gas (GHG) emissions. The study concludes that meaningful reductions could be achieved within 1–2 years, with the full impact on energy consumption and emissions becoming evident over 3–5 years.

6.3 Recommendations

Transition to Energy-Efficient Lighting Technologies: The study recommends accelerating the adoption of solar and LED lighting technologies in Mombasa City to replace conventional street lighting systems. This transition would reduce energy consumption, lower GHG emissions, and enhance the sustainability of urban infrastructure.

Promote Sustainable Urban Planning: The study recommends integrating sustainable lighting solutions, like solar street lighting, into urban planning frameworks to accommodate the growing demand for street lighting in rapidly urbanizing areas. Prioritizing renewable energy sources for street lighting can help mitigate the increased energy consumption and emissions caused by urbanization.

Invest in Local Solar Technology Production: To reduce the logistical challenges and costs associated with solar street lighting, the study recommends investing in local production and supply chains for solar technology. This would make solar street lighting more accessible and affordable for urban centers across Kenya.

Develop Financing Mechanisms and Supportive Policies: To overcome the financial barriers to adopting solar street lighting, it is essential to establish structured financing models. This can include public-private partnerships (PPPs), subsidies, or government-backed loans to offset the initial investment costs. Additionally, robust policy frameworks should be developed to align with national renewable energy goals and ensure the sustainability of solar street lighting projects.

Invest in Local Capacity Building and Skills Development: There is a need to strengthen local capacity for installing, maintaining, and operating solar street lighting systems. Training programs should be developed to equip the workforce with the necessary skills, focusing on

renewable energy technologies and sustainable urban infrastructure. The study revealed that scaling solar street lighting requires increased local capacity. By investing in education and training, the government can promote job creation and ensure the long-term sustainability of solar street lighting initiatives.

Streamline Approval and Procurement Processes: To facilitate faster implementation of solar street lighting projects, it is recommended that the government streamline the approval and procurement processes. Simplifying bureaucratic procedures and reducing red tape will enable quicker decision-making and project rollouts. This can be achieved through the digitalization of the approval process, the creation of clear guidelines, and the establishment of fast-track procedures for renewable energy projects.

Increase Awareness and Education Campaigns: The study recommends launching comprehensive awareness campaigns to combat public resistance and lack of awareness. These campaigns should aim to educate the public and key stakeholders about the environmental, economic, and social benefits of solar street lighting. Addressing misconceptions and highlighting the long-term savings and sustainability benefits, public support for solar energy solutions can be increased, fostering greater community acceptance.

6.4 Further Work

The study assessed the implementation and impact of solar street lighting in decarbonizing urban road infrastructure in Mombasa City. Having been limited to Mombasa Southern Bypass, the study's findings may not be generalized to other Cities in Kenya, including Nairobi City, Nakuru City, and Kisumu City. As such, future studies should focus on the implementation and impact of solar street lighting in decarbonizing urban road infrastructure in other cities in Kenya. Future studies should investigate the role of policy and institutional frameworks in promoting or hindering solar street lighting adoption. Studies could analyze existing policy gaps and propose new strategies for enhancing policy support for renewable energy infrastructure in urban areas. Further, future studies should explore advancements in solar technology, including energy-efficient LED lighting, smart grid integration, and energy storage solutions, and how these innovations could improve the performance and scalability of solar street lighting projects.

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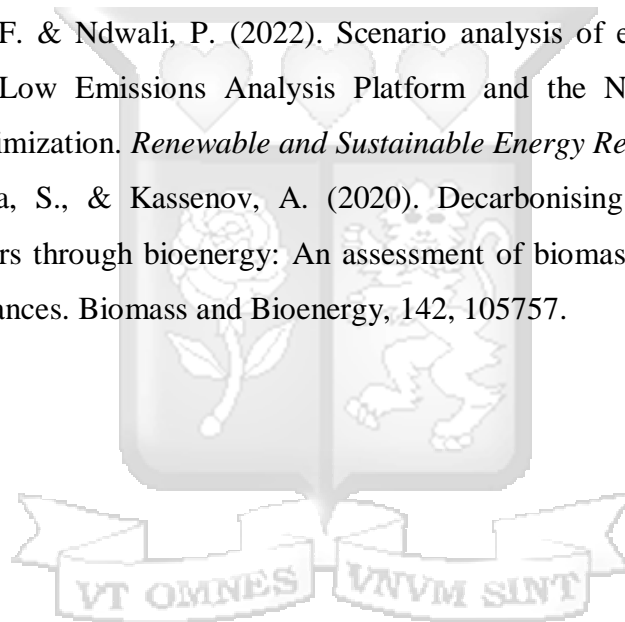
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APPENDICES

Appendix A: Similarity Report

FINAL DISSERTATION .pdf
by Paul Mabonga

Submission date: 22-Mar-2025 06:00PM (UTC+0300)
Submission ID: 2621854471
File name: 49201_Paul_Mabonga_FINAL DISSERTATION_234679_1748290331.pdf (3.17M)
Word count: 29782
Character count: 172522

Chapter 1: Introduction

1.1 Background of the Study

Kenya has a high rate of urbanization, and its urban areas are growing at unprecedented levels. Energy consumption and greenhouse gas (GHG) emissions are increasing with this urban growth rate, attributed to the transport and urban infrastructure sectors. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) supports several initiatives by assessing and reducing GHG emissions in developing countries, including the "Advancing Transport Climate Strategies in Rapidly Motorizing Countries" (TrACS). In Kenya, GIZ partnered with the University of Nairobi to get firm road transport CO₂ emission factors, emphasizing that time is overdue to address emissions from all the urban infrastructures, including street lighting. Street lighting is part of urban infrastructure, ensuring urban dwellers' safety, security, and quality of life (Luusa, 2019). Most streetlights in Kenya are associated with high energy consumption and emissions since they run on electricity generated from fossil fuels from the grid by at least 17%. As Kenya continues to urbanize, the demand for street lighting will increase further, worsening the challenge of managing energy consumption and reducing emissions (Welfle et al., 2020). Kenya has one of the highest potentials for solar energy in the world, which provides the country with a vast opportunity to decarbonize urban road infrastructure using solar street lighting systems.

The "Transport Sector Climate Change Annual Report 2021/2022" highlights the progress and challenges in reducing greenhouse gases in Kenya's transport sector. Emissions from the road subsector dominate the total emission from Kenya's transport sector compared to the railway, aviation, and maritime subsectors, which stand at 98% and 2%, respectively. A report to fulfill the mandate of the Climate Change Act 2016 details the priority actions, the status of their implementation in mitigation, and activities to reduce emissions to 3.5 MtCO₂e by 2030. It documents steps taken in public transport optimization, construction of non-motorized transport, development of resilient infrastructures, and other capacity-building activities. However, the report identifies the need for sustained capacity building, regulatory strengthening, and enhanced financial and technical support to ensure more investments for increased emission reduction targets for the future.

FINAL DISSERTATION .pdf

ORIGINALITY REPORT

10% SIMILARITY INDEX	8% INTERNET SOURCES	5% PUBLICATIONS	3% STUDENT PAPERS
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PRIMARY SOURCES

1	epra.go.ke Internet Source	1%
2	Samuel Chukwujindu Nwokolo, Anthony Umunnakwe Obiwulu, Paul C. Okonkwo. "Africa's Propensity for a Net Zero Energy Transition", CRC Press, 2024 Publication	<1%
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8	Ahmad Zaidi Abdullah, Nurhafiza Azizan, Zulhasrizal Bohari. "Implementation of Solar Street Lighting for Empowering Rural Communities", BIO Web of Conferences, 2024 Publication	<1%
9	www.badalona.cat Internet Source	<1%
10	Submitted to Strathmore University Student Paper	<1%

Appendix B: Ethical Clearance Release Letter



15th January 2025

Mr Mabonga Paul,
Paul.Mabonga@strathmore.edu

Dear Mr Mabonga, paul.mabonga@strathmore.edu

RE: Decarbonisation of Urban Road Infrastructure using Solar Street Lighting in Kenya: Assessing Implementation and Impact

This is to inform you that SU-ISERC has reviewed and **approved** your above SU-masters proposal. Your application reference number is SU-ISERC2334/24. The approval period is from **15th January 2025 to 14th January 2026**.

This approval is subject to compliance with the following requirements:

- i. Only approved documents including (informed consents, study instruments, MTA) will be used.
- ii. All changes including (amendments, deviations, and violations) are submitted for review and approval by SU-ISERC.
- iii. Death and life-threatening problems and serious adverse events or unexpected adverse events whether related or unrelated to the study must be reported to SU-ISERC within 72 hours of notification.
- iv. Any changes anticipated or otherwise that may increase the risks or affected safety or welfare of study participants and others or affect the integrity of the research must be reported to SU-ISERC within 72 hours.
- v. Clearance for the export of biological specimens must be obtained from relevant institutions.
- vi. Submission of a request for renewal of approval at least 60 days prior to the expiry of the approval period. Attach a comprehensive progress report to support the renewal.
- vii. Submission of an executive summary report within 90 days of completion of the study to SU-ISERC.

Before commencing your study, you will be expected to obtain a research license from National Commission for Science, Technology, and Innovation (NACOSTI) <https://research-portal.nacosti.go.ke/> and obtain other clearances needed.

Yours sincerely,

A handwritten signature in black ink, appearing to read "Ambrose Rachier".

Mr Ambrose Rachier,
Chairperson; SU-ISERC

Appendix C: Questionnaire

Introduction

This survey is designed to gather insights and assess the implementation and impact of solar street lighting in Mombasa City, with a particular focus on its role in the decarbonization of urban road infrastructure. As part of a research project, the survey aims to evaluate the current state of street lighting, explore the feasibility of solar street lighting, identify the challenges and barriers to its adoption, and estimate its potential impact on urban energy consumption and greenhouse gas (GHG) emissions reduction. Your responses will contribute valuable data to guide future decisions and policies on sustainable urban infrastructure development in Mombasa.

Section I: General Information

1. Gender

Male

Female

2. How long have you worked in your current role/department?

Less than 1 year 1-3 years

4-6 years Over 6 years

3. Age: (in Years)

Less than 18

18-30

31-45

46-60

More than 60

4. Occupation:

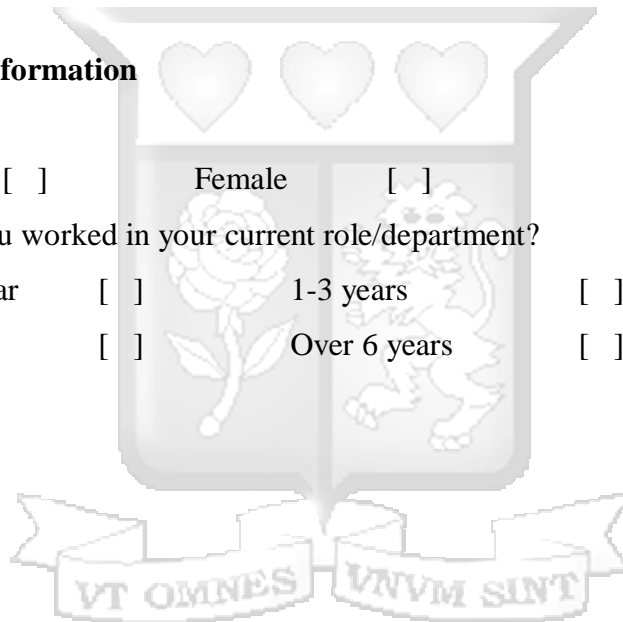
Government Servant

Urban Planner

Engineer/Technical Consultant

Member of Society

Other (Please specify): _____



Section 2: Status of Street Lighting Infrastructure and Urban GHG Emissions

5. What type of street lighting is most commonly used in Mombasa City?
- Conventional (e.g., incandescent or fluorescent lights) []
 - LED lights []
 - Solar lights []
 - Mixed (combination of conventional, LED, and solar) []
 - Other (please specify)
6. How would you assess the current condition of street lighting infrastructure in Mombasa City?
- Excellent [] Good []
 - Fair [] Poor []
7. How often does the current street lighting infrastructure in Mombasa City require maintenance or replacement?
- Frequently [] Occasionally []
 - Rarely [] Never []
8. To what extent do you think street lighting in Mombasa City contributes to urban GHG emissions?
- Major contributor []
 - Moderate contributor []
 - Minor contributor []
 - No contribution []
 - Not sure []
9. What do you think is the primary environmental issue caused by the current street lighting system in Mombasa?
- High energy consumption []
 - GHG emissions []
 - Light pollution []
 - Other (please specify)

Section 3: Feasibility and Potential Benefits of Solar Street Lighting

10. How feasible do you think it is to transition from conventional street lighting to solar street lighting in Mombasa City? []
- Very feasible []
 - Feasible but challenging []
 - Not feasible []

Not sure []

11. What potential economic benefits do you think Mombasa City could derive from adopting solar street lighting? (Select all that apply)

- Reduced energy costs for street lighting []
- Lower maintenance and operational costs compared to conventional lighting []
- Creation of local jobs (e.g., in installation and maintenance) []
- Increased investment in renewable energy technologies []
- Improved attractiveness for tourism and businesses due to better lighting []
- Savings in government expenditure on electricity bills []
- Other (please specify)

12. What potential environmental benefits do you think Mombasa City could derive from adopting solar street lighting? (Select all that apply)

- Reduction in greenhouse gas (GHG) emissions []
- Decreased reliance on non-renewable energy sources []
- Reduced light pollution []
- Conservation of natural resources (e.g., less energy consumption from the grid) []
- Improvement in air quality due to lower energy production requirements []
- Enhanced urban biodiversity (due to reduced light disruption to wildlife) []
- Other (please specify)

13. What potential social benefits do you think Mombasa City could derive from adopting solar street lighting? (Select all that apply)

- Improved public safety and security due to better lighting at night []
- Enhanced quality of life for residents in poorly lit areas []
- Increased community engagement and awareness about renewable energy []
- Greater sense of safety and wellbeing for pedestrians and drivers []
- Improved aesthetic appeal of urban areas, making them more attractive for tourists []
- Creation of new community-focused initiatives (e.g., community solar programs) []
- Other (please specify)

Section 4 Challenges and Barriers to Adopting Solar Street Lighting

14. What do you consider to be the primary barriers to adopting solar street lighting in Mombasa City? (Select all that apply)

- High initial installation costs []

- Lack of technical expertise or training []
- Insufficient government incentives or subsidies []
- Public resistance or lack of awareness []
- Limited availability of solar technology locally []
- Inadequate infrastructure support (e.g., grid connections) []
- Other (please specify)

15. How would you rate the current level of technical knowledge about solar street lighting among Mombasa’s infrastructure planners and decision-makers?

- Very high []
- High []
- Moderate []
- Low []
- None []

16. What policy changes would you recommend to overcome these barriers?

- Financial incentives such as tax breaks or subsidies []
- Streamlined approval and procurement processes []
- Public-private partnerships for financing and expertise []
- Increased awareness campaigns about the benefits of solar lighting []
- Other (please specify)

Section 5: Impacts of Solar Street Lighting on Urban Energy Consumption and GHG Emissions Reduction

17. What is your estimate of the potential reduction in energy consumption in Mombasa City by switching to solar street lighting?

- Less than 10% []
- 10% - 20% []
- 20% - 40% []
- Over 40% []
- Not sure []

18. How much do you think GHG emissions in Mombasa City could decrease if solar street lighting were adopted on a large scale?

- Less than 5% []
- 5% - 10% []
- 10% - 20% []
- Over 20% []

Not sure []

19. What overall impact do you foresee solar street lighting on Mombasa City's energy consumption?

Major reduction []

Moderate reduction []

Minor reduction []

No reduction []

Not sure []

20. How long will it take to see noticeable impacts on energy consumption and reduced GHG emissions from solar street lighting in Mombasa?

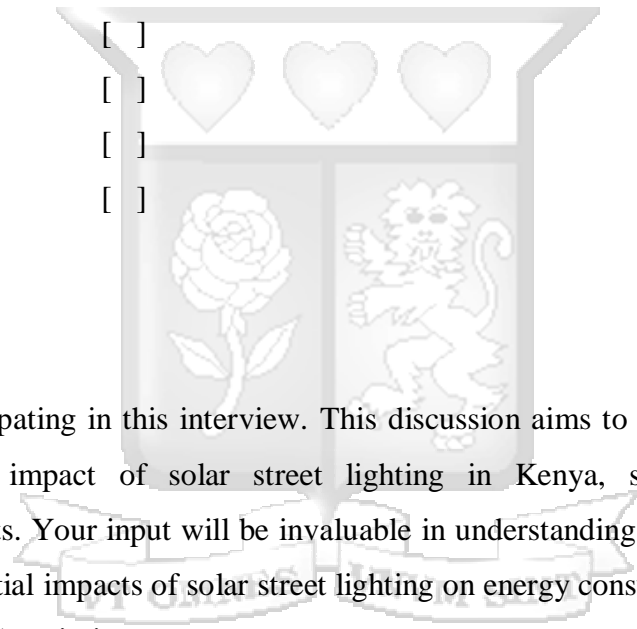
Less than 1 year []

1-2 years []

3-5 years []

Over 5 years []

Not sure []



Introduction

Thank you for participating in this interview. This discussion aims to gather insights on the implementation and impact of solar street lighting in Kenya, specifically in urban decarbonization efforts. Your input will be invaluable in understanding the status, feasibility, challenges, and potential impacts of solar street lighting on energy consumption and reducing greenhouse gas (GHG) emissions.

Section 1: Status of Street Lighting Infrastructure and Its Implication for Urban GHG Emissions

1. What types of street lighting technologies are commonly used in urban centers in Kenya?
2. How would you assess the effectiveness of the current street lighting in terms of energy efficiency and environmental impact?
3. What role do street lighting systems play in urban greenhouse gas emissions, and how significant is their contribution to the overall emissions in Kenyan cities?

Section 2: Feasibility and Potential Benefits of Solar Street Lighting

1. How feasible do you think it is to scale solar street lighting in urban areas in Kenya?

2. What are the significant benefits of implementing solar street lighting in urban areas (Probe for reducing electricity costs, reliance on the national grid, and environmental benefits)?

Section 3: Challenges and Barriers to Adopting Solar Street Lighting

1. What are the main challenges hindering street solar lighting adoption?
2. Are there financial barriers or funding challenges that prevent municipalities from adopting solar street lighting?
3. What are the technical and infrastructural barriers to implementing solar street lighting in urban areas?

Section 4: Impacts of Solar Street Lighting on Urban Energy Consumption and GHG Emissions Reduction

1. How do you think solar street lighting would affect overall energy consumption in urban areas?
2. how does solar street lighting contribute to the country's broader goals for decarbonization and climate change mitigation?

