

**PERFORMANCE EVALUATION OF SOLAR PHOTOVOLTAIC SYSTEM
FOR ENERGY MANAGEMENT AND ENVIRONMENTAL
SUSTAINABILITY IN MOI INTERNATIONAL
AIRPORT - MOMBASA, KENYA**

By

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DECLARATION

Declaration by the Candidate

This research is my original work and has not been presented for a degree in any other University or institution. No part of this thesis may be reproduced without the prior written permission of the author and/or Moi University.

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DEDICATION

I dedicate this work to my wife (Lydia), children (Ryan and Roy), parents, colleagues, and all those who supported me in the completion of this thesis. Thank you and May God bless you abundantly.

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First and foremost, I am thankful to God for his unconditional love, mercy, protection, and the gift of life.

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ABSTRACT

As a consequence of the increasing energy demand and the climate crisis in the world, the importance of alternative sustainable energy generation techniques that are clean and cheap needs to be explored. Globally, the airport industry has recently adopted the use of green energy technologies, but their utilization in Kenya remains low. The main objective of this study was to evaluate the technical, economic, and environmental analysis of the installed pilot solar photovoltaic system at Moi International Airport, Mombasa. The specific objectives were; to determine the electrical energy consumption of the airport, to perform Modelling and simulation of the solar photovoltaic system, to carry out a techno-economic analysis of the installed solar photovoltaic system, and to determine the reduction of the greenhouse gas emissions by the generated PV model. The methodology involved data collection in the form of meter readings of energy consumed at the airport and historical PV energy output from a data logger. The technical and economic data of the installed solar plant was obtained from secondary sources. Moreover, the temperature, wind, and humidity data were collected from the Meteorological Department weather station located within the airport. A Hybrid Optimization Model for Electric Renewable (HOMER) tool was utilized for modelling, optimization, sizing, and simulation. The hybrid model was designed as per the airport's electrical energy requirement (12561 kWh). The optimum system configuration was selected based on the least Net Present Cost (NPC) and least levelized cost of Energy (LCOE). The simulation results showed that the proposed hybrid system (grid-connected PV system without batteries) had the lowest NPC and LCOE of Kshs. 2,119,157,749 and Kshs.29.45/kWh, respectively. The technical results showed that the final yield (YF), capacity utilization factor (CUF), system efficiency (η), and performance ratio (PR) as 3.99, 16.6%, 12.10%, and 72.35%, respectively. Furthermore, the economic indicators were: net present value (NPV) of Kshs 81,843,034, internal rate of return (IRR) of 8.34%, discounted payback period (DPP) of 12 years, and simple payback period (SPP) of 9 years. The installation's least cost of energy was estimated to be Kshs 25.64/kWh. The selected model had a higher levelized cost of energy than the pilot project because of higher interest and inflation rates. On the environmental aspect, 221,283.48 Kgs of carbon dioxide emissions would be saved in 20 years by using solar photovoltaic system. As per the LCOE of the optimal model over the grid, it would be replaced by Ksh 29.45/kWh instead of Ksh 33.8/kWh, yielding a percentage savings of 87%. The evaluation results especially the high-performance ratio (72.35%) showed that the technology adopted and site meteorological factors favored the high output of the solar photovoltaic system. The study recommends the utilization of information by stakeholders to develop a framework for performance improvement of the optimal model and pilot project in airports.

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ABBREVIATIONS, SYMBOLS, AND ACRONYMS

A/C	Air Conditioning
AC	Alternating Current
APU	Auxiliary Power Unit
BEMS	Building Energy Management Systems
BESS	Battery Energy Storage System
CH ₄	Methane
CO ₂	Carbon Dioxide
CoE	Cost of Unit Energy
DC	Direct Current
DG	Diesel Generator
EA	Electric Aviation
EB	Energy Baseline
EMS	Energy Management System
EPIS	Energy Performance Indicators
EPRA	Energy and Petroleum Regulatory Authority
ESS	Energy Storage Systems
EV	Electric vehicle
FAA	Federal Aviation Board
GHG	Greenhouse gas
GHI	Global Horizontal Irradiance
GPU	Ground Power Unit
GSE	Ground Service Equipment
GWh	Gigawatt-hour
HES	Hybrid Energy Sources
HFC	Hydrofluorocarbon

HOMER	Hybrid Optimization Model of Electric Renewables
HVAC	Heating, Ventilation and Air Conditioning
ICAO	International Civil Aviation Authority
IEC	International Electrotechnical Commission
ISO	International Standards Organization
KAA	Kenya Airports Authority
KCAA	Kenya Civil Aviation Authority
KW-	Kilowatt
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Energy
LEAP	Long Range Energy Alternatives planning
LTO	Landing and Take Off
MPPT	Maximum Power Point Tracker
N ₂ O	Nitrous oxide
NASA	National Aeronautics and Space Administration
NMOT	Nominal Module Operating Temperature
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
OC	Operations Cost
PCU	Pre-conditioned Air Unit
PFC	Perfluorocarbon
PV	Photovoltaic
RES	Renewable Energy Sources
SAM	System Advisor Model
SF ₆	Sulphur hexafluoride

STC	Standard Test conditions
TNPC	Total Net Present Cost
TRNSYS	Transient System Simulation
W	Watt

DEFINITION OF TERMS

- Airport:** A place from which aircraft operate that usually has paved runways and maintenance facilities and often serves as a terminal.
- Airside:** The side of an airport terminal beyond passport and customs control.
- Emission:** The production and discharge of something, especially gas or radiation.
- Energy management:** The proactive and systematic monitoring, control, and optimization of energy consumption to conserve use and decrease energy costs.
- Environment:** The surroundings or conditions in which a person, animal, or plant lives or operates.
- Landside:** The side of an airport terminal to which the general public has unrestricted access.
- Photovoltaic:** The conversion of light into electricity using semiconducting materials
- Renewable:** A natural resource or source of energy that is not depleted by use, such as water, wind, or solar power
- Sustainability:** Avoidance of the depletion of natural resources to maintain an ecological balance.
- Terminal:** Refers to a building at an airport where passengers transfer between ground transportation and the facilities that allow them to board and disembark from an aircraft.

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

In the last two decades, global primary energy consumption and CO₂ emissions have increased by 50%. Despite uncertainties surrounding short- and medium-term economic growth, forecasts indicated that energy demand would rise sharply, increasing by approximately one-third between 2015 and 2040. This rapid escalation in energy consumption, primarily driven by population and economic growth, posed significant environmental challenges. As demand continued to soar, it was crucial to explore sustainable energy solutions and policies to mitigate potential ecological impacts and promote a more balanced approach to development and environmental stewardship (Ortega and Manana, 2016). To meet the growing global energy demand, there was an increasing push for alternative energy sources. The greenhouse gases emitted by fossil fuels were major contributors to global warming and climate change. Dependence on fossil fuels such as oil, natural gas, coal, and nuclear energy created economic and social instability, resource scarcity, and environmental degradation. Transitioning to renewable energy sources offered a way to rebalance energy needs while ensuring environmental sustainability, helping to mitigate the harmful impacts of climate change and promoting a healthier planet for future generations (Stevens, 2006). Airports have been essential to the international air transport system, enabling passenger and cargo movement while enhancing global connectivity and economic growth (ICAO, 2009) and act as hubs that integrate diverse elements and activities, enabling smooth interchange between air travel and surface transport modes. This facilitates efficient movement for both passengers and air cargo, enhancing overall transportation connectivity (Doganis, 2005). These airports deliver both non-aeronautical services, such as car parks and retail concessions, and aeronautical

services, including infrastructure and ground handling. These services have been designed to meet the needs of two main customer groups: air travellers and airlines (Marques & Brochado, 2008).

1.2 Airport Energy Structure

Airports have been energy-intensive due to high power demands for lighting and electrical equipment. The large facilities, including passenger terminals and non-passenger areas, rely significantly on heating and air-conditioning systems, further increasing their overall energy consumption (Baxter, 2021; Baxter, Srisaeng & Wild, 2018; Ortega & Manana, 2017). Around 70% of energy used in airport terminal buildings was used for air conditioning, cooling, and heating, emphasizing the need for efficient energy management systems (Akyüz, Altuntaş, & Çay, 2017).

Civil airports rely on various energy sources, including electric power, coal, natural gas, diesel, purchased heating, gasoline, and others. Electric power makes up approximately 52.06% of total energy consumption, followed by coal at 17.06%. Natural gas and diesel accounts for 10.86% and 10.38%, respectively, while purchased heating, gasoline, and other energy types accounts for smaller shares, highlighting the diverse energy mix used in airport operations (Li, Zhang, Wang, Xu & Su, 2017) as shown in Figure 1.1

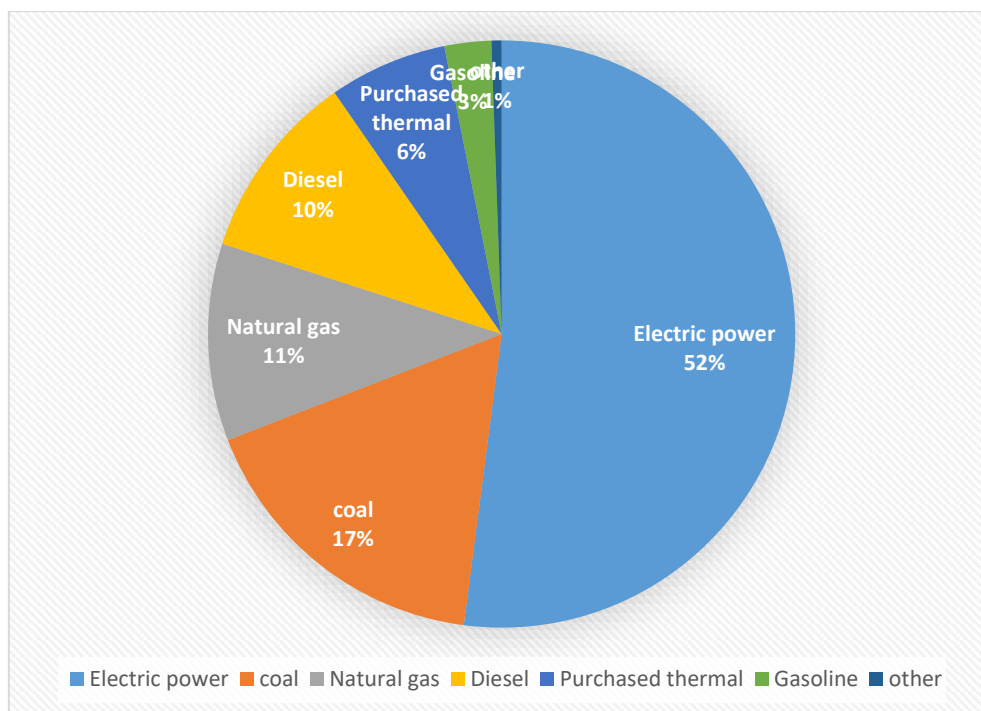


Figure 1.1: Energy consumption proportions at airports (Li, Zhang, Wang, Xu & Su, 2017).

The primary energy sources for these facilities being electricity and fuel, with electricity usually supplied from the grid. The global aviation community have committed to adopt sustainable practices in airport management plans and hence, renewable energy sources were being considered to enhance sustainability. This matter of sustainability has been pursued through various initiatives, including reducing engine emissions, minimizing noise output, recycling, effective waste management, and utilizing renewable energy. These practices constituted the main environmental criteria, aimed at monitoring and minimizing the ecological impact of airport operations, thereby promoting a more sustainable future for the aviation industry and its surrounding environments (Costa, Blanes, Donnelly, and Keane, 2012)

Apart from high energy demand in airports, greenhouse gases and their increasing impact have become a major global concern, with atmospheric carbon dioxide concentrations rising by about 40% over the last 250 years. The aviation industry has contributed to greenhouse gas emissions since its inception, currently accounting for

approximately 3.5% to 5% of global emissions. This figure would be expected to double over the next fifteen years, emphasizing the urgent need for sustainable practices to mitigate the environmental impact of air travel and address climate change effectively (ACI World, 2021). In 2019, global flights emitted around 915 million tonnes of carbon, with expectations for this figure to rise in the coming years (Air Transport Action Group, 2020). While airports accounted for a smaller share of emissions compared to air traffic operations, it would be crucial for all parts of the aviation sector to focus on mitigating and managing greenhouse gas (GHG) emissions. Such efforts would essentially ensure the industry meets global climate change targets and promotes sustainability (ACI World, 2021).

According to Barrett, Devita, Ho, & Miller (2014), renewable energy sources have gained significant attention as alternative energy solutions for airports due to their high power generation capacity, stability, and lower carbon emissions. With airports operating 24 hours a day and having ample space for installation, they present an ideal place for renewable energy implementation. This makes them well-suited for harnessing solar, wind, and other sustainable energy sources, ultimately enhancing energy efficiency and reducing environmental impact in airport operations (Shukla & Sudhakar, 2016). Numerous airports globally have successfully implemented sustainable energy systems centered on renewable sources and their implementation depended on the airport type, geographical location, and available resources. Therefore, conducting an energy audit to assess the needs of operators before investing in renewable energy projects is paramount (CIAL annual report, 2016). The energy audit enables operators to assess consumption, facilitating strategic investments in energy efficient technologies to optimize airport performance. By understanding their energy usage and pinpointing the most cost-effective improvement opportunities, operators

could make informed decisions about investing in renewable energy projects, enhancing sustainability and efficiency at the airport while reducing overall energy costs (Sugathan, John & Sudhakar, 2015)

The most common renewable energy source at airports worldwide was solar energy (Lew, 2018). PV microgrid distribution has expanded globally, harnessing free solar insolation during the day. However, its effectiveness has been significantly influenced by weather conditions, leading to variability and unpredictability. In Kenya's coastal region, the minimum global horizontal irradiation ranged from 4.2 to 5.8 kWh/m² (Solargis, 2019). To address the effects of fluctuating solar insolation, backup energy storage systems could be used. In grid-connected systems, these backups were activated during off-peak hours, power outages, or failures, ensuring a reliable energy supply when solar generation was low. This systems proved to have better results than diesel generators as highlighted by Kusakana and Vermaak (2013). They emphasized that their dependence on expensive fossil fuels and the subsequent environmental pollution they cause, presented significant economic and ecological challenges.

1.3 Current Energy Management Status in Kenyan Airports

Airports have not adopted sustainable planning due to insufficient information, lack of guidelines, limited funding, and weak enforcement regulations (Monsaluda, Ho & Rakas, 2014). In Kenyan airports, sustainability challenges related to energy management remain pressing, lacking an integrative framework and urgent solutions. Existing literature has not adequately defined energy management sustainability or created a cohesive framework for airports, leading to fragmented energy management models. Addressing these gaps was essential for enhancing sustainability in the aviation sector (Ahmed, Mahmood, Jamaludin, Talib, Sarip & Kaidi, 2022). However, the energy sector has been more concerned about the costs of production and maintenance

practices (McIlvennie, Sanguinetti, & Pritoni, 2020). To address these challenges, it would be crucial to adopt sustainable systems and energy management models. Additionally, energy consumption in airports have significantly impacted both the environmental and economic spheres, leading to national and international airport managers acknowledging the need for reducing energy use and enhancing efficiency. This awareness has been reflected in numerous environmental publications emphasizing the importance of sustainable practices in the aviation sector (Corporate Responsibility Report, London Heathrow Airport Environmental Report, & Frankfurt Airport Environmental Report, 2014). To effectively reduce or manage energy consumption in airports, it would be essential to understand energy sources and consumption behaviors through tools like energy models. However, the modelling of energy sources in airports remained a challenge, with numerous unresolved issues that needed to be addressed to enhance energy efficiency and sustainability.

1.4 Problem Statement

Despite increasing installations of solar PV systems to ensure reliable, clean and cheap power in other airports in the worldwide, Kenyan airports still face significant challenges like high energy demand, costly power, frequent power outages and reliance on fossil fuels by pack up power systems which emits greenhouse gases. Given these challenges, Moi International Airport (MIA) in Mombasa, which is a major gateway to East Africa became the first airport in the region to install a pilot solar PV system under the "Solar-at-Gate" project by ICAO to supplement grid electricity and reduce reliance on fossil fuels, decrease operational costs and improve energy reliability and contribute to national carbon reduction targets.

Since it's a pilot project, its success would accelerate demand for replication in MIA and other similar facilities within the country (Jomo Kenyatta, Kisumu, Eldoret) but

limited information or studies about its performance exists or available publicly. Hence, there was need for a focused localized research in this pilot project considering site conditions. Therefore, this research aimed to critically evaluate the performance of the pilot solar PV system at Moi International Airport in Mombasa, with a focus on determining its efficiency and quantifying environmental benefits. Furthermore, it investigated the techno-economic viability of integrating photovoltaic (PV) systems and battery energy storage systems (BESS) to support this growing electrification.

1.5 Objectives of the Study

1.5.1 General Objective

The main objective of this study was to perform a technical, economic, and environmental analysis of the solar photovoltaic systems installed at Moi International Airport in Mombasa.

1.5.2 Specific Objectives

The specific objectives were:

- i. To determine the electrical energy consumption of the airport.
- ii. To perform Modelling simulation of the solar photovoltaic system
- iii. To perform a techno-economic analysis of the installed solar photovoltaic system.
- iv. To determine the reduction of greenhouse gas emissions by the PV model.

1.6 Justification of the Study

The climate change has resulted to extreme weather patterns and rising sea levels. The concentration of greenhouse gases (GHG) such as carbon dioxide, methane, and nitrous oxide, emitted by human activities, continues to increase, contributing to the greenhouse effect and global warming. The primary anthropogenic source of carbon

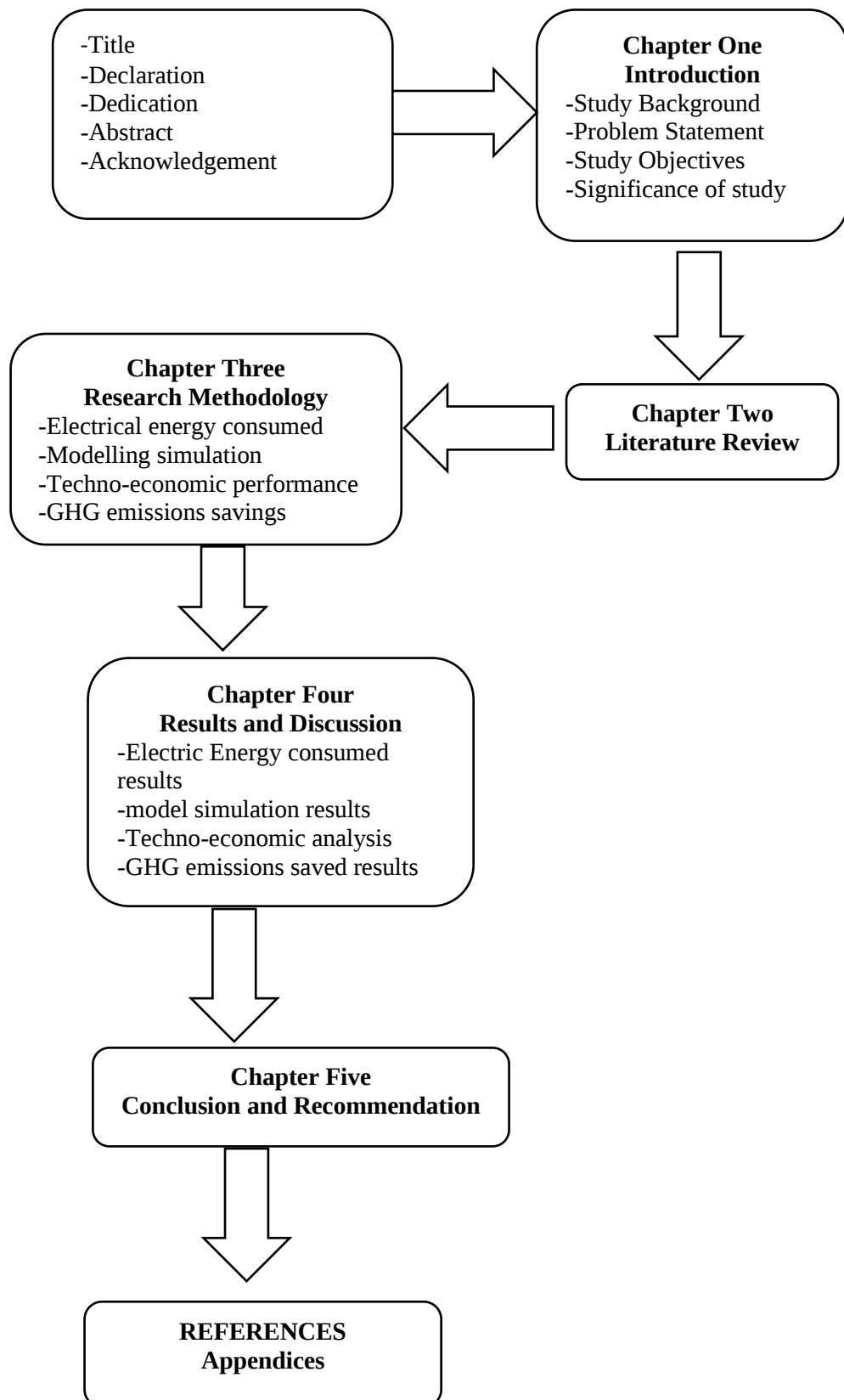
emissions was the burning of fossil fuels, including coal, oil, and gas. While renewable energy sources like solar and biofuels have emerged, fossil fuels still play a significant role in the global energy mix, serving as the main source for electricity generation worldwide, underscoring the need for a transition to more sustainable energy solutions.

Driven by national and regional energy targets, many jurisdictions have developed energy management standards to assist industries in formulating their own strategies and energy models. This study aimed to bridge gaps in existing research on airport energy management, focusing on sustainable practices in African airports, particularly in Kenya, to enhance the knowledge base. Additionally, it sort to review innovative technologies that contribute to sustainability in airport operations, providing valuable insights for improving energy efficiency and promoting environmentally friendly practices in the aviation sector.

1.7 Significance of the Study

The findings of this study would provide valuable insights to the government, stakeholders, and organizations about a promising investment opportunity in airport projects. This could aid airports in achieving their electricity generation targets by increasing energy production, enhancing economic resilience, and reducing greenhouse gas emissions. Additionally, the developed model would serve as a framework for replication in other airports, promoting sustainability across the aviation sector.

1.8 Structure of the Thesis



CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter is divided into five sections. The first section addresses the energy consumption patterns and energy sources of Airports. The second section addresses the energy management standards and models. Additionally, the third section examines the technical and economic performance of photovoltaic (PV) modules. The technical performance analysis focuses on how these modules operate under humid tropical savannah weather conditions, particularly in coastal regions. Furthermore, the economic performance of PV modules systems is deliberated. Fourthly, the study addressed the amount of Greenhouse gas emissions saved by the installation of solar PV systems. Lastly, the chapter is summarized with the knowledge contributions by the study.

2.2 Energy consumption and energy sources at Airports

2.2.1 Energy Consumption at Airports

Airports have extremely energy-intensive areas both on the airside and landside (Akyuz et al., 2017; Baxter et al., 2018; Ortega and Manana, 2017). Airside refers to the areas that serve aircraft, including runways, hangars, and control towers, while landside focuses on passenger needs, encompassing terminal buildings, parking lots, and other facilities. In airports, terminal buildings represent a major portion of energy consumption due to their large size and the extensive infrastructure required. This includes heating and air-conditioning systems, lighting, and electrical equipment, all essential for passenger comfort and operational efficiency. Furthermore, the various amenities located within the airport precinct contribute significantly to overall energy demands, underscoring the need for effective energy management strategies to optimize resource use and reduce environmental impact (Cardona et al., 2006). Sergio and Mario

(2016) reported that over 75% of total energy consumption at Santander Airport was attributed to the terminal building, mainly for air conditioning, cooling, and heating. This trend was likely to be reflected in other airports as well. Similarly, Gomri and Mebarki (2016) noted that air conditioning systems accounted for a substantial portion of energy consumption in airports, highlighting the need for improved energy management (Alba and Manana, 2016). Figure 2.1 shows the energy consumption by the facilities in Santander Airport.

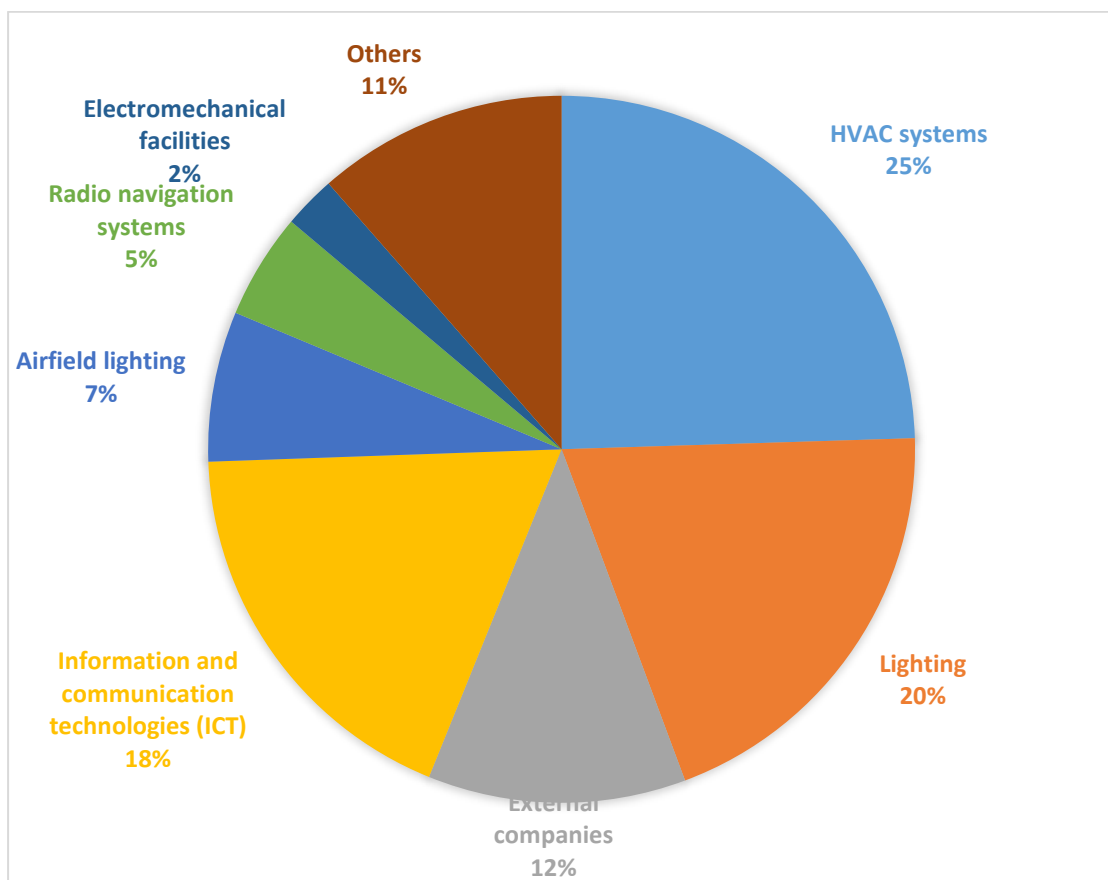


Figure 2.1: Energy consumption at Santander airport (Alba and Manana, 2016).

Energy consumption at airports can be divided into airside and landside activities. In the airside area, energy requirements include fuel used by aircraft during landing and take-off (LTO) cycles, as well as energy consumed by ground service equipment (GSE) and vehicles operating at the apron or gate complex. In contrast, the landside area

primarily consumes energy through airport ground access systems and facilities such as passenger and air cargo terminals, along with administrative buildings. Furthermore, fuel is utilized for heating boiler systems and emergency generators, adding to the overall energy demand. Understanding these energy consumption patterns is crucial for developing effective management strategies aimed at reducing costs and minimizing environmental impacts, ultimately leading to more sustainable airport operations (Ortega & Manana, 2016). Thus, energy management, including heating, ventilation, air conditioning, and lighting, is essential for sustainable airport operations (Graham, 2014).

According to Thomas and Hooper (2013), airports require a reliable, appropriately priced, and secure energy supply to meet peak demand from service partners and passengers, optimizing operational capacity. Maintaining a comfortable ambient temperature and air quality within passenger terminals typically represents the largest contribution to energy usage and management at most airports, underscoring the importance of effective energy strategies to enhance passenger comfort and operational efficiency.

The previous studies on energy consumption in airport terminals have primarily relied on site measurements or operational data from real-world locations. However, these datasets often focus on a particular area within an airport or cover only a limited time period. This presents a significant limitation, as it is widely recognized that energy usage can vary considerably depending on geographical location and seasonal changes. As a result, data gathered over short durations may not provide a comprehensive understanding of the energy consumption patterns of an entire airport. To develop a complete and accurate profile, it is essential to track the energy consumption of an entire building over an extended period, ideally at least one year. This allows for the capture

of fluctuations in energy use related to seasonal differences and varying operational demands. Without this long-term data, conclusions about the energy performance of airport terminals may be incomplete or misleading. Therefore, future studies should consider conducting long-term monitoring to fully understand the factors influencing energy consumption in such large, complex infrastructures (Liu, Liu, Zhang, & Li, 2019).

2.2.2 Airport Energy Sources

Industrialization and urbanization have flourished due to the availability of abundant and inexpensive energy, enabling mass production across various sectors, from lighting and heating to space technology. However, this progress has created significant challenges regarding the equitable distribution of energy resources. The excessive consumption of fossil fuels, which have taken thousands of years to form, has led to their gradual depletion, raising concerns among the global population. This anxiety is echoed by many scientists in the energy field, who warn that fossil fuels may be exhausted in the near future. As a result, there is an urgent need to shift towards more sustainable energy sources to mitigate the impact of fossil fuel depletion and ensure a stable energy future.

Güneş et al. (1999) argued that dependence on exhaustible resources such as oil, coal, and natural gas, which are becoming increasingly costly, will contribute to long-term inflation and create a grim outlook for countries reliant on these energy sources. Estimates suggest that, at current consumption rates, oil could be consumed in about 50 to 60 years, while coal may last 100 to 150 years. These alarming predictions indicate that the end of oil- and coal-dependent nations is approaching. In response to the depletion of these energy sources, there is a marked increase in the shift towards alternative energy sources. This trend highlights the urgent need for sustainable

solutions to ensure energy security and economic stability in the coming years, as noted by Shukla et al. (2016).

Airports are increasingly developing renewable energy sources to meet rising energy demands. To effectively utilize renewable energy, it's essential to assess the availability of natural resources, project feasibility, and the adequacy of infrastructure and capacity. Conducting these analyses will help airports evaluate renewable resource opportunities and create a long-term strategy that optimizes the development of renewable energy projects, along with waste reduction and recycling initiatives. This comprehensive approach will enhance energy sustainability and support the airport's broader environmental goals (Shukla and Sudhakar, 2016).

When assessing renewable resource alternatives for airports to replace fossil fuels for electricity services, options such as small wind turbines, photovoltaic systems, and off-site renewable energy systems should be considered. However, determining the most suitable options based solely on electricity requirements can be complex. It's essential to analyze the optimal configuration and performance of various renewable resources, along with how these options integrate into current airport operations and align with future strategic planning. While photovoltaic systems and wind turbine projects present promising solutions, they require thorough planning and execution to ensure effectiveness. Ultimately, implementing these renewable energy alternatives can have a substantial impact on reducing an airport's electricity costs and carbon emissions, contributing to enhanced sustainability and operational efficiency in the aviation sector (CIAL annual report, 2015).

Airports are essential centers for regional economic activities and transportation networks, making it crucial to provide economical and reliable electricity. While

renewable energy alternatives like solar, wind, biomass, geothermal, hydroelectric, and fuel cells are available, none is definitively superior, and their implementation at airports has been limited. A comprehensive evaluation of these options is necessary to determine the most suitable solutions for enhancing energy sustainability in airport operations (Kılıkış, 2014).

Historically, airports have relied primarily on electricity and fuel sources like diesel, natural gas, and propane (Ortega & Manana, 2016). Electrical energy is usually supplied directly through dedicated substations (Janić, 2011), and airports often purchase electricity from the commercial grid, provided by a power company (Ortega & Manana, 2016), highlighting the need for effective energy management. Recently, airports have begun adopting renewable energy sources to replace fossil fuels. These technologies include solar photovoltaic (PV), concentrating solar power, wind power, and steam-generated power production (Barrett et al., 2014). Despite this progress, many airports still depend on crude oil for fuel to power ground service equipment (GSE) and vehicles utilized in airside and landside operations, especially during aircraft ground handling. This reliance underscores the ongoing need to transition fully to sustainable energy solutions in airport operations (Janić, 2011).

The most effective way to address energy consumption issues at airports is by utilizing renewable, non-polluting energy sources. According to Kepekçi and Mizrak (2022), photovoltaic systems are the most widely adopted renewable energy technology in airports. Their popularity stems from their ability to harmoniously integrate into the airport environment. The relatively simple modular structure of photovoltaic panels allows for easy installation without major modifications, making it feasible to place them in areas not directly used for aviation activities.

Photovoltaic panels can be installed on the ground, on building surfaces, or above parking lots, providing shade in less-utilized areas of the airport (Rubeis et al., 2016). As the solar industry has expanded, there has been a growing trend among developers to implement photovoltaic systems at airports. While this transition offers significant advantages in terms of reduced energy costs and lower emissions, it also introduces new and unforeseen safety challenges.

The aviation community has raised concerns about whether solar power generation is compatible with aviation operations, particularly regarding issues like glare, radar clutter, and potential airspace penetration. Fortunately, because solar panel profiles are low, they do not physically penetrate airspace, which allows for their installation on building rooftops and in parking areas without significant risk.

Additionally, while metal components on the panels can cause reflected signals, the low altitude of these photovoltaic systems limits their potential to emit electromagnetic waves that could interfere with radar. As a result, the risk of radar confusion remains minimal, enabling airports to safely integrate renewable energy solutions while enhancing sustainability efforts (Kumar and Sudhakar, 2015).

The recent studies have identified that photovoltaic panels can produce glare, potentially affecting air traffic controllers and pilots. To mitigate this issue, the Federal Aviation Administration (FAA) has developed a glare modelling tool. This tool helps assess whether a proposed photovoltaic system, planned for a specific capacity and location, could create glare for air traffic control towers or arriving pilots during landing. By using this tool in the design phase, stakeholders can evaluate potential glare effects and explore alternative designs or locations. This proactive approach ensures that aviation safety is prioritized while integrating renewable energy solutions, enabling

airports to adopt sustainable practices without compromising operational effectiveness. Overall, careful planning and assessment can enhance both safety and sustainability (Sundaram and Babu, 2015).

In light of the increasing concerns surrounding energy consumption and pollution, the need for sustainable designs and practices has become critical, particularly in energy-intensive infrastructures like airports. Airports are major consumers of energy due to their continuous operations and extensive facilities, which include lighting, heating, cooling, and numerous electronic systems. Given this high level of energy demand, it is essential to incorporate sustainable approaches to mitigate environmental impact while ensuring efficient operations.

As discussed, many of the challenges related to energy consumption in airports can be addressed, either fully or partially, through the adoption of suitable sustainable practices. These include energy-efficient equipment, the use of renewable energy sources, and the implementation of smart technologies that optimize energy use. Implementing such measures can transform airports into more environmentally responsible entities while maintaining, or even improving, the quality of service they provide. By carefully integrating a combination of these sustainable techniques, airports can make substantial contributions toward reducing their carbon footprint and promoting a more sustainable future. With thoughtful planning and investment in energy-efficient technologies, the aviation industry can balance its operational needs with the urgent global push for environmental sustainability, helping shape a greener and more responsible future.

2.3 Energy management and Optimization in airports

2.3.1 Adoption of Energy management standards in airports

The International Organization for Standardization (ISO), in collaboration with the United Nations Industrial Development Organization, developed the ISO 50001 Energy Management System (EnMS) framework to enhance energy management sustainability. Introduced in June 2011, this international standard provides a unified approach for organizations to improve energy efficiency (Dzene et al., 2015; Gopalakrishnan et al., 2014; Yuriev & Boiral, 2018). By implementing ISO 50001, organizations can systematically assess and optimize their energy use, leading to improved energy performance. This framework not only helps in reducing operational costs but also contributes to lowering greenhouse gas emissions, aligning with global sustainability goals and promoting responsible energy management practices (Hasan & Trianni, 2020; Sola & Mota, 2020).

According to Brown and Desai (2014), the adoption of the ISO 50001 Energy Management System standard by the International Organization for Standardization (ISO) has unified previously separate national standards, providing a structured and globally accepted approach to energy management. This system allows organizations to assess their strengths and weaknesses in energy management. The benefits of implementing this standard include the ability to establish guidelines for improving the Energy Management System (EnMS) and achieving sustainability goals, ultimately leading to enhanced energy performance and reduced greenhouse gas emissions (Nakthong & Kubaha, 2019).

ISO 50001 provides a comprehensive framework for an Energy Management System (EnMS) aimed at improving energy performance (Poveda-Orjuela et al., 2018). This standard comprises five essential components: roles and responsibilities, energy policy,

energy objectives and targets, energy efficiency improvement plans, and monitoring, measurement, and analysis (Energy Efficient Singapore, 2021; International Organization for Standardization, 2021). These components guide organizations in implementing effective energy practices, achieving significant savings, and ensuring continuous improvement in energy efficiency. The main objective of ISO 50001 is to enable organizations to sustainably enhance their energy performance, which leads to reduced energy consumption and costs, while also mitigating the environmental impacts associated with climate change. By adopting this standard, organizations can align their energy management efforts with global sustainability goals. (Nakthong & Kubaha, 2020).

ISO 50001 Energy Management System is a voluntary standard (Lira et al., 2019) that has gained significant traction among organizations worldwide since its introduction (Laskurain et al., 2017). This standard offers numerous benefits, including a reduction in environmental impact, enhanced corporate reputation, and lower operational costs, which collectively contribute to improved competitiveness (International Organization for Standardization, 2018a). By adopting an ISO 50001-certified system, organizations can achieve compliance with various environmental regulations (Capital NDT, 2021; Eccleston et al., 2012).

A key advantage of the ISO 50001 standard is that it equips organizations with a powerful framework for continuous improvement in energy performance (Marimon & Casadesús, 2017). The standard emphasizes the importance of measuring energy performance improvements through established metrics such as energy performance indicators (EPIs) and setting an energy baseline (EB) for effective tracking (Nakthong & Kubaha, 2020). This structured approach not only facilitates better energy

management but also supports organizations in their sustainability goals and efforts to mitigate climate change impacts.

According to the EPRA report of 2019, energy efficiency and conservation were identified as key factors in improving productivity in industrial, commercial, and institutional facilities as well as conserving the environment. From the studies conducted by EPRA on the Energy management regulations and the benefits from the regulations in terms of cost savings and avoidance of grid emissions, the conclusions can be summarized as shown in Table 2.1. (EPRA, 2020)

Table 2.1: Estimated electrical energy and cost savings, and avoided emissions

Type of facility	No. of compliant facilities in the category	Projected annual savings (Gwh)	Projected annual cost savings (billion ksh)	Projected annual avoided CO2 emissions (Ton)
Industrial	634	924	16.4	107,199
commercial	679	178	2.8	20,667
Total	1313	1102	19.2	127,866

The study found that in 2019, full compliance with energy efficiency regulations resulted in an estimated 1,102 GWh of energy savings, with industrial facilities contributing 83% of this total. These energy savings translated to approximately Ksh.19.2 billion in cost reductions and the prevention of 127,866 tons of CO₂ emissions annually (EPRA, 2020). While these achievements are significant, they underline the need for greater focus on energy efficiency in commercial facilities, particularly airports. Commercial facilities accounted for only 17% of all compliant entities in the study, highlighting a gap in the adoption of energy-saving practices in this sector.

Given the substantial energy demands of airports, which operate continuously and require extensive resources for lighting, heating, cooling, and powering various

systems, improving energy efficiency in these facilities is critical. Airports have the potential to achieve significant energy savings and reduce their environmental impact through targeted strategies such as upgrading HVAC systems, utilizing energy-efficient lighting, and incorporating renewable energy sources.

By increasing compliance and implementing advanced energy management systems, airports can contribute more substantially to overall energy savings. This would not only help in reducing operational costs but also play a crucial role in minimizing their carbon footprint. As the study demonstrates, there is a clear need to expand energy efficiency initiatives beyond the industrial sector to commercial facilities like airports, where the potential for both economic and environmental benefits is considerable. Addressing this gap could lead to even greater energy savings and reductions in greenhouse gas emissions across the country.

The adoption of energy management standards in airports is a critical step toward reducing energy consumption and promoting sustainability in the aviation sector. Airports are large, complex infrastructures that operate throughout, requiring significant amounts of energy for lighting, heating, cooling, and powering various systems. By implementing energy management standards, airports can streamline their energy use, reduce waste, and lower their environmental impact.

The previous studies have examined airports worldwide that have implemented ISO 50001-certified Energy Management Systems (EMS). Airports that have adopted these energy management standards, such as Heathrow Airport and San Francisco International Airport, have demonstrated considerable success in reducing their energy usage and carbon emissions. These initiatives not only reduce operational costs but also enhance the airport's reputation as an environmentally responsible organization. These

systems are increasingly adopted and play a vital role in enhancing energy and environmental management. Airports in countries such as China, Cyprus, Hong Kong, and various European nations, India, Turkey, Sweden, the United Kingdom, and the United States have embraced this standard since its launch in 2011. However, there is limited information regarding the adoption of ISO 50001 by airports in Kenya. This gap highlights the need for further research to explore how Kenyan airports can benefit from implementing such energy management practices to improve efficiency and sustainability.

Integrating various types of airport energy management (EM) systems with ISO 50001 can be a crucial first step toward achieving sustainable airport operations. This integration focuses on enhancing energy efficiency while simultaneously reducing CO₂ emissions. ISO 50001 provides a comprehensive framework for organizations of all sizes, including governments and public and private facilities. However, establishing sustainable airports presents significant challenges. Therefore, modelling EM processes can serve as an essential starting point, enabling airports to better align their operations with sustainability objectives and improve their overall energy management practices. This proactive approach fosters long-term environmental benefits and operational efficiencies.

In conclusion, the adoption of energy management standards is essential for airports to manage their energy consumption more efficiently, contribute to global sustainability efforts, and improve operational performance. By setting benchmarks for energy use, monitoring progress, and making continuous improvements, airports can play a significant role in creating a more sustainable aviation industry. This study aims to develop an energy management model based on the ISO 50001 standard, addressing the knowledge gap in airport energy efficiency. The model will optimize the use of

existing resources and technologies while promoting environmental performance and reducing greenhouse gas (GHG) emissions, aligning operational practices with sustainability objectives.

2.3.2 Energy modelling in infrastructures

Energy modelling in airports aims to quantify energy consumption and predict the effects of new technologies on energy use. It also forecasts energy demand and identifies influencing factors (Swan and Ugursal, 2009). Numerous studies on energy modelling have been conducted across various building types, including airports, and these can be classified into distinct categories, as shown in Figure 2.2 (Wang et al., 2012; Alba and Manana, 2016). This modelling is essential for optimizing energy efficiency and reducing overall consumption in airport operations.

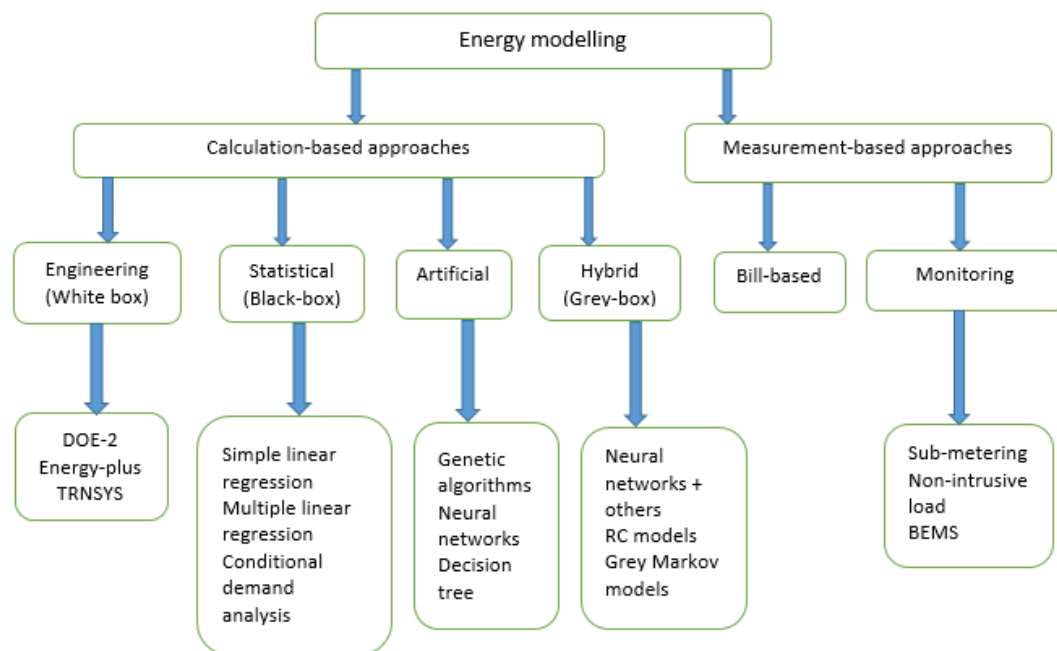


Figure 2.2: Scheme of energy modelling methods (Wang et al., 2012; Alba and Manana, 2016).

Calculation-based approaches use mathematical tools to simulate energy consumption in buildings, categorized into statistical, engineering, artificial intelligence, and hybrid

methods for enhanced accuracy and predictive capabilities (Swan and Ugursal, 2009; Zhao et al., 2012; Fumo, 2014)

- Statistical methods do not depend on physical data about the system. Instead, they use known inputs and outputs along with historical data to define a mathematical model, where the variables involved do not have direct physical meaning (Fumo and Biswas, 2015; Aranda et al., 2012).
- Engineering methods utilize detailed physics to model the energy behavior and thermal dynamics of a system, beginning with known inputs to predict outputs (Zhao et al., 2012). These approaches are characterized by the use of specialized software tools (Crawley et al., 2008) and require a high level of technical expertise. The accuracy of the models improves as more detailed information about system characteristics is gathered. To mitigate the complexity and technical demands, simplified methods, such as the degree-day or bin method, have been developed (Al-Homoud, 2001). These alternatives allow for effective energy modelling while reducing the need for extensive data and technical knowledge.
- Hybrid methods integrate simplified physics with statistical techniques to simulate system behavior. This approach minimizes the need for extensive training data and reduces calculation time by using operational data to derive model coefficients, enhancing efficiency in energy modelling (Wang et al., 1999; Braun et al., 2002)
- Artificial methods utilize historical data to model systems, effectively addressing nonlinear energy consumption issues through techniques like machine learning and neural networks for pattern recognition (Kalogirou, 2006; Lai, 2008; Yu, 2010; Ooka, 2009).

Measurement-based approaches assess energy consumption using methods from simple bill analysis to detailed monitoring systems (Wang et al., 2012). Bill-based methods are straightforward, relying on easily accessible electricity bills. However, this approach often provides limited insights, as monthly data lacks the granularity necessary for a thorough assessment of energy efficiency. Such aggregated data does not effectively characterize energy usage across different end-uses, making it challenging to identify specific areas for improvement (Field, 1997).

Monitoring methods play a crucial role in enhancing energy management in buildings and infrastructures. They facilitate better energy control, quantify energy efficiency, and detect faults. These methods can be categorized into end-use sub-metering, non-intrusive load monitoring, and building energy management systems (BEMS). Sub-metering involves installing separate meters for individual systems, allowing for precise energy data collection. While effective for detailed energy investigations, this method can be prohibitively expensive for conventional buildings (Philip and Chow, 2007). Non-intrusive load monitoring employs pattern recognition techniques to analyze energy consumption with minimal hardware installation, making it a cost-effective option (Pihala, 1998). BEMS, on the other hand, are advanced computer-based systems designed to manage, control, and monitor various facility operations, primarily heating, ventilation, air conditioning (HVAC), and lighting. These systems not only track energy usage but also provide valuable insights and tools to understand energy behavior, ultimately aiding in energy efficiency improvements (Masoero, 2010). By utilizing these monitoring methods, organizations can enhance their energy management practices, reduce consumption, and contribute to sustainability efforts.

The latest monitoring methods enable the collection of electric load profiles in evaluated buildings or infrastructures, providing detailed records of electric power

consumption at intervals typically ranging from 5 to 15 minutes. This extensive data set offers valuable insights into how facilities use energy, making it an effective tool for optimizing energy consumption (Mathieu, 2011).

Analyzing electric load profiles can reveal periodic patterns and fluctuations in energy demand, which can inform better energy management strategies. Current research has examined energy demand patterns across various infrastructures, including hotels, universities, office buildings, hospitals, department stores, residential buildings, and industrial facilities (Ortega & Manana, 2017). These studies demonstrate the applicability of monitoring methods in diverse settings and emphasize their critical role in enhancing energy efficiency and sustainability. By leveraging detailed energy usage data, organizations can implement targeted interventions to reduce consumption, lower costs, and minimize environmental impacts. However, no scientific research currently exists on energy demand patterns in airports, making them excellent candidates for focused energy research in this field.

Research on energy modelling in airports has primarily focused on calculation-based approaches, particularly hybrid methods like unbiased grey Markov models, RC models, and neural networks (Huang and Chen, 2015). Some studies also utilize commercial energy simulation programs to analyze energy consumption and improve efficiency (Falvo, 2013), offering valuable insights for better energy management in airport operations.

2.3.3 Simulation programs for the design of energy systems

The world is grappling with two critical challenges: the energy crisis and the climate crisis (Pürlü et al., 2022). In response, microgrid applications integrating renewable energy sources (RESs) have emerged as a popular solution to meet the increasing

energy demands of densely populated regions while reducing carbon footprints. On-grid hybrid energy systems (HESs) are designed to enhance the share of renewable energy, mitigate emissions, improve voltage profiles, reduce technical losses, and ensure a reliable energy supply. Conversely, off-grid (standalone) HESs operate independently of the main grid, incorporating a mix of RESs, non-renewable energy sources, and energy storage systems (ESSs) (Buts et al., 2021).

These systems utilize a variety of energy sources, including solar, wind, biomass, and diesel generators, along with storage solutions such as batteries and pumped storage. The selection, sizing, and placement of these components require careful analysis to provide technical, economic, and environmental benefits. A range of optimization algorithms and tools are employed in the design of HESs (Li et al., 2022), and various computer simulation software is available to analyze their performance and ensure effective integration of the energy components (Pürlü et al., 2023). This comprehensive approach is essential for sustainable energy management. Computer simulation software features can be summarized in Table 2.2.

Table 2.2: Simulation programs for the design of energy systems

Software	Free trial	Environmental	Technical	Economic	Optimization
PvSYST	√	√	√	X	√
SAM	√	√	√	√	X
RETScreen	√	√	√	√	X
HYBRIDS	X	√	√	X	√
HOMER	√	√	√	√	√
Hybrid2	√	√	√	X	X
LEAP	X	√	√	√	√
SolSim	X	√	√	√	√
TRNsys	√	√	√	X	X
HYDROGEMS	X	√	√	√	√
Ihoga	X	√	√	√	√

The HOMER software is a robust tool for designing and analyzing hybrid energy systems, which can include traditional power generators, cogeneration systems, wind turbines, photovoltaics (PVs), hydropower, batteries, fuel cells, and biomass. A distinctive feature of HOMER is its sensitivity analysis capability, which evaluates the impact of uncontrollable variables—such as wind speed and fuel costs—on system optimization (Al Alnazi et al., 2022). This allows users to refine their designs based on parametric changes.

Microgrid development aims to enhance energy resilience and reduce dependence on fossil fuels by utilizing locally available renewable energy sources. Proper unit sizing is essential in designing microgrid architectures; the right configuration can significantly affect total system size and costs. The types and numbers of microgrid units selected will greatly influence overall sizing (Kumar et al., 2014).

In a study by Shirzadi et al. (2020) at Concordia University, researchers focused on optimizing a renewable energy-based microgrid configuration to minimize net present costs. Their findings revealed a 50% reduction in energy costs, with vertical-axis solar trackers being the preferred technology for implementation. Similarly, Salisu et al. (2019) employed HOMER to conduct a techno-economic and environmental assessment of a microgrid, considering cost and sensitivity analyses. Their results demonstrated that the optimal design was not only environmentally friendly but also cost-effective, showcasing the software's effectiveness in achieving sustainable energy solutions. This underscores the potential of hybrid energy systems in addressing energy challenges while promoting economic viability.

A study in South Jordan utilized HOMER software to develop a smart grid design integrating photovoltaic (PV) and wind energy systems, aiming to reduce dependence

on imported energy and shift towards clean, cost-effective alternatives. The modelling results confirmed the economic feasibility of the design (Alsafasfeh, 2015). In Hargeisa, Somalia, Abdilahi et al. (2014) conducted a feasibility analysis of a hybrid renewable energy system using HOMER. The study found that implementing the hybrid system significantly increased the utilization of renewable energy sources and reduced energy costs compared to the traditional reliance on diesel generators, which had been the primary power source. Türkay and Telli (2011) also employed HOMER to analyze both autonomous and grid-tied hybrid systems for a university campus in Istanbul, Turkey. Their research aimed to identify the optimal system based on the area's solar radiation, wind resource potential, and hydrogen storage capabilities. The findings indicated that a grid-tied system was the most viable option, demonstrating HOMER's effectiveness in optimizing renewable energy configurations across different contexts.

This study selected HOMER software for its capabilities in both simulation and optimization. During simulation, HOMER evaluates the performance of a specific micropower system configuration hourly throughout the year, assessing its technical feasibility and life-cycle costs. In the optimization phase, it explores various system configurations to identify the one that meets technical constraints at the lowest life-cycle cost and Levelized Cost of Electricity (LCOE).

The primary focus was to design an optimal configuration for either a standalone photovoltaic (PV) system with batteries or a grid-connected PV system, with or without batteries, based on the electrical energy consumption patterns at the airport.

2.4 Techno-economic analysis of solar photovoltaic system

A techno-economic analysis of a solar photovoltaic (PV) system assesses both the technical performance and economic feasibility of solar energy projects. It involves evaluating energy yield, system design, installation costs, maintenance, and financial returns, ensuring that solar power provides a cost-effective, sustainable solution for energy needs in various infrastructures, such as airports (Duffie & Beckman, 2013)

Once a photovoltaic (PV) system is installed, understanding its performance becomes essential to ensure optimal energy production and efficiency (De-Lima et al., 2017). Outdoor performance often deviates from manufacturer specifications, which are typically derived from standard test conditions (STC). To assess the performance of grid-connected PV systems, specific parameters outlined in IEC Standard 61724 (1998) are commonly utilized. Among these, the most critical metrics include final energy output, performance ratio, and capacity factor. These parameters provide insights into energy production, utilization of available solar resource, and the overall impact of system losses. They also facilitate comparisons between different PV systems based on design, technology, geographic location, and prevailing weather conditions (Gongsin & Saporu, 2020; Beyer et al., 2011; Okello et al., 2015).

The performance discrepancies among PV systems can be attributed to a variety of factors. These include balance of system components (Congedo et al., 2013), meteorological influences such as temperature and humidity (D'Orazio et al., 2014; Pietruszko et al., 2012), solar irradiance levels (Al-Addous et al., 2017), cell temperature variations (Bai et al., 2016; Zaoui et al., 2015), and the accumulation of dust on the panels (Fouad et al., 2017; Chanchangi et al., 2020). Therefore, it is crucial to evaluate the performance of PV systems at their specific installation sites. One of the most significant factors affecting energy generation is the solar radiation incident on

the modules, underscoring the importance of site-specific performance assessments (Al-Aboosi, 2020).

The studies worldwide have analyzed the technical and economic performance of photovoltaic (PV) modules using one-year data (Alshare et al., 2020; Sreenath et al., 2021; Thotakura, 2020; Vidal et al., 2020). Martín-Martínez et al. (2019) emphasized that underestimating the complexity of dual tracking systems during the design phase can lead to inaccurate assessments of operation and maintenance (O&M) costs, impacting the Levelized Cost of Energy (LCOE). They recommend further research over longer periods to confirm observed trends and improve accuracy. Collecting more comprehensive data will enable the development of new mathematical models for PV systems, enhancing design accuracy and optimizing overall energy efficiency in PV power plants.

Table 2.3 summarizes the technical performances of photovoltaic (PV) modules across different regions, highlighting location-specific influences on performance and the need for more balanced regional research in this field. The regions studied include North Africa, the Middle East, Europe, Asia, West Africa, Southern Africa, and South America. Previous research (Chawla & Tikkiwal, 2021; Ngure et al., 2023; Martín-Martínez et al., 2019) emphasizes that technical analysis is critical for guiding decisions related to design, installation, and commissioning, which ultimately enhance system performance.

Several studies recommend that economic performance evaluations be conducted alongside technical assessments to offer a comprehensive view of the benefits of solar PV systems. By integrating these analyses, decision-makers can gain deeper insights into the feasibility and sustainability of solar energy projects, ultimately promoting the

adoption of renewable energy solutions in the region (Seme et al., 2019; Chawla & Tikkiwal, 2021).

Table 2.3: Selected studies of solar PV module technical performance

Author	Cell Tech.	YR (kWh/kW)	YF (kWh/kW)	CUF (%)	η (%)	PR (%)	Region
Martín-Martínez et al. (2019)	P-Si	5.64	4.71	19.64	10.82	83.62	Spain
Arora et al. (2019)	P-Si	5.13	4.28	17.8	14.77	82.7	India
Daher et al.(2018)	P-Si	5.6	4.69	16.38	12.68	84	Djibouti
Al-Badi (2020)		5.59	3.78	15	10.3	67	Middle East
Seme et al.(2019)			2.84	11.85		68.84	Europe
Sahouane et al. (2019)		6.2	4.4	18.58	10.99	71.89	North Africa
Vidal et al.(2020)			3.6	15.1		89	South America
Mensah et al. (2019)				16.2		70.6	West Africa

2.5 Greenhouse gas emissions

Greenhouse gases are specific gaseous emissions that contribute to the Earth's rising average temperature through the greenhouse effect. When solar radiation reaches the Earth, some of it reflects back into space. However, certain atmospheric gases trap this heat, preventing it from escaping. This process is considered the primary cause of global warming, leading to climate changes and various environmental impacts. The accumulation of greenhouse gases in the atmosphere intensifies this effect, resulting in significant challenges for ecosystems and human societies (ICAO Environment Report, 2022).

Greenhouse gases (GHGs) are emissions that contribute to the greenhouse effect, a phenomenon that leads to global warming. This effect occurs when certain gases in the atmosphere trap solar radiation, preventing it from escaping into space. The primary sources of GHGs include fossil fuel combustion, waste decomposition, and deforestation. Six main GHGs are identified as major contributors: carbon dioxide

(CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆) (Kyoto Protocol, 2018).

Airports are significant contributors to greenhouse gas (GHG) emissions due to the vast range of energy-intensive activities that take place, many of which go beyond the adoption of solar photovoltaic (PV) systems. A primary source of these emissions comes from aircraft operations, particularly during taxiing, idling, and take-off. Aircraft engines emit large amounts of carbon dioxide (CO₂), nitrogen oxides (NO_x), and particulate matter (PM), especially during ground operations before take-off and after landing. Additionally, the ground support equipment (GSE) used to service planes such as baggage carts, fuel trucks, and aircraft tugs are frequently powered by fossil fuels like diesel or gasoline, further contributing to CO₂ emissions (ICAO, 2022).

Another significant contributor is the energy consumption within airport terminals. Airports are large complexes that require extensive heating, ventilation, and air conditioning (HVAC) systems to maintain comfortable conditions for passengers and staff year-round. This energy demand is a key source of indirect GHG emissions, particularly in airports that rely on electricity generated from fossil fuels. Additionally, airports require extensive lighting, both inside terminals and outside on runways, taxiways, and parking areas, which further adds to their overall energy consumption (IEA, 2022).

Ground transportation to and from airports also plays a significant role in GHG emissions. Passengers and airport employees often rely on private vehicles or shuttle buses powered by gasoline or diesel, which contributes to CO₂ and other harmful emissions. While some airports are investing in electric or hybrid vehicles for internal transport, many still operate fleets of fossil fuel-powered shuttles and buses. Another

source of emissions comes from backup generators, which are typically diesel-powered and are used to ensure continuous power during grid failures. These systems add to the airport's overall carbon footprint, especially in regions where power reliability is an issue (European Commission, 2020).

Waste management within airports is another source of GHG emissions. Waste, especially organic material, decomposes in landfills and produces methane (CH_4), a potent greenhouse gas. Moreover, water and wastewater treatment processes can produce methane and nitrous oxide (N_2O) if managed inefficiently. Finally, the construction and maintenance of airport infrastructure, such as runways, terminals, and other facilities, involve high-emission activities due to the use of heavy machinery and materials like concrete and asphalt, which have substantial carbon footprints (ICAO, 2020).

In aviation, CO_2 is the most significant GHG emitted, primarily from aircraft during flight. N_2O represents a smaller percentage of emissions, while modern aircraft do not produce CH_4 , HFCs, PFCs, or SF_6 . Airports also generate GHG emissions from various sources, including ground support equipment, passenger vehicles, heating systems, waste management practices, de-icing agents, electrical consumption, and refrigerant losses (ACA Report, 2022). To effectively measure and report these emissions, international standards such as the Greenhouse Gas Protocol and ISO 14064 have been established. These frameworks guide organizations in developing and maintaining accurate emissions inventories, facilitating efforts to mitigate climate impact and enhance sustainability in aviation (ICAO, 2022). CO_2 is the most prevalent greenhouse gas (GHG), but different GHGs vary in their contributions to the greenhouse effect and atmospheric lifetimes. Some gases can remain for decades or centuries. To facilitate comparisons of emissions from various sources, GHGs are reported in carbon dioxide

equivalents (CO₂-eq). This standardization helps stakeholders understand the relative impacts of different gases, enabling more effective strategies for reducing overall GHG emissions across sectors.

The aviation industry is crucial to global transportation, moving over 4.4 billion passengers in 2018 (IATA, 2019) and 221 billion ton-kilometers of freight (World Bank Group, 2020). It accounts for approximately 2%–3% of global anthropogenic greenhouse gas (GHG) emissions (Graver et al., 2019; ICAO, 2020), a figure expected to rise as other sectors decarbonize more readily (Terrenoire et al., 2019). Much of the focus has been on mapping the carbon impact of aircraft operations, such as take-off, cruising, and landing, while airport operational activities—like lighting, runway maintenance, and servicing parked aircraft—receive less attention (Monsalud et al., 2015). Airports are estimated to contribute only about 5% of the aviation sector’s total GHG emissions (ACA, 2020), but this is likely an underestimate, as it does not account for all operational activities or their regional impacts (Greer et al., 2020). For effective climate change mitigation, comprehensive environmental accounting must encompass all emissions from airport operations, enabling the industry to identify opportunities for reducing its overall carbon footprint and improving sustainability efforts.

During turnaround operations, when an aircraft is parked at a gate, it requires electrical power and air conditioning to maintain system functionality and ensure passenger comfort. These needs are typically met by the aircraft’s auxiliary power unit (APU), which operates on jet fuel, or through a combination of the APU and diesel-powered ground service equipment (GSE). The APU, located at the rear of the aircraft, provides essential electrical power and air conditioning, while additional GSE units supply further support.

The combustion of both the APU's jet fuel and the GSE's diesel results in the emission of greenhouse gases (GHGs) and various air pollutants, including nitrogen oxides (NO_x), particulate matter (PM), volatile organic compounds, and sulfur dioxides (Kinsey et al., 2012; Lobo et al., 2015; Winther et al., 2015; Padhra, 2018; Mokalled et al., 2019; Xu et al., 2020). These emissions pose significant risks to human health (Harrison et al., 2015; Yim et al., 2015) and contribute to global warming by adding anthropogenic GHGs to the atmosphere (Pachauri et al., 2014).

The resulting temperature anomalies are expected to cause drastic changes in the climate system, leading to increased frequency and intensity of droughts, wildfires, hurricanes, and coastal sea level rise. These impacts have long-ranging negative consequences for ecosystems and human communities, underscoring the urgent need for more sustainable operational practices in the aviation industry. One effective strategy is to reduce reliance on auxiliary power units (APUs) and ground service equipment (GSE) by utilizing electricity-powered gate equipment for parked aircraft. When stationed at the gate, aircraft can receive electricity from the airport's electrical grid through 400 Hz ground power cables, while thermal comfort is maintained using hoses connected to preconditioned air (PCA) units, typically located near the passenger boarding bridge (PBB).

Recent analyses indicate that gate electrification significantly reduces ambient concentrations of nitrogen oxides (NO_x) and particulate matter (PM) on the airport apron, which is crucial for mitigating health risks for nearby populations (Benosa et al., 2018; Fleuti, 2018; Preston et al., 2019). Additionally, it has been qualitatively suggested that utilizing 400 Hz and PCA units helps lower fuel costs for airlines (ACRP et al., 2012). Gate electrification is recognized as a vital greenhouse gas (GHG)

reduction strategy for airports (Barrett, 2019), although the specific scope of its GHG reduction potential remains largely unquantified.

In conclusion, mitigating GHG emissions at airports requires a multifaceted approach. While solar PV systems can reduce energy use, other strategies—such as electrifying ground support equipment, improving energy efficiency in buildings, promoting public transportation, and incorporating sustainable aviation fuels—are necessary to tackle the diverse sources of emissions and move toward a sustainable future. While GHG emissions from airport activities, such as the landing and take-off cycles of aircraft, have been examined (Dissanayaka et al., 2020), there is a notable lack of studies quantifying emissions from energy generation related to gate electrification.

This research seeks to address this gap by focusing on a Kenyan airport, contributing to a better understanding of sustainable practices in the East African region. Furthermore, the study will review innovative technologies that have been implemented or proposed for mitigating GHG emissions from airports, enriching the existing knowledge base on environmental sustainability in aviation.

2.6 Knowledge Gap and Contribution of the Study

From the reviewed literature it can be indicated that;

1. This study enhances understanding of energy dynamics in airports, an area that remains underexplored. Most existing research focuses on electric energy consumption in terminal buildings, overlooking the entire airport context. Furthermore, there is limited information on electric energy generation and energy efficiency in Kenyan airports. By addressing these gaps, this research aims to provide valuable insights into improving energy management and sustainability practices.

2. The performance studies of photovoltaic (PV) modules are often location-specific and regionally unbalanced. Currently, there is little to no information available on PV module performance in the humid tropical savannah climate of the Kenyan coastal region, making this study essential to address this knowledge gap.
3. Studies address holistic airport microgrid modelling, including grid, PV, and battery pack up leading to the development of an energy model that can form a framework to be replicated in other airports.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

Chapter three consists of four sections. It begins with the descriptions of the study area, installation configurations, measurement methods, and data collection procedures. Additionally, it details the energy consumption of the airport, including that of its clients. Section two presents the simulation tool used to model the PV system for optimal configuration. Section three addresses the technical and economic performance of photovoltaic (PV) modules in the humid tropical savannah climate of Moi Airport. It outlines the parameters and performance indicators used to evaluate the effectiveness of the PV modules. Lastly, section four describes the methodology employed to estimate the greenhouse gas (GHG) emissions reductions achieved through the use of the solar PV system.

3.2 Location and Installation Descriptions

3.2.1 Study Location

The research was conducted at Moi International Airport in Mombasa County, situated along Kenya's coastal region. Figure 3.1 displays the map of Moi International Airport and the study site location. The site was approximately positioned at 04°02'05" S and 039°35'39" E, with an elevation of around 20 meters above sea level, just outside Mombasa Island. Meteorological data were obtained from the airport's meteorological department. Moi International Airport, situated near Mombasa, Kenya, was classified under the humid tropical savanna climate according to the Köppen climate classification. The region experienced consistently warm temperatures throughout the year, with only a five-degree Fahrenheit difference between the hottest month, January, and the cooler months of July and August. While humidity levels were high due to the airport's coastal location, ocean breezes helped to prevent excessive heat. The wettest

months were April and May, with heavy rainfall, while January and February were the driest. This combination of stable temperatures, high humidity, and seasonal rainfall made the site ideal for environmental and aviation studies that considered climate impacts. According to the data available, Moi International Airport received an average ambient temperature, relative humidity, wind speed, and solar irradiance of 26.12°C, 76.92% 5.01m/s, and 5.87 kWh/m² respectively.

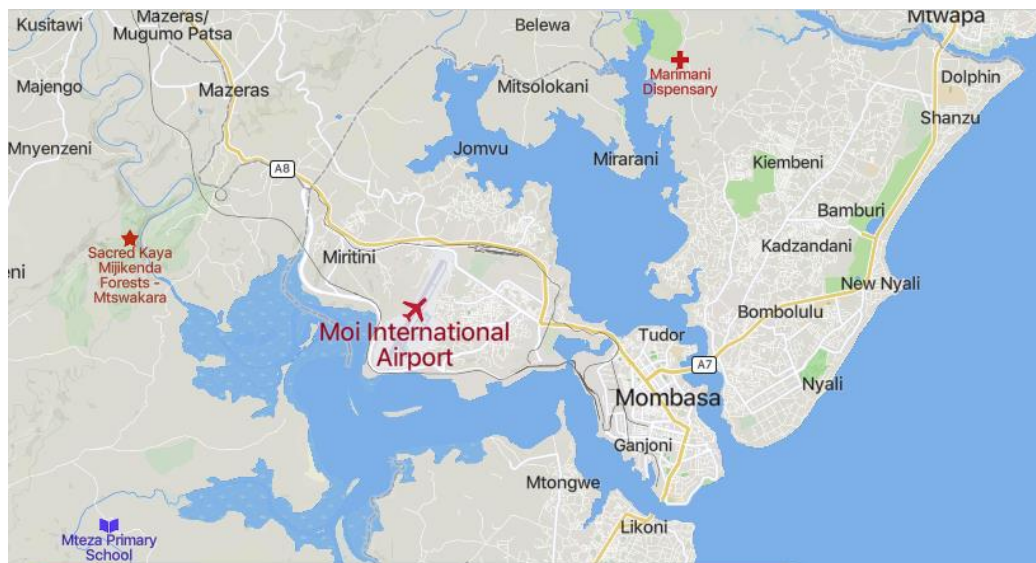


Figure 3.1: Aerial view of Moi International Airport



Figure 3.2: Solar Photovoltaic plant at Moi International Airport, Mombasa (ICAO, 2019).

3.2.2 Installation Descriptions

This study was conducted on a solar PV installation (solar-at-gate) at Moi International Airport which has been operating since April 2019. Figure 3.2 shows the installed solar photovoltaic system. The system occupied an area of around 1.5 acres (0.60 hectares) with an installed capacity of 507kw. The plant comprised of 1,560 PV modules, with each module having a rated peak power of 325 watts. The modules were ground mounted, tilted at 10^0 to the horizontal axis, and oriented towards the South. The modules were arranged into 88 strings, 80 of which had 18 modules each while the other 8 strings had 15 modules each. Each string consisted of modules connected in series, and the system was linked to the grid via 11 DC-AC inverters, each with a capacity of 40 kW. The voltage was stepped up from the inverters' nominal voltage of 415V to the network's 11kV by 630kVA 415V/11kV step-up transformer. Table 3.1 presents the technical specifications of the solar modules utilized in the installation.

Table 3.1: Selected Solar module Technical Data at STC (irradiance 1000w/m², AM 1.5 and cell temp 25°C)

Solar module type	CS6U 325P
Cell type	Poly-crystalline silicon
Cell arrangement	72(6x12)
Nominal Max. power (Pmax)	325W
Opt. Operating Voltage (Vmp)	37.0V
Opt. Operating Current (Imp)	8.78A
Open Circuit Voltage (Voc)	45.5v
Short Circuit Current (Isc)	9.34A
Module Efficiency	16.72%
Operating Temperature	-40 ⁰ C
Max. System Voltage	1000V(IEC/UL) or 1500V(IEC/UL)
Dimensions	1960 x 992 x 35 mm
Weight	22.4 kg

Table 3.2: Selected solar module technical Data at NMOT (irradiance 800w/m², AM 1.5, ambient temperature 20°C and wind speed 1m/s)

Nominal Max. power (Pmax)	239W
Opt. Operating Voltage (Vmp)	34.0V
Opt. Operating Current (Imp)	7.03A
Open Circuit Voltage (Voc)	42.4V
Short Circuit Current (Isc)	7.54A
Temperature Coefficient (Pmax)	-0.40% / °C
Temperature Coefficient (Voc)	-0.31% / °C
Temperature Coefficient (Isc)	0.05% / °C
Nominal Module operating temperature(NMOT)	43 ± 3°C

Table 3.3: Selected specifications of Smart String Inverter

Inverter type	Huawei SUN2000-36KTL
Max. Efficiency	98.8% @480Vac 98.6% @380Vac/400Vac
European Efficiency	98.6% @480Vac 98.4% @380Vac/400Vac
Max. DC usable power	40,800W
Max. input voltage	1,100V
Max. current per MPPT	22A
Max. short circuit current per MPPT	30A
Min. operating Voltage/Start input voltage	200V/250V
Full Power MPPT Voltage Range	480 V ~ 850 V @380Vac / 400Vac 580V~850V @480Vac
MPPT Operating Voltage Range	200 V ~ 1000 V
Rated Input Voltage	620 V @380Vac / 400Vac 720V @480Vac
Rated Output Voltage	220V / 380V, 230V / 400V
Max. Output Current(@380V/400V/480V)	60.8 A / 57.8 A / 48.2 A

3.2.3 Data collection and monitoring

The installation included a Huawei Smart Logger 2000 data logger that monitored and recorded the DC output from the solar array, AC output from the inverters, and other pertinent data at 20-minute intervals. This data was transmitted to a communication receiver in the control room for monitoring purposes. Additionally, a pyranometer (SPM 11) measured the in-plane solar radiation on the modules. The study utilized five years data collected between April 1, 2019, and December 31, 2023, which also included environmental parameters such as solar irradiance, relative humidity, ambient temperature, and wind speed from airports meteorological station.

3.3 Electrical Energy consumption in the airport

This study focused on an airport due to its significantly higher energy consumption, hence, need of assessing energy efficiency and the potential benefits of renewable energy systems. The airport's energy consumption was found to be in two areas: buildings, which required lighting, HVAC, and maintenance, and functional facilities, such as baggage systems, airfield lighting, and ground service equipment.

The electrical energy consumption data was gathered from historical records provided by the airport operator and through in situ measurements using a smart monitoring power meter. This approach facilitated improved energy control, quantification of energy efficiency, and identification of facility faults. Monthly data collection resulted in a comprehensive dataset that offered detailed insights into the facility's electrical energy usage over time.

3.4 System modelling

Modelling refers to the process of analysing the behavior, performance, and interactions of components within a system. This involved defining the components, relationships,

and dynamics within the system, allowing for simulations and predictions about how the system operated under various conditions.

The system modelling using HOMER software involved the simulation and optimization of energy systems to evaluate their performance and cost-effectiveness. HOMER (Hybrid Optimization of Multiple Energy Resources) allowed users to design and analyze both grid-connected and off-grid power systems, incorporating various energy sources such as solar, wind, diesel, and battery storage. By inputting parameters such as resource availability, load profiles, and component costs, the software generated scenarios to identify the optimal configuration for meeting energy demands while minimizing costs and emissions. This modelling process was crucial for decision-making in renewable energy projects, ensuring sustainable and efficient energy solutions tailored to specific environmental and economic conditions.

Optimization played a vital role in enhancing the efficiency, economics, resiliency, and robustness of microgrid energy management systems (EMS). In microgrids with multiple distributed energy resources (DERs), an EMS was essential for effectively managing power allocation, controlling energy production costs, and reducing emissions. This ensured sustainable operation and efficient resource utilization. Figure 3.3 shows an EMS in a microgrid (Lawan & Abidin, 2020).

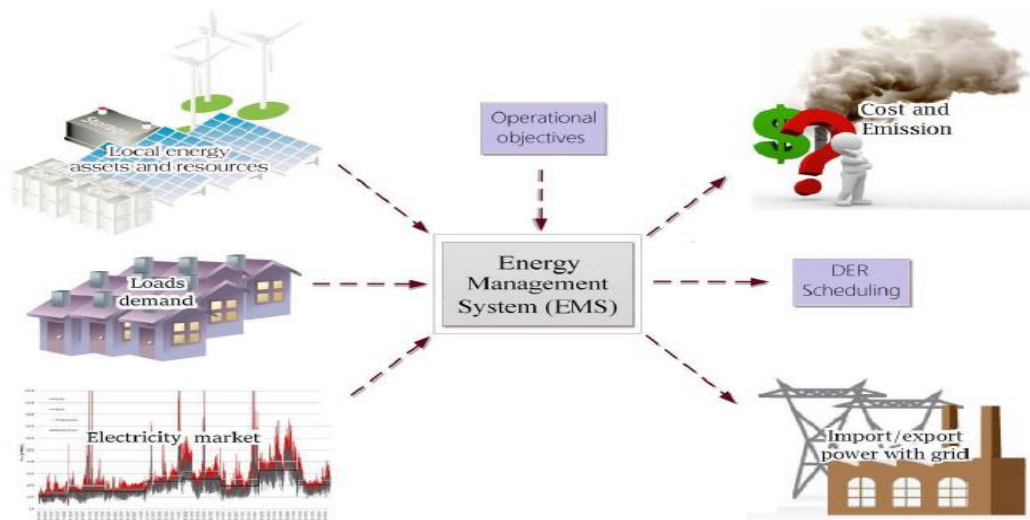


Figure 3.3: Energy management system in a microgrid

This study utilized a simulation-based optimization technique using the HOMER tool. Creating an optimal conversion model ensured consistent energy generation from renewable energy sources for effective management. Following the simulation step, the optimization process generated a sorted list of configurations ranked by Total Net Present Cost (TNPC). The optimal system configuration varied based on the selected sensitivity variable, which allowed users to see how adjustments impact overall performance. The sensitivity phase was optional and presented variables such as wind speed, solar radiation, and fuel costs. This feature enabled users to understand how different conditions affect the optimal system design, ensuring that the selected configuration was both cost-effective and efficient under varying circumstances.

In this study, HOMER software allowed for simulation and optimization of various models of electric renewables. The study evaluated the economic advantages of remaining connected to the grid versus opting for an off-grid solution. It served as a techno-economic optimization tool to compare grid-connected, stand-alone, and battery-backed PV systems. Key performance indicators included the cost of unit energy (CoE), net present cost (NPC), operational cost (OC), and initial cost. The

HOMER tool was chosen for its ability to assess various factors, including technological feasibility, climate conditions, load consumption, and economic parameters. Figure 3.4 shows the simulation and optimization procedures (Qiu, & Entchev, 2022).

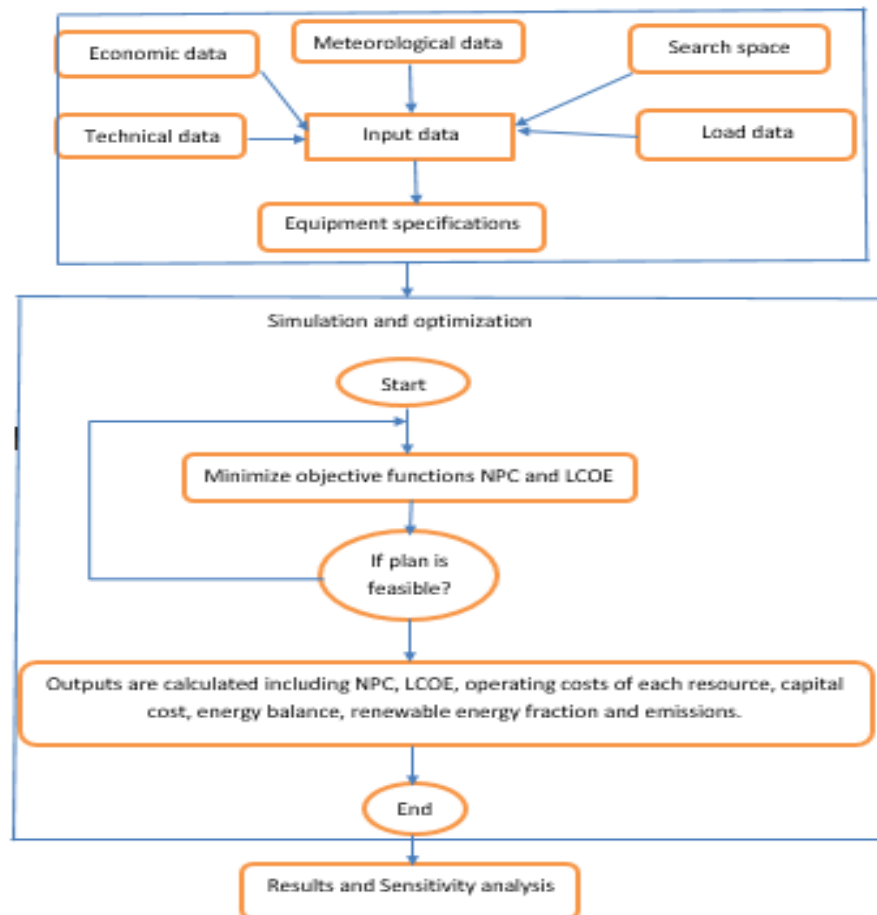


Figure 3.4: HOMER simulation and optimization procedures

3.4.1 Electrical Load Simulation in HOMER

In any power-generating system, defining the load was essential for optimal sizing of components. Some loads, like communication technology systems, required continuous power supply due to their critical nature. These systems must be operated day and night, necessitating uninterrupted service and high-quality, reliable electrical energy. Ensuring a stable power supply for these critical loads was vital for maintaining

operational efficiency and supporting essential communication infrastructure effectively.

In this research, the primary load data was gathered from the airport's main power consumption meters, encompassing both landside and airside operations over a monthly period as presented in appendix 1. The data for the year 2022 was chosen for this simulation because the operations of the airport during the prior years (2019 to 2021) was affected by the covid 19 outbreak and therefore, the data of energy consumption during that period does not give the real situation. As shown in Figure 3.5, HOMER used the load data to simulate daily, seasonal, and annual profiles, enabling the calculation of both average and peak loads.



Figure 3.5: load profile of Moi International Airport

3.4.2 Proposed System Configurations for the Airport

Figures 3.6 to 3.8 depict the suggested configured system setups for the airport. The designs focused on solar energy as the renewable source, exploring three scenarios for analysis. The first scenario was a standalone system, while the second was a grid-connected system without batteries. The third scenario involved a grid-connected system with batteries for additional backup. Connecting the second and third systems to the grid enhanced power stability and reliability, ensuring that backup power was available during periods of low or no electricity generation from the deployed renewable sources, thus maintaining continuous service.

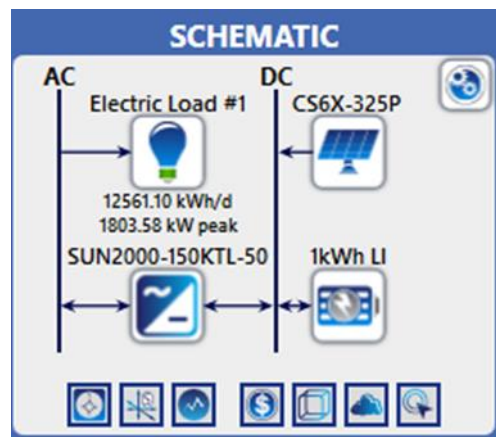


Figure 3.6: Schematic diagram of the proposed standalone PV system

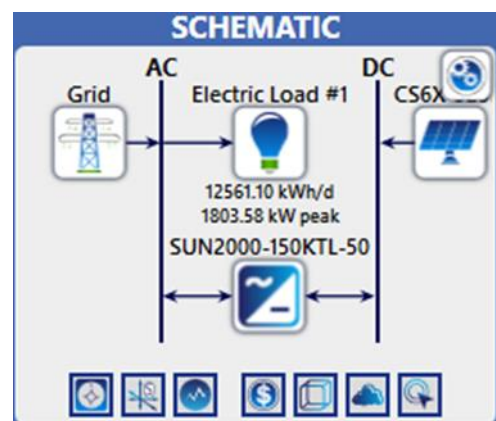


Figure 3.7: Schematic diagram of the proposed Grid-connected PV system without batteries

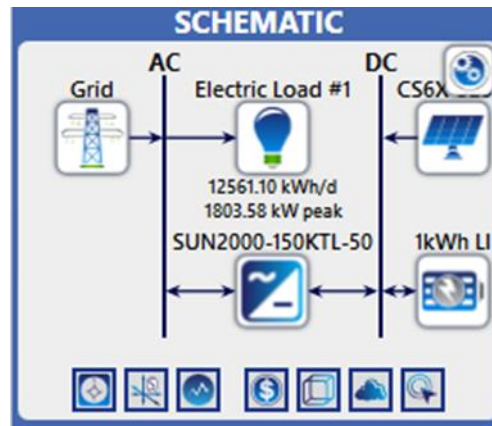


Figure 3.8: Schematic diagram of the proposed Grid-connected PV system with batteries

3.4.3 Resources of the Location

Moi International Airport solar plant was located at the coordinates 04° 02' 05" S and 039° 35' 39" E, and the time zone of (UTC+03:00) Nairobi was used to access the location resources. Component specifications were entered into the HOMER software model while solar irradiance and temperature data were sourced from NASA's global energy resource predictions.

3.4.4 Properties of Components

The components used in this study were grid, solar modules, Lithium batteries, and converters.

i. Solar PV properties

The Canadian Solar MaxPower CS6X-325P PV module was selected after evaluating multiple simulation results from various PV modules to identify the most optimal solution for the project. Given the PV system's lifespan of 25 years, there would be replacement costs throughout its life cycle. Performance losses might occur due to factors such as ambient temperature, dust accumulation, shading, wiring losses, and PV degradation. The derating factor for this specific PV module was taken as 88%, and a

temperature coefficient of -0.41% per degree Celsius. Under standard test conditions, the PV system exhibited an efficiency of 16.94% and consisted of 72 polycrystalline cells, each with a capacity of 325 watts. Polycrystalline PV panels were generally less expensive than single-crystalline silicon cells and demonstrated better performance in slightly shaded conditions. Notably, this design did not incorporate a tracking system, simplifying installation and maintenance. The PV system with steel support structure was set at Ksh.390, 000 per kW, with an O&M fee of Kshs.1300/kW per year.

PV  Name: CanadianSolar MaxPower (Abbreviation: CS6X-3; Remove Copy to Library ?

Properties
 Name: CanadianSolar MaxPower
 Abbreviation: CS6X-325P
 Panel Type: Flat plate
 Rated Capacity (kW): 3000
 Temperature Coefficient: -0.41
 Operating Temperature (°C): 45.00
 Efficiency (%): 16.94
 Manufacturer: Canadian Solar
[Data Sheet for CS6X-325P](#)
 Notes:
 72 Poly-crystalline cells.

Cost

Capacity (kW)	Capital (Ksh)	Replacement (Ksh)	O&M (Ksh/year)
1	390,000.00	325,000.00	1,300.00

Lifetime
 time (years): 20.00 More...

Site Specific Input
 Derating Factor (%): 88.00

Sizing
☐ HOMER Optimizer™
☒ Search Space
 kW
 0
 3000

Electrical Bus
☐ AC ☒ DC

Figure 3.9: Simulated PV system considered for optimization

Prior research by Almutairi et al. (2021) and Jahangiri et al. (2019) highlighted that the power output of photovoltaic (PV) panels was affected by factors including solar irradiation, cell efficiency, and daytime ambient temperature. Additionally, the performance of solar PV systems was influenced by the type of cell technology used, the geographical location, the tilt angle of the panels, and the accumulation of dust. Also, various models for solar PV power generation resulted in different calculation formulas (Hoff & Perez, 2010), highlighting the need for accurate performance prediction in diverse conditions (Dolara et al., 2015; IEC, 2021). Equation 3.1 was used in this study

$$P_{PV} = P_{OFPV} \frac{I_T}{I_S} (1 + \alpha (T_C - T_S)) \quad (3.1)$$

Where; P_0 represented the nominal power of the solar PV panel, f_{PV} was the derating factor accounting for losses due to soiling and ambient temperature effects, I_T denoted the incident radiation (kW/m^2), and I_s signified the incident radiation on the cell surface under standard conditions (1 kW/m^2). Additionally, α was the temperature coefficient, T_C was the cell temperature during operation, and T_S was the cell temperature under standard test conditions.

ii. Bi-directional Converter

Solar PV systems produced electricity in DC form, requiring a converter to transform it into AC. This conversion powered AC loads and allowed excess electricity to be sold to the grid, ensuring compatibility with grid standards and efficient energy distribution. In the case of a configuration with batteries, this device would regulate the charge and discharge cycles of the batteries to prevent overcharging or under-discharging. In this study, a 4000 kW Huawei SUN2000-150KTL three-phase hybrid converter was chosen for its capability to efficiently power the load by delivering high current (Katche, Makokha, Siagi, & Muiyiwa, 2024). A Huawei SUN2000-150KTL converter with a capacity of 4000kW and an efficiency of 97% with a relative capacity of 100% was used. The converter had a 15-year life expectancy, with a considered capital cost of Ksh. 117,000/kW, a replacement cost of Kshs. 117,000/kW and an annual O&M expense of Kshs. 6,500/kW/year. The capacity of this converter was slightly higher (approximately 33%) than the rated power for safety purposes.

CONVERTER  Huawei SUN2000-150KTL-50 Name: Huawei SUN2000 Remove
Complete Catalog Abbreviation: SUN200 Copy to Library ?

Properties
Name: **Huawei SUN2000-150KTL-50**
Abbreviation: **SUN2000-150KTL-50**
[Huawei Technologies Co., Ltd](#)
Notes:
Off-grid. HUAWEI micro grid inverter use the integrate design, the MPPT solar controller, battery charger, bi-directional inverter all in one converter.per converter

Costs

Capacity (kW)	Capital (Ksh)	Replacement (Ksh)	O&M (Ksh/year)
1	Ksh117,000	Ksh117,000.00	Ksh6,500.00

Click here to add new item

Multiplier:

Capacity Optimization
☐ HOMER Optimizer™
☒ Search Space
Size (kW)
0
4000

Huawei Technologies Co., Ltd

Inverter Input
Lifetime (years): 15.00
Efficiency (%): 97.00
☒ Parallel with AC Generator?

Rectifier Input
Relative Capacity (%): 100.00
Efficiency (%): 97.00

Figure 3.10: Simulated converter system considered for optimization

iii. Battery Storage properties

The previous studies by Bagheri et al. (2018) indicated that incorporating batteries into integrated energy systems significantly enhances system reliability. Batteries function as energy storage mediums, capturing surplus renewable energy and supplying power during capacity shortages. In this study, a generic Li-ion battery was utilized, featuring a nominal voltage of 6V, a maximum capacity of 167Ah, an efficiency of 90%, a maximum charge current of 167A, and a lifespan of 15 years. Lithium-ion batteries were selected due to their considerable price reduction over the past decade, with expectations for further declines as battery technology advances. Since both the PV system and battery were connected to the DC bus, their output voltages needed to match. The cost of this battery was defined as ksh. 75,500, and its initial state of charge was 100%, with a minimum state of charge of 20%.

STORAGE

Name: Generic 1kWh Li-Ion Abbreviation: 1kWh L

Properties

Idealized Battery Model

Nominal Voltage (V): 6
 Nominal Capacity (kWh): 1
 Nominal Capacity (Ah): 167
 Roundtrip efficiency (%): 90
 Maximum Charge Current (A): 167
 Maximum Discharge Current (A): 500

www.homerenergy.com

This is a generic 6 volt lithium ion battery with 1 kWh of energy storage.

Cost

Quantity	Capital (Ksh)	Replacement (Ksh)	O&M (Ksh/year)
1	75,500.00	75,000.00	1,300.00

Lifetime

time (years): 15.00

throughput (kWh): 3,000.00

Sizing

☒ HOMER Optimizer™
☒ Search Space

strings

0
25073

Site Specific Input

String Size: 1 Voltage: 6 V

Initial State of Charge (%): 100.00

Minimum State of Charge (%): 20.00

Figure 3.11: Simulated battery system considered for optimization

The amount of energy stored by the battery depended on the capacity of the battery, the state of charge (SOC) of the battery, and the rate of charge and discharge of the battery. The battery storage capacity was given in equation 3.2 (Xu, Ruan, Mao, Zhang, & Luo, 2013).

$$C_{wh} = \frac{(E_L \times AD)}{(\eta_{inv} \times \eta_{batt} \times DOD)} \quad (3.2)$$

Where: DOD was the battery depth of charge, the battery and inverter efficiency was $\eta_{battery}$ and η_{inv} respectively, AD was the days of autonomy, and E_L was the daily average load energy.

The state of charge (SOC) at time t could be estimated during the charging phase as indicated in equation 3.3 (Bossoufi, Lamnadi, Trihi, & Boulezhar, 2019).

$$SOC(t) = SOC(t-\Delta t) + (P_{PV}(t) \times \eta_{DC-DC}) + P_{WG}(t) \times \eta_{AC-DC} - \left(\frac{P_{load}(t)}{\eta_{wr} \times \eta_{inv}} \right) \times \frac{\eta_{cha}}{U_{bus}} \times \Delta t \quad (3.3)$$

SOC at time t could be estimated during the discharging phase as shown in equation 3.4.

$$\text{SOC}(t) = \text{SOC}(t-\Delta t) + (P_{PV}(t) * \eta_{DC-DC}) + P_{WG}(t) * \eta_{AC-DC} - \left(\frac{P_{load}(t)}{\eta_{wr} * \eta_{inv}} \right) * \frac{1}{U_{bus} * \eta_{dech}} * \Delta t \quad (3.4)$$

Where: P_{load} was the power consumed by the load at time t , t was the simulation time step, η_{DC-DC} was the efficiency of a DC-DC, η_{AC-DC} was the efficiency of an AC-DC, η_{inv} was the efficiency of a DC-AC converter, η_{DC-DC} was $\eta_{AC-DC} = \eta_{inv}$, η_{ch} was the battery efficiency during charging, η_{dech} was the battery efficiency during discharging, η_{wr} was the efficiency introduced to consider wire losses and U_{bus} was the nominal DC bus voltage.

iv. Main grid connection

Due to the intermittency of solar resources and the risk of system failure, connecting to the grid allowed for electricity supply and backup support. This connection also facilitated the sale of excess energy to the grid. HOMER's advanced grid module enhanced integration by incorporating real-time rates, scheduled rates, grid extension options, and reliability features. For this study, the advanced grid modelling using simple rates was chosen, providing an effective framework for analyzing the economic and operational aspects of the solar PV system alongside the grid. The grid purchase price was assumed to be atmost Kshs.33.8/kWh, whereas the sell-back price was assumed to be Kshs.15.6/kWh.

3.4.5 Economic analysis in the HOMER tool

Developing a hybrid energy system required robust economic support, and to achieve this, HOMER software was utilized for optimal sizing and techno-economic analysis. This analysis concentrated on two key economic metrics: the Levelized Cost of Energy (LCOE) and the Net Present Cost (NPC). Both indicators played a critical role in assessing the economic viability of various configurations. Notably, NPC proved to be

the most cost-effective metric within the HOMER tool, providing crucial insights for optimizing the overall system. By focusing on these economic factors, the analysis aimed to enhance the efficiency and cost-effectiveness of the energy system, ensuring a sustainable and financially viable solution for energy production and consumption in the hybrid configuration (Hafez, O. and Bhattacharya, K., 2012).

i. Levelized Cost of Energy (LCOE)

The Levelized Cost of Electricity (LCOE) was an economic metric that evaluated the long-term costs of electricity generation across various technologies. It included initial investment, operational expenses, and total output, aiding investors in assessing the economic viability of energy sources. It was mathematically expressed as shown in equation 3.5 (Hafez, O. and Bhattacharya, K., 2012);

$$LCOE = \frac{C_{T-ann}}{E_{off-grid} + E_{on-grid}} \quad (3.5)$$

Where;

$E_{off-grid}$ = grid-supplied electrical energy

$E_{on-grid}$ = microgrid's total quantity of electricity sold to the grid

ii. Net Present Cost (NPC)

NPC was the total cost and revenue of a project across its whole life cycle, and it was represented by the expression 3.6 (Rezk, H. et al, 2019);

$$NPC = \frac{C_{T-ann}}{CRF(i,t)} \quad (3.6)$$

Where;

C_{T-ann} = Annualized total cost of the system.

CRF = Capital recovery factor

i = Annual interest rate or discount rate

t = Project lifetime.

The annual effective interest rate was a percentage of the balance at the end of the year in which interest was paid or earned and it was represented as shown in equation 3.7;

$$i = \frac{i' - f}{1 + f} \quad (3.7)$$

Where;

i' = Nominal interest rate

f = Annual inflation rate.

The capital recovery factor was the number of yearly payments required at a discount rate to achieve present value after a given number of years. It was given by equation 3.8;

$$\text{CRF}(i, n) = \frac{i(1+n)^n}{(1+n)^n - 1} \quad (3.8)$$

Where;

n = number of years.

3.5 Technical Performance of installed PV Modules

The performance of the installed PV system was evaluated using various performance parameters to assess effectiveness (IEC Standard 61724, 1998). The most essential technical indicators included final energy output, capacity factor, and performance ratio. Others include reference yield, final yield, and system efficiency. These parameters provided valuable insights into the system's energy production, the

effectiveness of solar resource utilization, and the overall effects of system losses on performance.

3.5.1 Final Energy Generated (kWh)

The final energy output was defined as the amount of alternating current (AC) power generated by the system over a specific period. The total energy output (kWh) was calculated monthly and annually to assess performance using Equation 3.9 as presented below (Congedo et al., 2013).

$$E_{AC} = \sum_{t=1}^N E_{AC}(t) \quad (3.9)$$

Where E_{AC} (kWh) was the final energy output at time t and N was the number of the data set.

3.5.2 System Yields

The system yields reflected the actual performance of the array compared to its rated capacity. According to IEC definitions, key yield parameters included array yield, final yield, and reference yield (Quansah et al., 2017). This study focused on AC power, commonly used in the facility, excluding array yield.

i. Final yield

The final yield (YF) was the inverter's energy output (AC energy) normalized by the rated capacity of the PV system. The final energy yield was then determined as in equation 3.10.

$$YF = \frac{E_{AC(kwh)}}{P_{rated(kw)}} (\text{kWh/kW}) \quad (3.10)$$

ii. Reference yield

The reference yield (YR) was defined as the ratio of total in-plane solar radiation to the array's reference irradiance. It measured the theoretical energy available at a specific location over a specified period, indicating solar resource potential. The reference yield was calculated using Equation 3.11 as presented; where H_T was the in-plane radiation and G_O was the reference irradiance.

$$YR = \frac{H_T}{G_O} \quad (3.11)$$

3.5.3 Performance ratio

The performance ratio (PR) measured the overall effect of losses on the rated output of the system, considering environmental conditions, installation component efficiencies, and installation angles such as tilt and orientation. It indicated how closely the solar PV system's performance approaches the ideal scenario during real-life operation, reflecting operational efficiency. Mathematically, it was expressed by the equation 3.12.

$$PR = \frac{E_{AC}}{P_{IC}} * \frac{G_{STC}}{H_C} = \frac{Y_f}{Y_R} \quad (3.12)$$

Where H_c (kWh/m²/day) was the in-plane array radiation, G_{STC} (kW/m²) was the reference irradiance and Y_R was the reference yield.

3.5.4 Capacity factor

The capacity factor of a solar PV installation was defined as the ratio of the final energy produced over a specified period to the energy output that would have been generated if the system operated at full capacity throughout that entire duration, reflecting operational efficiency. It was given by the equation 3.13 as shown;

$$C_f = \frac{E_{AC(t)}}{P_{IC} * T_h} \quad (3.13)$$

Where T_h was the total expected number of hours of operation in a given period, commonly taken as a year (for a regular year, which consists of 365 days, $T_h = 8760$ hours) and $E_{AC(t)}$ (kWh) was the actual total final energy generated within this given period.

3.5.5 System efficiency

The efficiency of the PV module system was calculated as the inverter AC output power (P_{AC}) divided by the total in-plane solar irradiation ($G_T W/m^2$) multiplied by the total PV array area ($A_{am} m^2$) and was determined using Equation 3.14 as presented;

$$\eta_{system} = \frac{P_{AC}}{G_T A_a} * 100\% \quad (3.14)$$

3.5.6 Total Energy Losses

Total energy losses (LT) of the PV plant, which included losses from irradiance levels, array temperature, module quality, wiring losses, mismatch, and inverter losses, represented the difference between the reference yield (YR) and the final yield (YF) of the system, and it was calculated using Equation 3.15 as presented by (Adaramola & Vågnes, 2015);

$$L_T = Y_R - Y_F \quad (3.15)$$

3.6 Economic Performance Indicators

The economic analysis in this section utilized financial indicators such as the Levelized Cost of Energy (LCOE), Net Present Value (NPV), Simple Payback Period (SPP), Discounted Payback Period (DPP), and Internal Rate of Return (IRR). The total installation cost for the 507 kW solar project amounted to Ksh. 195,147,201.16. The

goal of this analysis was to assess the costs and benefits of the investment, evaluating the economic viability of the airport's PV project.

3.6.1 Levelized Cost of Energy

The Levelized Cost of Energy (LCOE) was an economic metric that measured the total cost of building and operating a solar PV system over its entire lifespan, divided by the total energy it generated. It reflected the minimum price at which electricity needed to be sold to break even, ensuring the project remained financially viable. The LCOE was expressed by equation 3.16 as,

$$LCOE = \frac{CRF * C_1 + C_{o\&m}}{E_a} Cost/kWh \quad (3.16)$$

Where; C_1 represented the initial investment cost, $C_{o\&m}$ was the annual operation and maintenance cost, E_a was the annual electricity generated by the installation, and CRF was the capital recovery factor, which was given by equation 3.17:

$$CRF (i, n) = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (3.17)$$

Where i was the interest rate (in fraction) and n was the payment period (in years).

3.6.2 Net Cash Flow (NCF_t)

Cash flow referred to the movement of cash and its equivalents in and out of a business over a given period, typically on an annual basis. Net annual cash flow was the difference between the annual inflows (revenues) and outflows (expenses), providing a snapshot of the project's financial status. It was calculated using Equation 3.18, as outlined by Tudisca et al. (2013). A value greater than zero ($NCF > 0$) was preferred for a feasible project.

$$NCF_t = \sum_{t=1}^n AR_t - \sum_{t=1}^n C_{o\&m_t} \quad (3.18)$$

Where NCF_t was the net cash flow at year t , AR_t was the annual income (revenue) at year t ,

($AR_t = E_{a,t} \times P_t$) and $Co \& m_t$ was the annual operation and maintenance cost at year t . $E_{a,t}$ and P_t was annual electricity production and price of electricity, respectively a year.

3.6.3 Net Present Value (NPV)

The Net Present Value (NPV) assessed the feasibility of the solar PV power plant project. A positive NPV signified that the project was economically viable, while a negative NPV indicated that the project was not financially feasible. It was calculated using Equations 3.19 as indicated by (Behar et al., 2021):

$$NPV = -C_0 + \sum_{t=1}^n \frac{NCF_t}{(1+r)^t} \quad (3.19)$$

Where;

Co = an initial capital investment,

NCF_t = the discounted cash flow in the year;

t = the cash flow time; n was the lifespan of the project

r = the discount rate.

3.6.4 Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) was the discount rate at which the Net Present Value (NPV) of a project's cash flows equals zero. A project was deemed favorable if its IRR surpassed a predetermined reference or required discount rate, indicating that the investment was expected to generate a return greater than the cost of capital. The IRR was determined using Equation 3.20 as illustrated by (Behar et al., 2021).

$$NPV = -C_0 + \sum_{t=1}^n \frac{NCF_t}{(1+IRR)^t} = 0 \quad (3.20)$$

3.6.5 Simple Payback period

The payback period represented the time it took for an investment to recover its initial costs through the revenue or savings it generated. It helped assess how long it took for an investor to break even, making it a useful metric for evaluating the risk and return on investment. The simple payback period (SPP) was given by equation 3.21 as:

$$SPP = \frac{C_0}{A_r - C_{O\&M}} = \frac{C_0}{A_s} \quad (3.21)$$

Where A_r was the annual revenue and A_s was the annual saving.

3.6.6 Discounted payback Period

While the simple payback period method was easy to understand and provided a useful estimate of the time it took to recover an investment, it fell short in considering the time value of money (TVM). This limitation made it less appropriate for making significant business decisions. The discounted payback period, which incorporated the time value of money (TVM), offered a more accurate assessment of how long it took to recoup an investment by considering the present value of future cash flows. This approach allowed for a better evaluation of the financial viability of an investment compared to the simple payback period method. And was determined from equation 3.22 (by solving for t):

$$DPP = \sum_{t=1}^n \frac{NCF_t}{(1+i)^t} = C_0 \quad (3.22)$$

3.7 Greenhouse Gas Emissions Saved

Solar PV energy systems offered several advantages, notably the absence of greenhouse gas (GHG) emissions during electricity generation. The grid emission factor (GEF)

quantified the total greenhouse gas emissions produced per unit of electricity generated by a country's power plants, typically expressed in tons of carbon dioxide equivalent per megawatt-hour (tCO₂ eq/MWh). This metric was crucial for calculating emissions reductions from grid-connected power plants and was also vital for assessing energy efficiency or energy-saving projects under programs like the Clean Development Mechanism (CDM) and other carbon trading initiatives, promoting more sustainable energy practices. In Kenya, the average grid emission factor (GEF) was 0.4999 tCO_{2eq}/MWh, while the emission factor for solar PV systems was 0.4087 tCO_{2eq}/MWh (UN Framework Convention on Climate Change, 2020). This solar PV emission factor reflected the carbon dioxide emissions that could be mitigated by utilizing solar PV technology for energy generation in the country. The electricity distribution and transmission losses were estimated to be 18% (Asumadu-Sarkodie and Owusu, 2016). The annual greenhouse gas emission reduction was estimated using Eq. (3.23) (Kebede, 2015):

$$GHG_r = (E_b - E_p)X_p(1 - \gamma_p) \text{ (Metric tons)} \quad (3.23)$$

Where:

GHGr = Annual GHG emission reduction (tCO₂)

E_b = Grid GHG emission factor (tCO₂/kWh)

E_p = PV system's GHG emission factor (tCO₂/kWh)

X_p = PV system's annual electricity generated (kWh)

γ_p = PV system's electricity transmission and distribution (T&D) losses (as a decimal)

CHAPTER FOUR: RESULTS AND DISCUSSIONS

This chapter discusses the results of the power consumption in the airport, models simulation, and the technical and economic performance of PV modules in humid tropical savanna climatic conditions of the site. In addition, the greenhouse gas emissions saved by using renewable energy sources are also discussed.

4.1 Electrical Energy Consumed at the Airport

Figure 4.1 illustrates airports' energy consumption pattern. While a similar curve shape was observed daily, power demand varied seasonally based on the operational hours of the airport. This variation was primarily due to the operation of HVAC and lighting systems. The electrical energy consumed ranged from 11,500 kWh to 13,500 kWh per day. Notably, energy consumption peaked in August, September, October, November, December, January, February, and March compared to other months, primarily due to the intensive use of HVAC systems during these hotter months. The increased energy requirement was necessary for heating or cooling the terminal building, leading to higher consumption by the HVAC systems.

In contrast, April, May, June, and July saw reduced energy consumption due to milder outside temperatures, which lessened the need for heating or cooling. Furthermore, during the rainy season, fewer hours of daylight resulted in more intensive use of artificial lighting because of later sunrises and earlier sunsets. This phenomenon is further illustrated in Figure 4.1, which depicts the monthly energy consumption for the entire airport. The data used for this analysis was collected from a power meter installed at the electrical panel board supplying electricity to the airport over the course of the year 2022. This detailed monitoring enabled a clear understanding of energy usage

patterns, facilitating better management and planning for energy efficiency and renewable energy integration at the airport.

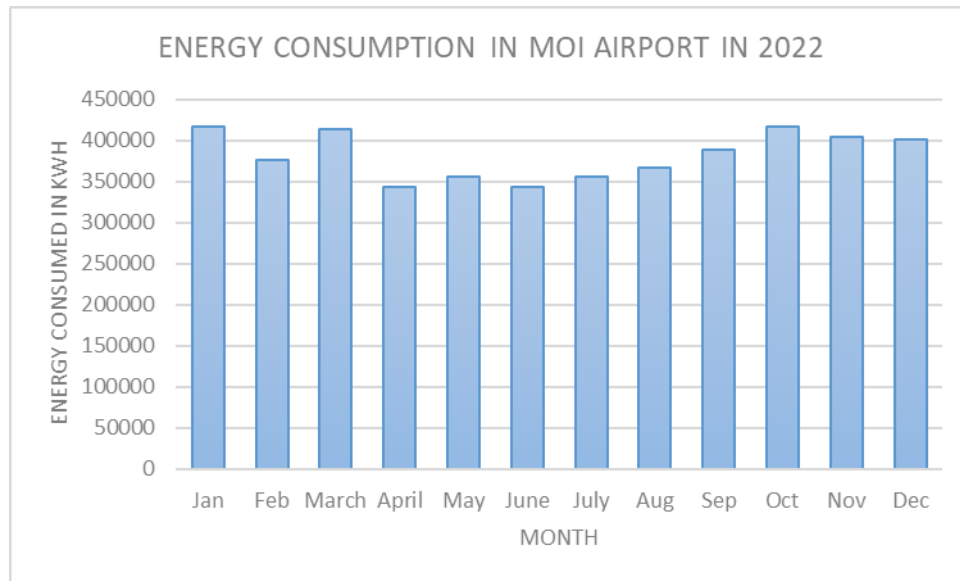


Figure 4.1: Energy consumed in the airport in the year 2022

Generally, the energy consumption of each functional zone within airports could be attributed to the energy usage of buildings and the demands of associated functional facilities and equipment. Terminals were the major energy consumers as they differed significantly from ordinary public buildings in architectural design, indoor environmental requirements, utilization intensity, and the types of facilities and equipment present. These unique characteristics necessitated targeted energy management strategies to optimize efficiency and minimize overall energy consumption in airport terminals. Terminal buildings typically featured expansive and varied architectural designs, resulting in relatively high shape coefficients. This characteristic increased the heat transfer load entering the interior through enclosure structures, leading to higher energy consumption for heating and air conditioning. Furthermore, the indoor environmental requirements in terminals were stringent; to maintain high service levels and satisfy passenger needs. Additionally, passenger flow concentration significantly impacted comfort levels within terminals. During peak

hours, the rapid increase in passenger volume at key locations, such as check-in islands, boarding gates, and baggage claim areas, increased the demand on air conditioning systems, requiring them to operate at higher capacities to manage peak loads effectively. Therefore, addressing these challenges was essential for optimizing energy efficiency while ensuring a comfortable experience for passengers.

4.2 Model Optimization

This section presents the results and discussions of the three simulated systems using HOMER software. Despite variations in solar radiation and wind speed values, the optimization focused on achieving the lowest Net Present Cost (NPC) based on an average scaled solar radiation value of 4.92 kWh/day.

As stated in Chapter Three, the three scenarios of PV systems chosen for this analysis were classified as:

- i. Standalone PV system with batteries.
- ii. Grid-connected PV system with batteries.
- iii. Grid-connected PV system without batteries.

4.2.1 HOMER input resources

i. Load demand

The simulation results indicated a scaled average load demand for the airport of 12,561.1 kWh/day, producing an average peak demand of 1,804 kW and a base load demand of 348 kW. These values were derived by accounting for random variations in the load, with a 10% day-to-day base variation and a 20% time step, as these percentages effectively covered the airport's energy requirements, ensuring reliable supply amidst fluctuating demand patterns. Choosing a value below 10% could result

in under-sizing the system, while a value above 20% would lead to oversizing, increasing costs unnecessarily. Consequently, these variability constants caused the peak load to rise to 12,869 kWh/day, highlighting the importance of balancing parameters for optimal system efficiency.

ii. Solar resource

Global Horizontal Irradiance (GHI) quantified the total solar radiation received on a horizontal surface, encompassing both direct sunlight and diffuse sky radiation. The average monthly GHI values presented in this study were derived from NASA data collected over a span of 22 years. This long-term data provided a robust basis for assessing the solar energy potential of the site, facilitating more accurate predictions of solar power generation and enhancing the planning and optimization of solar photovoltaic systems (Morad et al., 2019). The clearness index was a dimensionless value ranging from 0 to 1, defining atmospheric clarity. It exhibited high values during clear, sunny weather and low values under cloudy conditions. For this location, the annual average radiation was measured at 5.29 kWh/m²/day. Generally, Moi Airport experienced adequate solar radiation from August to March, making this period favorable for harnessing solar energy. Conversely, from April to July, the levels of solar radiation were significantly lower, impacting energy generation potential during these months.

Figure 4.2 illustrates the average solar radiation trend and the clearness index throughout the year. This data highlighted the fluctuations in solar radiation levels and the associated clearness index, which indicated the proportion of available sunlight that reaches the Earth's surface. Analyzing these trends was crucial for understanding the

solar energy potential of the installation and for optimizing the performance of solar photovoltaic systems.

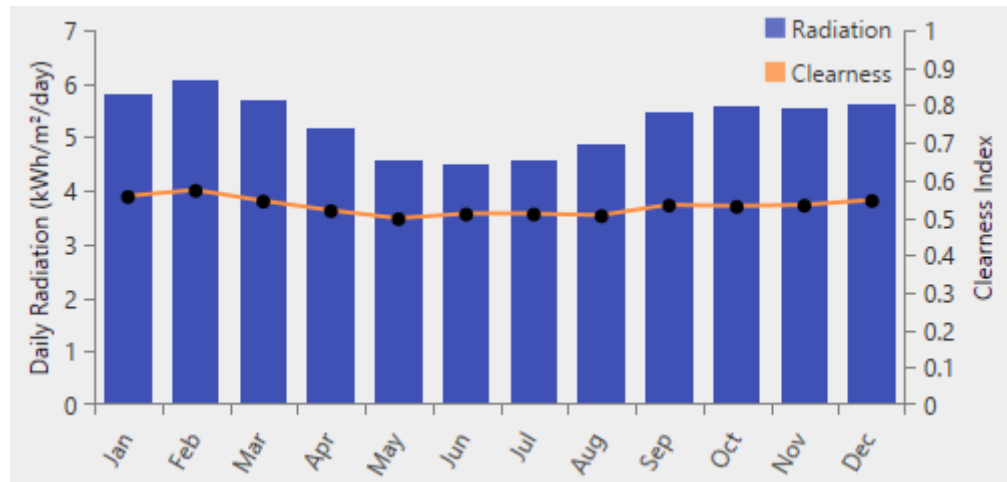


Figure 4.2: Moi Airport monthly daily solar radiation and Clearness index

iii. Temperature

The rising temperatures directly impacted the performance of photovoltaic (PV) cells, as increased cell temperatures could degrade their efficiency. Effective cooling strategies could help maintain the operational efficiency of PV modules by regulating their temperature, particularly during extreme heat conditions. Figure 4.3 displays the temperature data for Moi Airport, revealing minimal losses in solar energy generation. This conclusion aligned with the standard temperature coefficient used to assess efficiency losses in PV modules, which typically applied to temperatures exceeding 25°C, as indicated by solar panel manufacturers. The monthly temperature data was collected over a 30-year period, providing a robust foundation for this analysis.

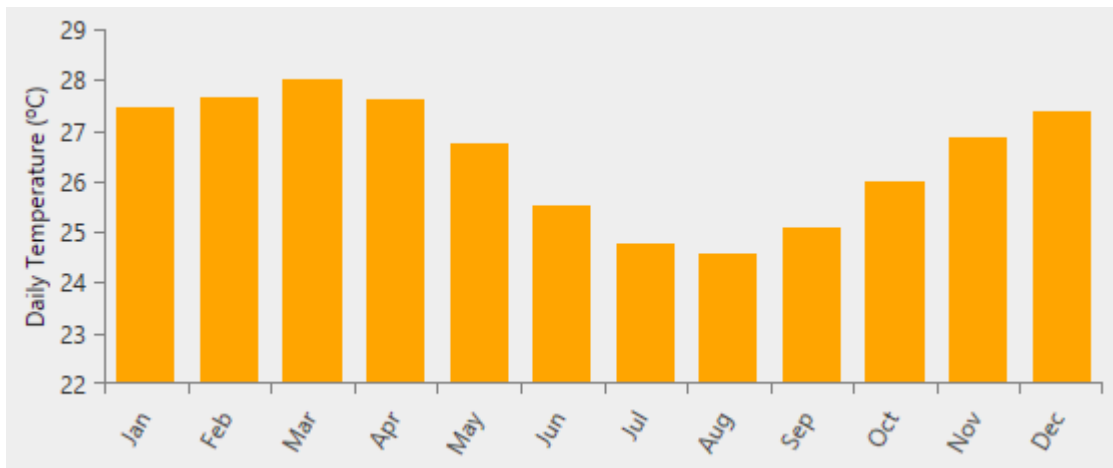


Figure 4.3: Average monthly mean temperature data for Moi Airport

4.2.2 Technical and Economic Results from Simulation

HOMER software required the components data to be input to perform simulation and optimization of the various configurations to obtain an optimal feasible configuration.

This study used the technical data indicated in Table 4.1.

Table 4.1: Technical data of the proposed models

Scenario	Grid (kW)	Solar module- CS6X-325p (kW)	Li-ion battery (6V/167Ah) (kWH)	Inverter- SUN2000- 150KTL (KWH)
Grid only	999,999			
Standalone PV with battery		3000	25,073	4000
Standalone PV without battery		3000		4000
Grid-connected PV system without batteries	999,999	3000		4000
Grid-connected system with batteries	999,999	3000	12,537	4000

The project had a planned lifetime of 20 years, with a discount rate of 5.88% and an inflation rate of 2%. In grid-tied systems, the annual capacity shortage was assumed to be zero, reflecting the reliability of grid connectivity. In contrast, for stand-alone systems, a 10% capacity shortage was anticipated, acknowledging the limitations in energy storage and generation variability inherent to such systems.

After simulation, the configuration with the lowest Levelized Cost of Energy (LCOE) and Net Present Cost (NPC) was identified as the optimal solution, as detailed in Table 4.2. The selected optimal system was the solar PV connected to the grid without battery backup. This configuration offered the most cost-effective and efficient approach for energy production, maximizing the benefits of solar power while minimizing the associated costs. This results was aligned closely with the findings of Oueslati and Mabrouk (2023).

Table 4.2: Optimization results

System configuration	NPC (KSHS)	LCOE (KSHS/kWh)	Operating Costs (kshs/yr)
Grid only		33.8	155M
Standalone PV with batteries	4.75B	95.78	105M
Grid-connected PV system without batteries	2.12B	29.45	41.5M
Grid-connected system with batteries	3.46B	49.22	75.4M

The total energy production of this system was 4,697,013 kWh/year, fulfilling approximately 73.9% of the load energy consumption. Since no excess energy was produced by the PV plant, around 26.1% of the energy consumed was purchased from the grid, totalling 1,657,211 kWh/year. The grid connection ensured that the base load was consistently covered, with the renewable energy fraction estimated at 73.3%. This setup allows the grid to remain continuously operational to supply additional power during high consumption periods. Furthermore, any excess electricity generated by the PV system could be sold back to the grid, as energy storage was not utilized in this configuration. Overall, this approach enhanced the global efficiency, stability, and reliability of power generation.

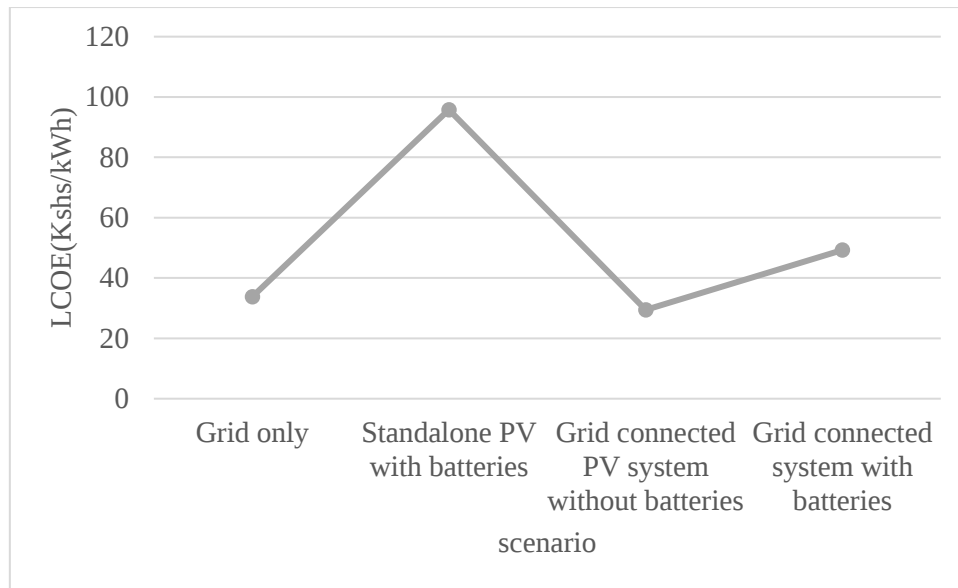


Figure 4.4: LCOE of models simulated

The standalone PV system with batteries had a levelized cost of energy (LCOE) of Ksh. 95.78/kWh and a net present cost (NPC) of Ksh. 4,751,975,000, which was higher than the grid-connected PV configuration with batteries that had an LCOE of Ksh. 49.22/kWh and an NPC of Ksh. 3,457,224,571, as illustrated in Figures 4.4 and 4.5.

In the grid-connected PV configuration with a limited battery energy storage system (BESS) providing 1 day of autonomy, the system produced 4,697,013 kWh/year, effectively meeting 75.4% of load energy consumption. Grid purchases totaled 1,530,437 kWh/year, accounting for 24.6% of total load energy consumption. Notably, no excess energy was produced by the PV plant since all generated energy was utilized to charge the batteries (12,537 kWh). This configuration resulted in renewable energy comprising 74.8% of total energy consumption.

Compared to the previous scenario without BESS, this setup demonstrated improved utilization of solar resources. During normal operation, the energy generated by the PV system was primarily used to meet the load demand. When the generation exceeded demand, the surplus energy charged the batteries to full capacity. Any additional energy was directed to a dump load. In peak load situations where renewable generation fell

short, the grid automatically engaged to supply the remaining load, but it did not charge the batteries during these instances. This strategy enhanced energy efficiency and reliability in meeting energy demands.

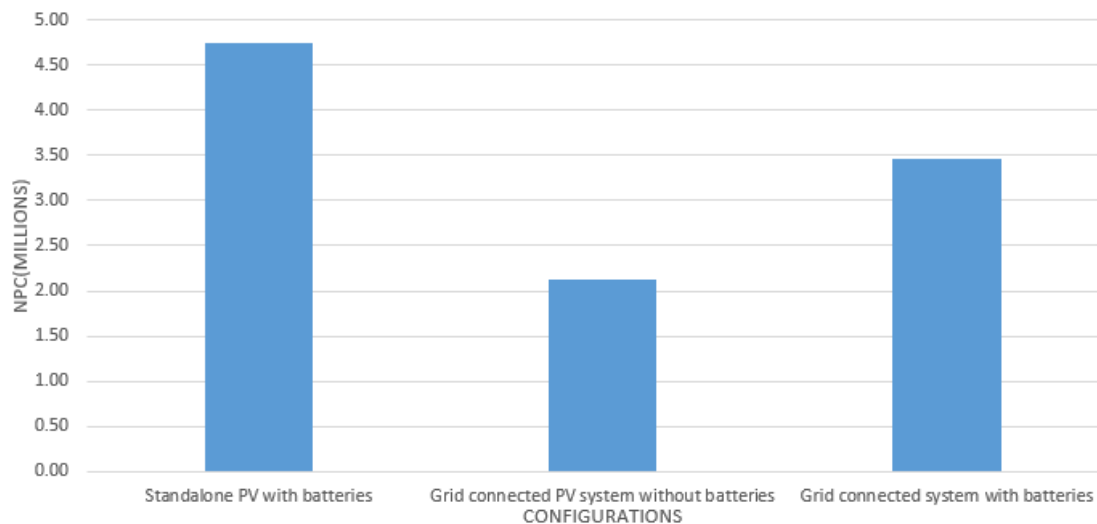


Figure 4.5: NPC of the models simulated

The standalone PV system produced a total energy output of 4,697,013 kWh/year, meeting 100% of load energy consumption. In this optimization scenario, the excess electricity generated by the PV system amounted to 133,374 kWh/year, which corresponded to 3.1% of the total electricity distributed by the PV and battery energy storage system (BESS) combined (4,309,487 kWh/year). The BESS capacity of 25,073 kWh ensured 2 days of autonomy. The excess energy was a result of the significantly larger PV nominal power; however, exploiting this excess necessitated a larger BESS, which was not economically viable due to the associated capital and installation costs.

Table 4.3: Summary of Energy production and consumption

	Production		Consumption				
Scenario	Energy generated (Kwh/yr)	Grid Purchases (KWh)	load (kWh)	Grid sales (KWh)	Excess energy (kWh)	Unmet electric load	Capacity shortage
Standalone PV with batteries	4,697,013	0	4,284,414	0	133,374	300,387	544,109
Grid-connected PV system without batteries	4,697,013	1,657,211	4,584,802	1,628,512	0	0	0
Grid-connected system with batteries	4,697,013	1,530,437	4,584,802	1,481,273	0	0	0

4.3 Summary of the Optimal Configuration

The initial capital expenditure for the system amounted to Kshs. 1,638,000,000, yielding a return on investment (ROI) of 2%, an internal rate of return (IRR) of 3.3%, and a simple payback period (SPBP) of 13.43 years. From Figure 4.5, the net present cost (NPC) of the grid-connected PV system without batteries was Ksh. 2,119,157,749, which included grid operations and maintenance costs. Since these costs were borne by the utility operator rather than the renewable energy producer, the actual NPC was calculated by subtracting the grid O&M cost, resulting in a new NPC of Ksh. 2,083,342,483. Additionally, compared to the grid's levelized cost of energy (LCOE) of Ksh. 33.8/kWh, this system reduced the LCOE per kWh by 13%, leading to a decrease in monthly electricity charges and financial gains for the airport. Table 4.4 shows the comparison using the year 2022 as the base. Koko (2022) and Musong et al. (2024) also reported a reduction in electricity bills when using grid-tied PV systems.

Therefore, based on the analysis of the economic indicators of the optimal model, this system was deemed profitable and represented a worthwhile investment.

Table 4.4: Comparison of the existing system with the current/model system

Year	Existing system- Base year (2022)	Current/model system	The annual cost to be saved in %
Annual energy consumed from the grid	4,584,802.5kWh	1,657,211kWh	
Annual energy consumed from solar PV	739,724kWh	4,584,803kWh	
Annual cost of energy (Kshs)	143,426.630.10	56,013,731.80	
Annual cost to be saved (Kshs)	-	87,412,898.30	61%

Table 4.5 presents the emissions calculated by the HOMER software to analyze the environmental impact of the simulated configurations. The greenhouse gases (GHGs) emitted during the projected 20-year project life cycle were from conventional grid sources. The emissions included carbon dioxide (CO₂), sulfur dioxide (SO₂), and nitrogen oxides (NO_x).

Table 4.5: Greenhouse gas emissions

Configuration	CO ₂ (Kgs)	CO (Kgs)	SO ₂ (Kgs)	N ₂ O ₂ (Kgs)	Unburnt hydrocarbons (Kgs)	Particulate matter (Kgs)
Grid only	2,897,595	0	12,562	6,144	0	0
Standalone PV with batteries	0	0	0	0	0	0
Grid- connected the PV system without batteries	18,138	0	78.6	38.5	0	0
Grid- connected system with batteries	18,138	0	78.6	38.5	0	0

Table 4.6: Emission analysis results of the existing and optimum model selected.

Emission	Existing system -grid (Kg/yr)	Current/optimal model system (Kg/yr)
CO ₂	1,902,928.85	18,138
SO ₂	0	78.6
N ₂ O ₂	0	38.5

Table 4.6 shows comparison results of the emissions from the existing system (grid) with those of the optimal model. The carbon dioxide equivalent of the grid was calculated by taking 0.4999 tCO₂/MWh as the operating margin CO₂ emission factor for the national grid of Kenya (UN Framework Convention on Climate Change, 2020). Therefore, the adoption of the proposed model consisting of renewable technologies such as solar PV connected to the grid and without pack up had many advantages which included power reliability and stability, and reduction of GHG emissions. Al Anazi et al. (2022) reported similar findings and therefore it could be applied in airports for energy management and sustaining the environment.

Under the Kyoto Protocol, member countries were required to reduce greenhouse gas emissions (Haffaf, Lakdja, Abdeslam, & Meziane, 2021). Under this regulation, industrialized countries pledged to reduce greenhouse gas emissions by up to 5% over ten years and support developing nations in utilizing renewable energy, despite the ongoing pollution from conventional methods in grid power supplies (Zhao, P., Xu, W., Zhang, S., Wang, J., & Dai, Y. (2020), and this has resulted to pollution costs. Therefore, the use of a grid photovoltaic system would eliminate pollution costs, which would have been a significant amount in the lifetime of a power plant.

4.4 Technical and Economic Performance of Installed Solar PV system

The parameters evaluated in the technical analysis include energy output, reference yield, final yield, system efficiency, capacity utilization factor, and performance ratio.

The economic indicators analyzed in this section consist of net present value (NPV), simple payback period (SPP), discounted payback period (DPP), internal rate of return (IRR), and levelized cost of energy (LCOE). The workings of these technical and economic indicators are presented in appendices 2 to 7.

4.4.1 Technical Analysis

In this study, data of five years were utilized to assess the performance of the solar PV plant, as illustrated in Figure 4.6. In contrast, previous studies (Ayadi, Colak, Genc, & Halil, 2019; Gopi, Sudhakar, Keng, Krishnan, & Priya, 2021) employed only one year data to evaluate PV system performance. Such short-term analyses might underestimate or overestimate the performance of PV modules due to trends and degradation factors. Analyzing five years data provided a more comprehensive understanding, which was beneficial for the design and techno-economic performance assessment of a PV module.

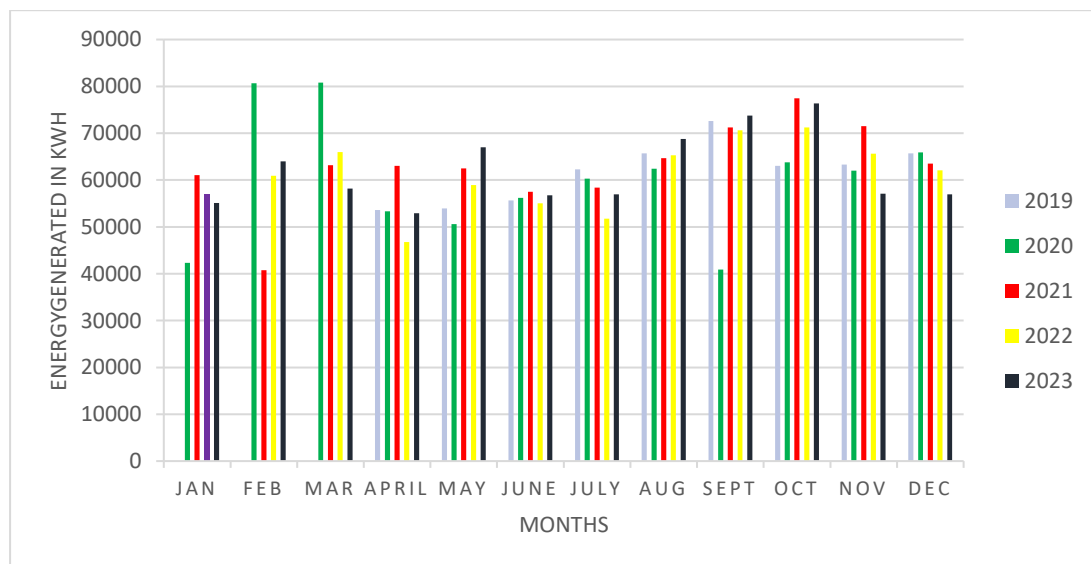


Figure 4.6: Monthly solar generation in Kwh from 2019 to 2023

There was a variation in total annual energy production, as shown in Figure 4.7. The total annual energy output for the years 2019, 2020, 2021, 2022, and 2023 was 555.899

MWh, 719.208 MWh, 754.821 MWh, 741.135 MWh, and 743.730 MWh, respectively. The output for year 2019 was the lowest because the plant started operations in April and therefore, the annual mean average for 4 years (2020 to 2023) was 739.724MWh. The variation in the performance of the solar PV plant was attributed to the effects of weather and meteorological conditions, the efficiencies of the system's main components, and their responses to environmental factors, including installation conditions such as tilt angle and orientation (Oloya, Gutu, and Adaramola, 2021). The previous studies by Chawla and Tikkiwal (2021) and Martín-Martínez et al. (2019) further supported the notion that environmental conditions vary by location, significantly influenced solar PV module performance based on differing weather parameters across geographical regions. Therefore, conducting a technical analysis was essential to provide relevant data that aided in decision-making and promoted improvements in design, installation, and commissioning processes for better performance.

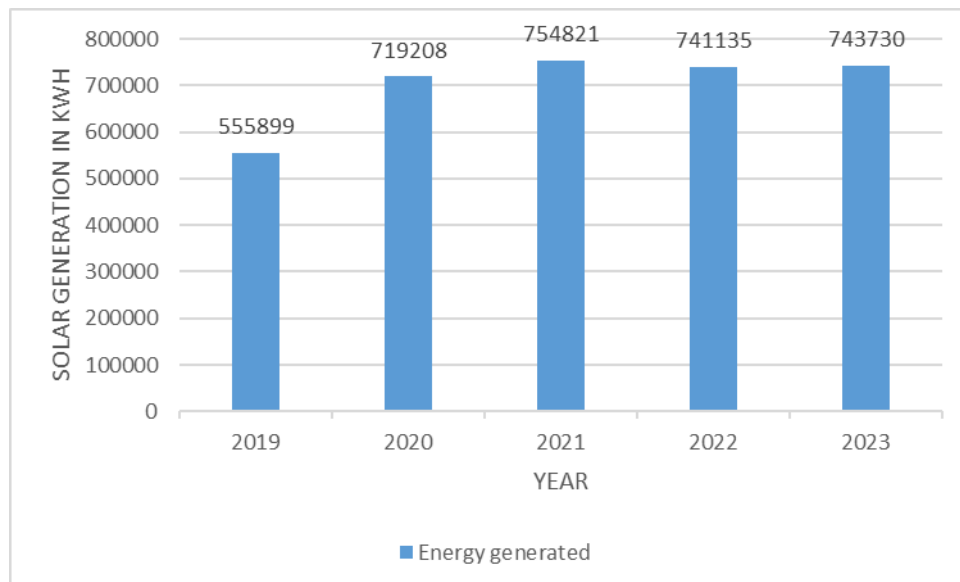


Figure 4.7: Annual solar energy generated

Figure 4.8 presents the average daily annual reference yield (YR) calculated for the installation site over 5 years. The results indicate a variation in the average reference

yields, with a maximum value of 5.65 kWh/kW-day in 2021 and a minimum value of 5.50 kWh/kW-day in 2020. The average daily annual reference yield (YR) was determined to be 5.57 kWh/kW-day. These values fall within the range of 3.62 kWh/kW-day to 10.02 kWh/kW-day reported for eight different solar plants by Martín-Martínez et al. (2019).

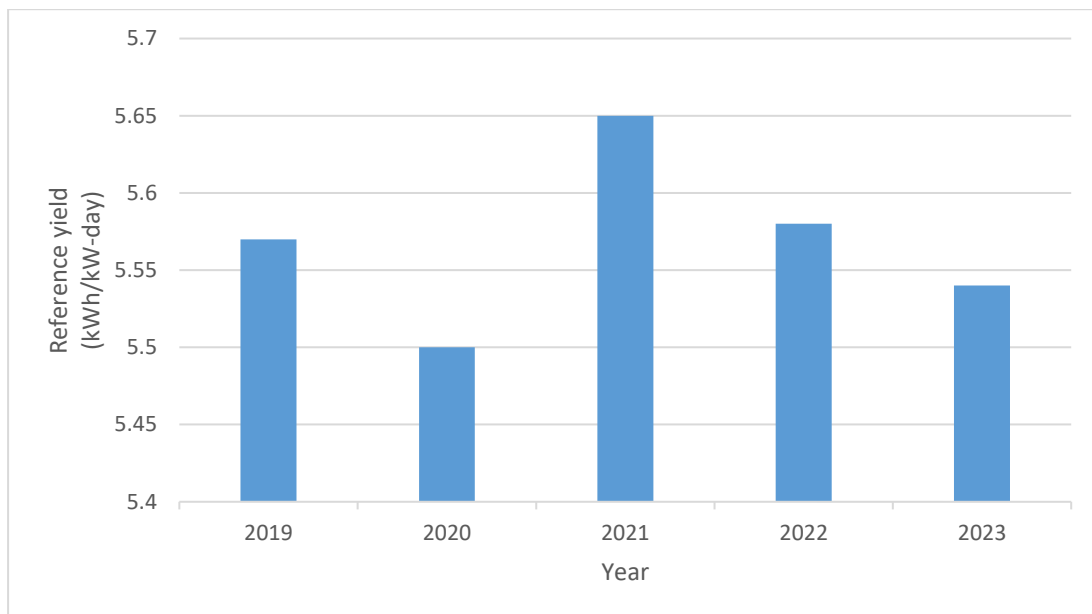


Figure 4.8: Reference Yield (kWh/kW-day) in years

Table 4.7: Technical Performance Indicators

Year	YF(kWh/kW-day)	E _{AC} (MWh)	PR, (%)	CUF, (%)	η, (%)
2019	3.99	555.899	74.07	17	12.38
2020	3.90	719.208	70.87	16	11.85
2021	4.07	754.821	72.49	17	12.12
2022	3.95	731.135	71.36	16	11.93
2023	4.02	743.730	72.97	17	12.20
MEAN	3.99	737.224	72.35	16.6	12.10

Table 4.7 presents the technical performance indicators of the system installed at a fixed angle of 10° and oriented south. The table indicates that the maximum final yield (YF) was recorded in 2021 at 4.07 kWh/kW-day, while the minimum was 3.90 kWh/kW-day in 2020. The annual average final yield was established at 3.99 kWh/kW-day. Similar

average values of 3.78 kWh/kW-day and 3.99 kWh/kW-day were reported by Al-Badi (2020) and Martín-Martínez et al. (2019), respectively.

Additionally, the study indicates that the system generated a minimum energy output of 719.208 MWh in 2020 and a maximum output of 754.821 MWh in 2021, excluding 2019 due to incomplete data. The annual average energy output generated by the system was 737.224 MWh. Moreover, the study shows an average performance ratio (PR) with a maximum of 72.97% in 2023 and a minimum of 70.87% in 2020. The annual average PR was determined to be 72.35%. The previous studies by Quansah et al. (2016) indicated that performance ratios for various grid-connected solar photovoltaic (PV) systems in humid tropical climates ranged from 70% to 84.3%. Therefore, the results of this study were within that range.

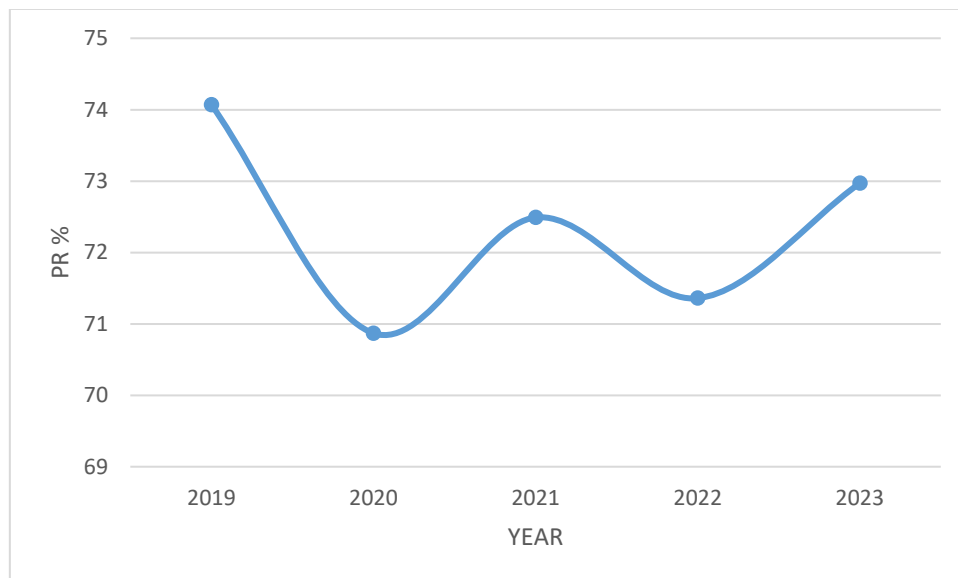


Figure 4.9: Performance ratios of the year 2019 to 2023

Furthermore, the results of the study indicate an average Capacity Utilization Factor (CUF) for the system, with a minimum value of 16% in the years 2020 and 2022, and a maximum value of 17% in 2019, 2021, and 2023. The annual average CUF for the system was determined to be 16.6%. This finding was similar to results reported by the

previous studies in various locations, such as Shiva and Sudhakar (2015) with 17.68%; Saxena and Sudhakar (2021) with a range of 19% to 21%; Khare, Saxena, Saxena, and Sudhakar (2021) with 19.27%; Sreenath, Sudhakar, and Af (2021) with 14.25% to 17.09%; and Sreenath, Sudhakar, and Yusop (2022) with 16.5% to 18.8%.

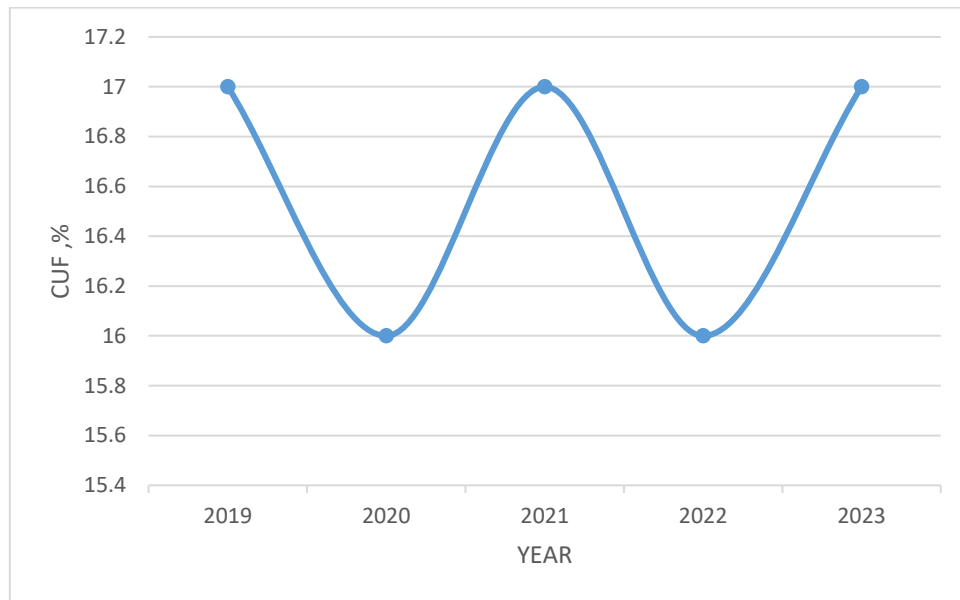


Figure 4.10: Utilization Capacity factors of the system for the year 2019 to 2023

Finally, Table 4.10 shows that the average system efficiency was a minimum of 11.85% in 2020 and a maximum of 12.38% in 2019. The annual average efficiency of the system was determined to be 12.10%. Martín-Martínez et al. (2019) reported the efficiency of eight different solar plants, which varied from 8.40% to 11.98%. Ngure et al. (2023) calculated the system efficiency of various solar photovoltaic (PV) systems installed in different regions and reported a variation ranging from 10.3% to 14.77%. Therefore, the findings of this study were aligned with the results obtained from other regions under real-life climatic conditions.

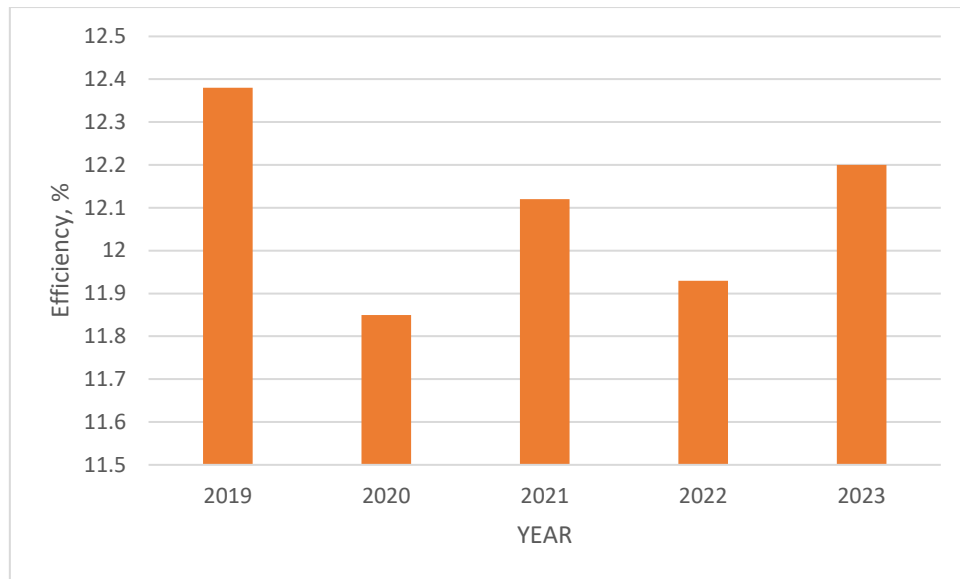


Figure 4.11: System efficiency from 2019 to 2023

In summary, the technical performance analysis of the pilot PV plant yielded results comparable to those from other regions, indicating a consistent performance ratio of the PV systems based on actual recorded data. The performance ratio varied annually due to various factors impacting the system's rated output. The losses could be classified into non-temperature-related factors, such as inverter inefficiency, wiring issues, mismatch, soiling, system availability, component failures, shading, and aging, all of which affected the overall efficiency. Additionally, temperature-related factors arose from deviations in module temperature from the standard 25 °C during real operation. Addressing these factors was crucial for enhancing the efficiency and reliability of solar PV systems.

4.4.2 Economic Analysis

In estimating the economic indicators discussed in this section, the following assumptions were established to ensure reliable analysis:

- i. For values denoted in dollars, a constant exchange rate of 1 USD = Ksh 130 was utilized.

- ii. For revenue estimation, an approved tariff of Ksh 15.60/kW was used, along with the unit cost of electrical energy in Kenya, which varied from Ksh 23.40/kWh to Ksh 33.80/kWh during this period. The energy consumed by the owner was considered savings and was calculated at Ksh 33.80/kWh.
- iii. The installation's economic life was established at 20 years, which aligned with the approved Feed-in Tariff (FiT) policy set by the Ministry of Energy in 2012.
- iv. The installation's annual operation and maintenance cost was taken as constant (Kshs. 4,537,152.1/year) for the entire economic life
- v. The 5-year average capacity factor of the installation was 16.6% (refer to Section 4.3.2) and was assumed to remain constant. This indicated that the annual energy production from the installation was steady, calculated to be 737.259 MWh (see Section 4.3.1).
- vi. Due to the limited information available on the discount rate used for project financing, and considering that the project was funded by the European Union (European Investment Bank), which primarily provided grants and low-interest loans to poorer and underdeveloped countries, specific financial details about this project remained unclear. Consequently, a discount rate of 4% was utilized in this study after conducting a sensitivity analysis with rates of 2%, 8%, 10%, and 12%.

Using the assumptions outlined above, the results of the economic indicators for the project are presented in Table 4.9. The financial indicators included a net present value (NPV) of Ksh 81,843,034, an internal rate of return (IRR) of 8.34%, a discounted payback period (DPP) of 12 years, and a simple payback period (SPP) of 9 years. Additionally, the levelized cost of energy (LCOE) for this installation was estimated to

be Ksh 25.64. The working Excel sheet detailing the economic analysis for a 20-year period can be found in Appendix 8.

The previous studies had reported varying results regarding levelized cost of energy (LCOE) and payback periods. Sreenath, Sudhakar, and Af (2021) found an LCOE of US\$0.0102 and a payback period of 7.9 years. Mensah, Yamoah, and Adaramola (2019) indicated an LCOE of US\$0.2411 with a discounted payback period (DPB) of 14.95 years. Alshare et al. (2020) reported a payback period of 4.32 years and an internal rate of return (IRR) of 30.11%. Additionally, Yazdani and Yaghoubi (2021) indicated an LCOE of US\$0.099/kWh and a DPB of 5.82 years. The LCOE value determined in this study was relatively lower than those reported in other studies, as noted earlier. This might be attributed to the low-cost financing of the project, with a discount rate of 4%, and a relatively high energy yield compared to other studies conducted in different climatic regions. However, the discounted payback period aligns with findings from other studies, falling between 12 and 14 years.

Table 4.8: Economic performance indicators of the installed pilot solar PV system

CRF	0.0736
LCOE	0.1972 \$ (Kshs.25.64)
SPP	9yrs
DPP	12yrs
IRR	8.34%
NPV	629561.8 \$ (kshs.81,843,034)
i	4%

The calculated levelized cost of energy (LCOE) for this solar power project was Ksh 25.64/kWh, exceeding the global weighted average of Ksh 8.84/kWh while remaining below the grid purchase price (IRENA, 2019). Moreover, irrespective of the assumed discount rate, the estimated LCOE for this project aligned with the ranges reported for utility-scale solar PV by the International Energy Agency (IEA) in 2019, indicating its

competitiveness in the market. The simple payback period and discounted payback period were estimated as 9 years and 12 years, respectively. For an economically viable utility-scale grid-connected solar PV system, a payback period between 8 and 18 years was recommended by IFC (2015).

Therefore, at this tariff rate, it could be concluded that the Moi Airport solar power plant was economically viable. Furthermore, the internal rate of return (IRR) was within the recommended range of 5% to 10% for projects supported by a feed-in tariff mechanism, indicating that the project was financially viable investment opportunity (The Feed-in Tariff Handbook, n.d). Additionally, another economic indicator, the net present value (NPV) of Ksh 81,843,034, supported the economic viability of this project. Consequently, it could be inferred that if the assumptions used in this analysis were valid, the approved feed-in tariff (FiT) should have been lower than Ksh 25.64 per kWh, reflecting a more favorable economic outlook for the project.

4.5 Quantity of Greenhouse gas (GHG) emissions saved

In this study, the current grid emission factor and solar PV emission factor in Kenya, the quantity of electricity generated by the installed pilot solar PV plant, and the percentage of transmission and distribution loss were used to calculate the total amount of GHG emissions saved using equation 3.22. A total of 55,320.87 kilogrammes of carbon dioxide were avoided over the monitoring period, with an average of 11,064.174 kilogrammes per year. Therefore, for the entire lifetime of solar PV systems, the total amount of greenhouse gas emissions that would have been saved in terms of CO₂ equivalent were approximately 221,283.48 kilograms. However, the previous studies by Akpahou, Odoi-Yorke, and Osei (2023) noted that this figure applied only during electricity generation. They highlighted a widespread misconception that solar modules

produced zero emissions. To provide a more accurate assessment, they suggested that emissions from production, construction, maintenance, and decommissioning of solar modules should also be taken into account. It was estimated that the average emissions from PV technologies were about 50.0 g CO₂eq/kWh (NREL, 2012) and 98.3–149.3 g CO₂eq. It was estimated that the average emissions from photovoltaic (PV) technologies ranged from about 50.0 g CO₂eq/kWh (NREL, 2012) to between 98.3 and 149.3 g CO₂eq/kWh, depending on various factors such as manufacturing processes and installation methods (Mehedi, Gemechu, & Kumar, 2022).

It was estimated that airports accounted for only 5% of the aviation sector's total greenhouse gas (GHG) emissions (ACA, 2020). However, this figure was likely an underestimate, as it did not encompass the full range of emissions from all operational activities, including regional and embodied impacts (Greer et al., 2020). According to the ACA report of 2022, modern airports had many other sources of emissions such as from ground support equipment and passenger vehicles, boilers and furnaces, waste management activities, de-icing substances, and refrigerant loss. Therefore, comprehensive environmental accounting in the aviation industry must consider greenhouse gas (GHG) emissions from all airport operational activities to identify opportunities for mitigating climate change effectively.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

This section concludes the research by summarizing the findings and providing suggestions for future studies and improvements.

5.1 Conclusion

This study performed the technical, economic, and emission analyses of a solar PV power plant at Moi International Airport, Mombasa. The first objective was to determine the electrical energy consumption at Moi International Airport-Mombasa. The study has revealed that in the year 2022, a minimum of 11,500kWh and a maximum of 13,500kWh of energy was consumed daily with a mean average of 12,561kWh/day. These results confirmed that airports were highly energy-intensive, highlighting the need for Kenyan airports to enhance both energy generation and efficiency. Additionally, high consumption was experienced in August, September, October, November, December, January, February, and March because of the use of HVAC systems as compared to lower values in April, May, June, and July. This trend demonstrated that airport energy consumption was closely related to the climatic features of their location, emphasizing the impact of environmental factors on energy usage patterns. A promising solution was the adoption of renewable energy sources, with solar photovoltaic (PV) systems emerging as a feasible, reliable, and cost-effective option.

The second objective of the study was to perform a modelling simulation of the solar photovoltaic to obtain the optimum configuration of the system. In this research, the three designed PV models were simulated using the HOMER software. The configurations of the models were developed using a grid, solar PV modules, a converter, and batteries. From the simulation results, grid-connected solar PV without batteries configuration was selected as the feasible and optimal model. This

configuration had the lowest NPC of Ksh. 2.12 billion and LCOE of Ksh.29.45/kWh. The chosen model (grid-connected solar PV system without battery backup) would reduce greenhouse gas emissions (18,255kg/yr) when compared to the grid only (2,916,301kg/yr). Furthermore, renewable energy constituted 73% of total energy consumption in this scenario, highlighting its environmental benefits and emphasizing the importance of transitioning to sustainable energy sources for a greener future.

The third objective of this study was to evaluate the technical and economic performance of the solar photovoltaic (PV) modules installed at Moi Airport. The analysis yielded a final yield (YR) of 3.99, a capacity utilization factor (CUF) of 16.6%, a system efficiency (η) of 12.10%, and a performance ratio (PR) of 72.35%. Economically, the project demonstrated a net present value (NPV) of Ksh 81,843,034, indicating strong financial viability. The internal rate of return (IRR) was calculated at 8.34%, while the discounted payback period (DPP) stood at 12 years, and the simple payback period (SPP) was 9 years. Additionally, the levelized cost of energy (LCOE) for this installation was estimated at Ksh 25.64 per kW. These findings underscored the technical efficiency and economic feasibility of solar PV systems at Moi Airport, supporting future investments in renewable energy solutions.

The study's final objective examined the reduction of greenhouse gas emissions achieved by implementing solar photovoltaic (PV) systems at the airport. During the monitoring period, the system's energy output resulted in the avoidance of 55,320.87 kilograms of carbon dioxide (CO₂), with an annual average of 11,064.174 kilograms. Over the solar PV system's entire lifetime, the total greenhouse gas emissions to be saved were estimated to be around 221,283.48 kilograms of CO₂ equivalent. This highlighted the substantial environmental impact of using solar energy at airports,

significantly reducing their carbon footprint while promoting cleaner, more sustainable operations. The findings underscored the potential of renewable energy in mitigating climate change and lowering greenhouse gas emissions.

5.2 Future Recommendations

1. To establish uniform standards for comparability of energy consumption data, measurement methods accuracy should be improved
2. To enhance techno-economic analysis and optimal sizing, multiple optimization tools should be combined for comprehensive evaluation.
3. To perform microgrid optimization for the site using a variety of available renewable energy resources employing different optimization tools.

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APPENDICES

Appendix 1: Monthly energy consumption at Moi Airport for the year 2022 (kWh)

month	Jan	Feb	march	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Av.daily	Av. monthly
Energy (kWh)	417176	376766	414121	343740	355202	344781	355161	368484	388841	417151	403791	401584	12561.1	382066.7

Appendix 2: Monthly solar generation in Kwh from 2019 to 2023

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
2019	0	0	0	53602	53963	55660	62310	65690	72604	63020	63320	65730	555899
2020	42350	80675	80806	53340	50570	56190	60270	62418	40870	63814	62012	65893	719208
2021	61070	40730	63172	63043	62502	57529	58352	64685	71236	77482	71492	63528	754821
2022	56847	60941	65974	56790	58926	55020	51765	65297	70605	71233	65634	62103	741135
2023	55071	63974	58197	52896	67,003	56755	56977	68739	73730	76357	57084	56947	743730

Appendix 8: Economic performance analysis of the PV system

YRS(N)	C1	Ea(Kwh)	Pt(USD/kwh)	ARt(usd)	O and Mt	NCf	i	(1+i)^N	(NCf/(1+i)^N)	DPP	SPP
0	1501132.3									-1501132	-1501132
1		737259	0.26	191687.3	34907.16	156780.18	0.04	1.0400	150750.17	-1350381.83	-1344351.82
2		737259	0.26	191687.3	34907.16	156780.18	0.04	1.0816	144952.09	-1205429.74	-1187571.64
3		737259	0.26	191687.3	34907.16	156780.18	0.04	1.1249	139377.01	-1066052.73	-1030791.46
4		737259	0.26	191687.3	34907.16	156780.18	0.04	1.1699	134016.35	-932036.37	-874011.28
5		737259	0.26	191687.3	34907.16	156780.18	0.04	1.2167	128861.88	-803174.49	-717231.10
6		737259	0.26	191687.3	34907.16	156780.18	0.04	1.2653	123905.65	-679268.84	-560450.92
7		737259	0.26	191687.3	34907.16	156780.18	0.04	1.3159	119140.05	-560128.79	-403670.74
8		737259	0.26	191687.3	34907.16	156780.18	0.04	1.3686	114557.74	-445571.05	-246890.56
9		737259	0.26	191687.3	34907.16	156780.18	0.04	1.4233	110151.67	-335419.37	-90110.38
10		737259	0.26	191687.3	34907.16	156780.18	0.04	1.4802	105915.07	-229504.30	66669.80
11		737259	0.26	191687.3	34907.16	156780.18	0.04	1.5395	101841.42	-127662.88	223449.98
12		737259	0.26	191687.3	34907.16	156780.18	0.04	1.6010	97924.44	-29738.45	380230.16
13		737259	0.26	191687.3	34907.16	156780.18	0.04	1.6651	94158.11	64419.67	537010.34
14		737259	0.26	191687.3	34907.16	156780.18	0.04	1.7317	90536.65	154956.31	693790.52
15		737259	0.26	191687.3	34907.16	156780.18	0.04	1.8009	87054.47	242010.78	850570.70
16		737259	0.26	191687.3	34907.16	156780.18	0.04	1.8730	83706.22	325717.00	1007350.88
17		737259	0.26	191687.3	34907.16	156780.18	0.04	1.9479	80486.75	406203.75	1164131.06
18		737259	0.26	191687.3	34907.16	156780.18	0.04	2.0258	77391.11	483594.86	1320911.24
19		737259	0.26	191687.3	34907.16	156780.18	0.04	2.1068	74414.52	558009.38	1477691.42
20		737259	0.26	191687.3	34907.16	156780.18	0.04	2.1911	71552.43	629561.81	1634471.60
				3833747	698143.2				2130693.81		

Appendix 9: Plagiarism Awareness Certificate



SR716

ISO 9001:2019 Certified Institution

THESIS WRITING COURSE

PLAGIARISM AWARENESS CERTIFICATE

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LAGAT AMOS KIPKOECH

ENG/MS/SEA/4799/23

In recognition for passing the University's plagiarism

Awareness test for Thesis entitled: **PERFORMANCE EVALUATION OF SOLAR PHOTOVOLTAIC SYSTEM FOR ENERGY MANAGEMENT AND ENVIRONMENTAL SUSTAINABILITY IN MOI INTERNATIONAL AIRPORT - MOMBASA, KENYA** with similarity index of 14% and striving to maintain academic integrity.

Word count: 22136

Awarded by

Prof. Anne Syomwene Kisilu
CERM-ESA Project Leader Date: 27/09/2024