

**TECHNICAL PERFORMANCE ASSESSMENT OF THE GARISSA SOLAR
POWER PLANT IN KENYA**

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ACCESS**

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DECLARATION

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I hereby do declare that this thesis is my original work and has not been submitted for the award of degree in another University.

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DEDICATION

I dedicate this research work to my beloved mother, father, and my siblings for their support and encouragement through the research period.

ABSTRACT

The Garissa Solar Power Plant is a significant contributor to Kenya's goal of achieving 100% clean energy by 2030. Despite its significance, the lack of publicly available analyzed technical performance data limits optimization of the plant's efficiency and output. The main objective of this study was to assess the plant's technical performance based on key performance indicators. The study employed a structured approach to evaluate the plant's performance, adhering to the IEC61724-1 international standards. It focused on key indicators, namely; capacity utilization factor, specific yield, array yield, and performance ratio. The monthly and daily energy generation data were obtained from the Rural Electrification and Renewable Energy Corporation, while meteorological data were collected from the Photovoltaic Geographical Information System and the National Solar Radiation Database. Microsoft Excel software was utilized to apply theoretical formulas for computing and analyzing data. System Advisor Model software was used to conduct a performance analysis by integrating weather data, optimizing tilt and orientation, and simulating system design to determine the most efficient system. Lastly, the study compared the simulated and computed results based on the selected performance indicators. The power plant was analyzed over five years from 2019 to 2023. It exhibited an average annual performance ratio of 71.8%, capacity factor of 18.11%, system efficiency of 11.62% and specific yield of 1586.09 kWh/kWp. Analysis of irradiance data demonstrated a direct correlation with energy output: the highest recorded energy output was 7721 MWh at an irradiance of 204.34 kWh/m²/month, while the lowest was 6469 MWh at 169 kWh/m²/month. The wind speed and ambient temperature highlighted additional factors influencing solar power plant performance: variations in cell temperature from 37°C to 41°C and up to 49°C correspond to energy outputs of 6469 MWh, 7812 MWh, and 7721 MWh, respectively. The tilt angle of 4°, closely aligned with the latitude of 0.34°S that was optimal and facilitated self-cleaning during rainy seasons. The study found the applied azimuth angle of 140° to be suboptimal for a location in the southern hemisphere, where the azimuth angle should face north to maximize exposure to sunlight throughout the day. The actual Ground Coverage Ratio (GCR) of 0.625 exceeded the recommended range of 0.3–0.5 and the optimal row spacing was calculated as 0.4 meters, less than the current 2 meters, indicating potential for increasing the number of arrays by reducing row spacing. Comparative analysis of actual versus simulated data revealed discrepancies, with simulated values indicating marginally higher performance metrics—specifically, a performance ratio of 80%, a capacity factor of 20.5%, system efficiency of 13.17%, and a specific energy yield of 1797 kWh/kWp. In conclusion, while the power plant's performance was average, significant opportunities for optimization existed to enhance efficiency and energy output. Recommendations included adjusting the azimuth angle to 0°, reducing inter-row spacing to 0.4 meters to accommodate more arrays, and implementing tailored maintenance strategies to mitigate soiling and vegetation growth, thereby improving the overall system efficiency of the solar power plant.

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ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
AV	Agrovoltaic
CSP	Concentrated Solar Power
CUF	Capacity Utilization Factor
DAS	Data Acquisition System
DC	Direct Current
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal irradiance
EPRA	Energy Petroleum Regulatory Authority
FF	Fill Factor
GCR	Ground Coverage Ratio
GHI	Global Horizontal Irradiance
IRR	Internal Rate of Return
IV	Current-Voltage
KenGen	Kenya Electricity and Generating Company
KIPPRA	Kenya Institute for Public Policy Research and Analysis
KPLC	Kenya Power & Lighting Company
kWh	Kilowatt-hour
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MW	Mega Watts
MWh	Mega Watts hours
NMBU	Norwegian University of Life Sciences

NOCT	Nominal Operating Cell Temperature
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
PCE	Power Conversion Efficiency
POA	Plane of Array
PR	Performance Ratio
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
PVSyst	Photovoltaic System
REREC	Rural Electrification and Renewable Energy Corporation
RETScreen	Renewable Energy Technology Screening Model
SAM	System Advisor Model
SCADA	Supervisory Control and Data Acquisition
STC	Standard Test Conditions
W/m ²	Watts per meter square
E_a	Actual Energy Generated annually
E_{AC}	AC energy generated daily
E_{DC}	DC energy generated daily
I_R	Reference irradiance on the solar modules
I_{SC}	Short-Circuit Current
I_T	Total in plane irradiance
P_C	Installed Capacity

V_{OC}	Open-Circuit Voltage
W_p	Watt peak
Y_A	Array yield
Y_F	Final yield
Y_R	Reference yield

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND AND MOTIVATION OF THE STUDY

1.1.1 Energy and the Need for Sustainable Solutions

Energy is a global driver of progress, powering economies, improving lives and addressing climate challenges (*World Energy Outlook 2024 – Analysis - IEA*, 2024). It is essential for economic development, social well-being, and environmental sustainability. As global energy demands continue to rise, the need for sustainable energy solutions becomes increasingly urgent. Nevertheless, depending on conventional fossil fuels to fulfill these demands has had a considerable negative impact on the environment. Climate change, resulting from greenhouse gas emissions produced by fossil fuel combustion, presents a serious threat to the planet's future (IPCC, 2022).

Renewable energy has become an essential solution for addressing environmental issues and ensuring energy security in the context of climate change (Larsson, 2018). These energy sources, often referred to as clean energy, draw from natural processes that are perpetually replenished, such as sunlight, wind, biomass, water, and geothermal heat. This is in clear contrast to non-renewable sources like fossil fuels, which are finite and contribute significantly to environmental degradation. Unlike fossil fuels, renewable sources provide a sustainable and virtually inexhaustible energy supply. They are environmentally friendly, generating little to no greenhouse gas emissions, which helps decrease air pollution and combat climate change. Moreover, they align with sustainable development goals by reducing ecological impacts and conserving natural resources.

Making this transition is vital for managing the rise in global temperatures and fulfilling the objectives established by international agreements, including the Paris Agreement. Renewable energy contributes to energy security by broadening the energy supply and lowering reliance on imported fossil fuels, which is particularly beneficial for countries that depend heavily on energy imports. This shift helps mitigate their risk related to geopolitical issues and changes in market conditions. Moreover, investing in renewable energy infrastructure fosters economic growth and creates jobs in sectors such as manufacturing, installation, and maintenance.

The International Renewable Energy Agency (IRENA) reported that more than 12 million individuals were employed in the renewable energy sector worldwide in 2020, with expectations for substantial growth in the coming years (*Renewable Energy and Jobs: Annual Review 2024*, 2024) (IRENA, 2024). Additionally, renewable energy contributes to several Sustainable Development Goals (SDGs), such as SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 8 (Decent Work and Economic Growth). By reducing environmental impacts and preserving natural resources, renewable energy plays a vital role in advancing the broader objectives of sustainable growth (*World Economic Forum*, 2024) (International Energy Agency, 2023).

1.1.2 The Role of Solar Energy in Energy Transition

Solar energy has emerged as a leading renewable energy source due to its vast availability and potential to significantly lower greenhouse gas emissions (*Solar Energy*, 2024). Various technologies are utilized to capture sunlight for different energy applications, including solar photovoltaic systems, solar thermal systems, and concentrated solar power (CSP) systems.

Photovoltaic systems convert sunlight directly into electrical energy through solar cells. In contrast, solar thermal systems collect heat from the sun for purposes like heating water or spaces. CSP systems focus sunlight using mirrors or lenses to generate steam for electricity production. This clean energy process emits no harmful pollutants, positioning solar energy as a crucial element in the fight against climate change and reducing reliance on fossil fuels.

Utility-scale solar systems function as centralized energy sources, directly feeding electricity into the national grid (Khazieva, 2024). These large installations are vital for producing substantial power and ensuring the stability and dependability of the overall electricity supply. By being tied to the grid, these solar plants enhance efficiency, reduce transmission losses, and help meet electricity demands during peak usage periods. Meanwhile, decentralized systems, such as rooftop solar, provide localized energy production. Both centralized and decentralized approaches contribute significantly to energy security and promote a shift toward sustainable power solutions.

1.1.3 Solar Power Plant Performance Assessment

Assessing the performance of solar energy plants is vital to ensure their efficiency and reliability (Khazieva, 2024). Performance evaluation includes analyzing the plant's energy production, operational performance, and its overall capability in transforming solar energy into electrical power. By conducting a thorough performance assessment, areas for improvement can be identified, optimize maintenance practices, and enhance the plant's overall performance. This leads to increased energy output, reduced operational costs, and a more reliable supply of clean energy.

Key technical performance indicators include the Performance Ratio (PR), which measures how efficiently the system converts available solar energy into usable electricity, and the Capacity Utilization Factor (CUF), which indicates the actual energy output compared to the maximum possible output. Other critical parameters include System Efficiency (η), Final Yield (Y_F), Reference Yield (Y_R), and Availability Factor, which assess the plant's operational effectiveness and uptime. By conducting a thorough performance assessment, areas for improvement can be identified, maintenance practices optimized, and the plant's overall efficiency enhanced. This leads to increased energy output, reduced operational costs, and a more reliable supply of clean energy (Guoqing et al., 2021).

1.1.4 Case Study: The Garissa Solar Power Plant

The Garissa Solar Power Plant, located in North-Eastern Kenya, was utilized as a case study in this thesis (*Garissa Solar Park, Kenya*, 2024). It is a significant utility-scale solar power project and one of the largest in East Africa. Operational since 2018, the plant has a generating capacity of 54.65 MWp and produces more than 76 GWh of electricity annually. By replacing diesel-powered electricity generation, the plant significantly reduces greenhouse gas emissions, cutting down approximately 43,000 tons of CO² emissions per year (*Rural Electrification and Renewable Energy Corporation*, 2024a). The power plant serves as a model for future renewable energy projects in Kenya and beyond, demonstrating the viability and benefits of large-scale solar power in addressing energy challenges and promoting sustainable development.

1.2 PROBLEM STATEMENT

The Garissa Solar Power Plant, the largest utility-scale solar power plant in Central and East Africa, became operational in 2018 with an installed capacity of 54.65 MW. (*Rural Electrification and Renewable Energy Corporation*, 2024b). The plant was predicted to generate approximately 76,473 MWh annually, contributing around 2% to Kenya's national energy mix. This output corresponded to a capacity factor of about 16%, which was typical for solar installations in the region (*Garissa Solar Park, Kenya*, 2024). The plant purpose was to significantly reduce energy costs and promote clean, reliable, and affordable electricity in the country. However, its technical performance and factors affecting its output required further analysis to ensure optimal efficiency and long-term sustainability. A thorough technical evaluation of the Garissa Solar Power Plant identified factors affecting its output and allowed system optimization to improve efficiency. This approach was crucial for enhancing the plant's performance and maximizing its contribution to Kenya's energy mix. The assessment examined various technical factors, including reference yield, performance ratio, capacity factor, system efficiency, specific yield and environmental impacts on efficiency. By optimizing these elements, the Garissa Solar Power Plant will significantly support Kenya's renewable energy initiatives, reduce energy costs, and ensure a reliable electricity supply for local communities and the nation. Moreover, the findings from this evaluation will inform future solar power projects, aiding in the development of tailored operational strategies and design features for specific environmental contexts. This expertise will foster the creation of more efficient solar energy systems, ultimately strengthening the sustainability and reliability of Kenya's energy infrastructure.

1.3 RESEARCH OBJECTIVES

1.3.1 Main Objectives

The main objective of this research was to investigate the performance of the Garissa solar power plant based on selected technical performance indicators.

1.3.2 Specific Objectives

- i) To examine the performance of the power plant using selected performance indicators.
- ii) To analyze the effect of environmental factors on the performance of the power plant.
- iii) To simulate an optimal design for the plant using SAM software, together with data analysis tools for maximum energy generation.
- iv) To validate the simulated results with actual performance of the plant.

1.4 JUSTIFICATIONS OF THE STUDY

Climate change poses a significant threat to ecosystems and communities worldwide, emphasizing the necessity for a shift to renewable energy sources from fossil fuels. Nations are setting ambitious targets and collaborating through initiatives like the Paris Agreement to limit global temperature rise. As nations strive to meet renewable energy targets, the performance evaluation of these alternative renewable energy sources becomes integral. This includes solar farms, which have been embraced and integrated into the energy mix globally.

Though several studies have evaluated the performance of solar power plants in various locations worldwide, it is well recognized that the performance of these installations is site-specific, heavily influenced by factors such as environmental conditions and geographical

location. Conducting a meticulous performance assessment of the Garissa Solar Power Plant provides valuable insights specific to its unique environmental context.

1.5 SIGNIFICANCE OF THE STUDY

Understanding and optimizing the efficiency of solar facilities contributes directly to the global efforts to minimize reliance on fossil fuels and curb carbon footprints. Insights gained from such assessments inform best practices, enhance operational effectiveness, and play a crucial role in achieving the ambitious renewable energy goals set on the international stage.

This study targets to evaluate the contribution of the Garissa plant to the country's energy mix, offering a detailed analysis of its operational efficiency and effectiveness. By understanding and optimizing the performance of this solar facility, stakeholders will obtain critical data that can inform future investment plans in solar energy for regions with similar environmental conditions.

This case study not only enhances the local operational efficiency but also contributes to the global agenda of reducing carbon emissions through the strategic deployment of renewable energy technologies. The findings from Garissa will aid in planning and implementing solar projects in comparable climates, thereby supporting sustainable energy development worldwide.

1.6 LIMITATIONS OF THE STUDY

Data protection and privacy policies enforced by the operator restricted access to financial data on the plant, posing a challenge for assessing its economic performance. As a result, the

research relied on secondary sources for meteorological data, such as irradiance, temperature, and wind speed, obtained from the NSRDB and PVGIS databases. While these databases provide valuable and reliable information, they are not without limitations. The data from these sources may not be entirely accurate, as their resolution and granularity can vary, and they may not capture localized conditions as effectively as on-site measurements. Collecting data on site would have provided more precise and site-specific information, enhancing the accuracy of the performance assessment. Future studies could benefit from installing dedicated meteorological stations at the plant site to gather detailed, high-resolution data, ensuring a more comprehensive and precise analysis. A formal data request to NACOSTI is recommended to address this limitation in future research.

1.7 THESIS SUMMARY

The study is systematically arranged into five main chapters:

Chapter 1 provides the background and motivation for the study, introduces the problem statement, outlines the main objectives followed by the specific objectives that support these primary goals, the justification and significance of the study and finally discusses the limitations of the study.

Chapter 2 delves into the literature review. It examines the renewable energy mix globally. It also reviews relevant journals, articles, and related literature focused on the performance assessment of solar power plants, offering a comprehensive understanding of existing research in this area.

Chapter 3 describes the methodologies used to achieve the objectives of the study. It explains the key concepts essential to the research, providing a theoretical foundation. The chapter then details the methodological approaches, describing the specific methods and techniques employed in the study. It also presents various equations and calculations used to achieve the study's objectives, ensuring a clear understanding of the research process.

Chapter 4 presents the results obtained from analyzing the collected data, focusing on how these results achieve the listed objectives. It discusses the impact of these results on the performance of the power plant, providing a detailed analysis of the findings. The chapter also explores the broader implications of the results, discussing their significance in the context of the study.

Chapter 5 summarizes the key findings of the study, presenting the conclusions drawn from the research. It offers various recommendations that can be applied to the Garissa power plant and other similar projects to improve its operational efficiency. The chapter provides actionable suggestions, emphasizing practical steps that can be taken to enhance the performance of the power plant based on the study's findings.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

This chapter presents an extensive review of prior research, focusing on factors affecting the performance of solar power plants globally. The literature review delves into various studies addressing the technical performance of solar photovoltaic (PV) plants, the techno-economic aspects of solar power plants, and the design and optimization considerations relevant to solar PV plants. This comprehensive exploration of existing literature provides valuable insights into the multifaceted dimensions of solar power plant evaluations, encompassing both the technical intricacies and the economic viability of these sustainable energy systems.

2.2 GLOBAL ENERGY

Numerous nations have established ambitious renewable energy goals to decrease their dependence on fossil fuels and shift towards cleaner energy sources. Figure 2.1 shows some of the leading regions and their targets by 2030 regarding renewable energy. These targets have led to significant investments in renewable energy infrastructure globally (Delbeke et al., 2019). Under the Paris Agreement, China committed to raise its renewable energy share to 28% by 2030, India plans to attain 40% zero-carbon generation by the same year, and the European Union has proposed reaching 42.5% renewables by 2030 (Larsson, 2018). Despite these commitments, some countries are falling behind in meeting their targets, highlighting the need for accelerated efforts to deploy more wind and solar power in the coming years.

Country / Region	2030 Target	Annual Average Wind and Solar Capacity Additions Needed to Hit 2030 Target			Actual Capacity Additions in 2022		
		Wind	Solar	Total	Wind	Solar	Total
India	40% zero-carbon generation by 2030 (includes nuclear)	16 GW	19 GW	35 GW	2 GW	18 GW	20 GW
China	28% renewables by 2030	57 GW	44 GW	101 GW	55 GW	115 GW	170 GW
United States	739 GW of wind and solar by 2030 to reach zero-carbon electricity by 2035	34 GW	35 GW	69 GW	11 GW	21 GW	32 GW
United Kingdom	60% renewables by 2030	4 GW	3 GW	7 GW	4 GW	1 GW	5 GW
European Union	REPowerEU: 42.5% renewables by 2030	38 GW	48 GW	86 GW	16 GW	38 GW	54 GW

Figure 2.1: Advancements towards renewable energy in leading countries (Delbeke et al., 2019)

The current global development of renewable energy power installations is marked by significant growth and expansion. In 2023, a record 473 GW of renewable energy capacity was added globally, with solar energy accounting for 73% of the growth and wind power accounting for 24% (*Record Growth in Renewables, but Progress Needs to Be Equitable*, 2024). In 2023, solar PV generation saw a record increase of 320 TWh, marking a 25% growth and surpassing 1,600 TWh in total output. This represented the largest absolute increase among all renewable energy technologies for the year (*Solar - IEA*, 2023). Renewable energy now constitutes 30% of the world's installed capacity, with solar and wind power installations steadily rising (*Solar - IEA*, 2023). However, the growth of renewable energy is not uniform across regions, with Asia, particularly China, leading the charge, while other regions like Africa and Latin America witness slower growth rates (*Installed Renewables Capacity Is on the Rise | Enel Green Power*, 2024). Solar photovoltaics and wind power are anticipated to contribute 96% of new capacity additions in the coming years, driving even faster growth in these sectors (*Renewable Energy: Global Capacity Increased*

by 50% in 2023 | *World Economic Forum*, 2023). Forecasts indicate that renewable energy will comprise 35% of global electricity generation by 2025, with solar and wind energy leading the way. (*Renewable Energy Will Produce 35% of Global Electricity by 2025: IEA | World Economic Forum*, 2023). Remarkably, renewable energy has become the fastest-growing energy source in the United States, with solar power experiencing a 90% increase from 2000 to 2020. By 2020, it accounted for nearly 20% of electricity generation from utility-scale sources (*Renewable Energy - Center for Climate and Energy Solutions*Center for Climate and Energy Solutions, 2020).

2.2.1 Energy in the East African Community

In East Africa, Kenya holds the highest installed capacity of 3311MW in 2023, making up 43% of the total capacity in the region (EPRA, 2023). Figure 2.2 displays the composition of installed capacities in the countries of the East African Community for the years 2018 through 2023.

	Dec 2018 (MW)	Dec 2019 (MW)	Dec 2020 (MW)	Dec 2021 (MW)	Dec 2022 (MW)	Jun 2023 (MW)
Burundi	91	91	99	114	112	112
Kenya	2,351	2,712	2,840	2,984	3,121	3,311
Rwanda	222	226	238	263	311	331
Tanzania	1,518	1,603	1,602	1,609	1,824	1,863
Uganda	984	1,253	1,269	1,365	1,401	1,610
Zanzibar	25	25	25	25	25	25
Total	5,191	5,910	6,073	6,360	6,794	7,252

Figure 2.2: Installed capacities in EAC Members States (EPRA, 2023)

According to EPRA Energy report 2023, solar energy contributed 4% of the overall energy mix in the region, with hydro energy taking the lead with a share of 42% (EPRA, 2023). The

region exhibits a notable effort in adopting renewable energy technologies; for instance, wind energy and solar energy had a total of 10% with Kenya having 86% of the capacity. Figure 2.3 illustrates this.

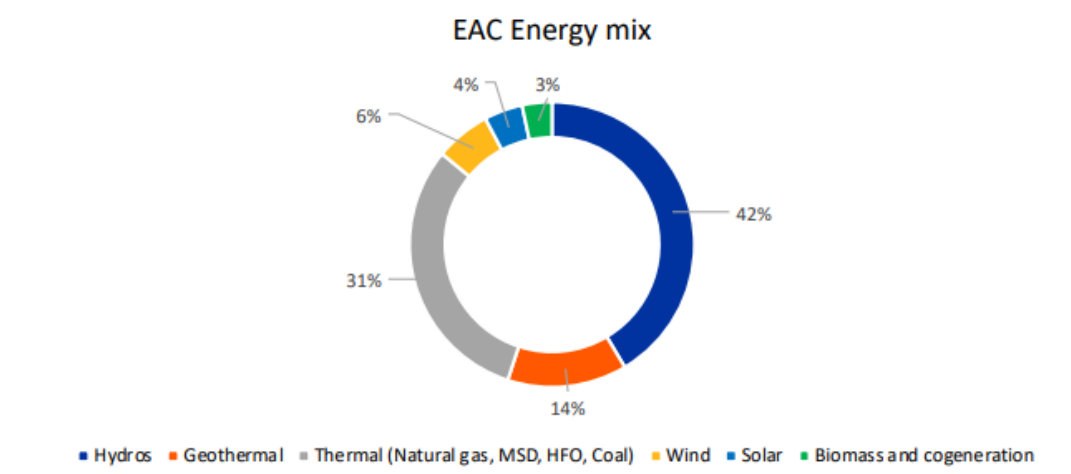


Figure 2.3: EAC energy mix (EPRA, 2023)

2.2.2 Kenya's Energy Mix

In Kenya, energy plays a focal role in propelling the nation to a brighter, more green future through investments in renewable energy, energy efficiency and expanded access. The country generated a total of 13,289.63 GWh of energy in 2023 with a present effective installed electricity capacity of 3155.8 MW with a peak demand of 2149 MW (EPRA, 2023). In the year 2023 it was reported that 84.65% of the total energy generated in Kenya was obtained from renewable energy resources with solar energy contributing 3.34% from total installed capacity of 8.15% (EPRA, 2023) (*Kenya - Energy-Electrical Power Systems*, 2024). 10.5% of the country's energy in 2023 was derived from thermal oils while the remaining 4.85% was imported as displayed by Figure 2.4.

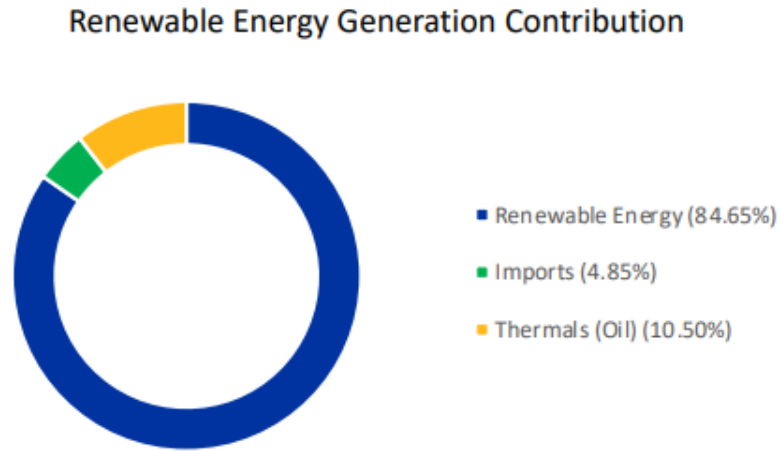


Figure 2.4: Kenya's renewable energy contribution in year 2023 (EPRA, 2023)

Approximately 85% of Kenya's electricity comes from renewable energy sources, with geothermal being the dominant contributor. Solar energy accounts for a smaller share but is steadily growing. Wind power also plays a key role, particularly with the Lake Turkana Wind Power Project, Africa's largest wind farm (International Renewable Energy Agency (IRENA), 2022)(Kenya - Energy-Electrical Power Systems, 2024). This is as displayed by Table 2.1.

Table 2.1: Kenya Energy Mix 2023

Energy Source	Installed Capacity (MW)	Percentage
Geothermal	993	29.9%
Hydro	827	24.9%
Wind	435	13.1%
Solar	268	8.15%
Thermal	646	19.4%
Imports (Ethiopia)	50	1.5%

EPRA 2023 annual statistical report documents the commendable annual energy generation increase by 5% every year from 2017 to 2023 with a notable decline of 0.25% in 2020 due

to the COVID-19 pandemic in Kenya as demonstrated by Figure 2.5 (EPRA, 2023). This boost in yearly energy generation directly compares with the economic growth in the country.

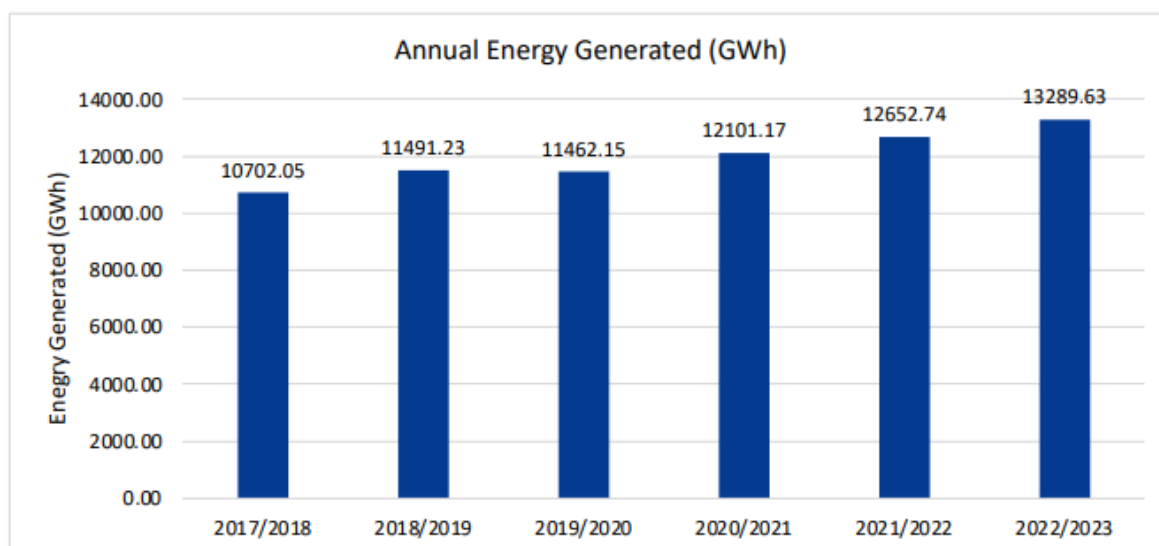


Figure 2.5: Trend in annual energy generated (EPRA, 2023)

Kenya has shown significant increase in the annual solar energy generated from the year 2017 to 2023 as displayed by Figure 2.6 (EPRA, 2023). This indicates that the country is working on harnessing the immense solar resource available in their advantageous global location along the equator.

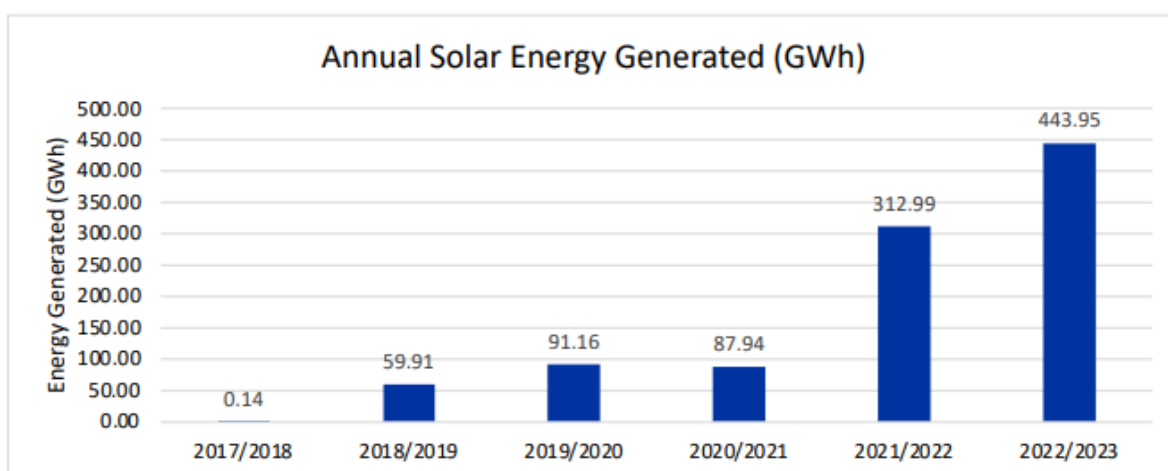


Figure 2.6: Trend in annual solar energy generation in Kenya (EPRA, 2023)

2.2.3 Global Solar Resource

The global solar resource is the quantity of solar energy that hits the Earth's surface. The solar resource is enormous and differs depending on the season, time of day, location, and weather conditions.

The global solar energy potential is vast, with estimates varying based on assumptions about technology, land availability, and efficiency. According to the International Renewable Energy Agency (IRENA), the technical potential for global solar photovoltaic (PV) energy is approximately 124.7 petawatts (PW) with a land utilization factor of 50% (IRENA, 2024). Similarly, the International Energy Agency (IEA) projects that, under a high-renewable scenario, global solar PV capacity could reach 4.7 terawatts (TW) by 2050, with more than half of this capacity deployed in China and India, positioning solar power as the world's largest source of electricity (*Renewables*, 2024). This reveals that a substantial portion of the world's land area is suitable for solar energy generation, providing a vast opportunity for harnessing renewable energy. This significant potential can have a great impact on the universal energy situation, as it offers a viable alternative to fossil fuels and can help mitigate climate change. By harnessing this potential, countries can reduce their dependence on non-renewable energy resources, minimize greenhouse gas emissions, and contribute to a more sustainable energy future.

The World Bank Group, in collaboration with Solargis, has developed a Global Solar Atlas that provides a review of solar power potential and solar resources worldwide (*Global Solar Atlas*, 2024). The atlas enables users to quickly access data and perform straightforward calculations for electricity output at any location included in the solar resource database. It

also ranks and compares countries and regions based on their photovoltaic (PV) power potential, estimated levelized cost of electricity (LCOE), and correlations with socio-economic indicators. As illustrated in Figure 2.7, approximately 70 countries have favourable conditions for solar PV, with average daily outputs exceeding 4.5 kWh per installed kW of capacity (kWh/kWp), sufficient to boil about 25 litres of water. Overall, 93% of the global population resides in countries with an average daily solar PV potential ranging from 3.0 to 5.0 kWh/kWp. The Global Solar Atlas is a complimentary resource for governments, developers, and the public, aimed at facilitating the growth of solar energy projects around the world (*Global Solar Atlas*, 2024).

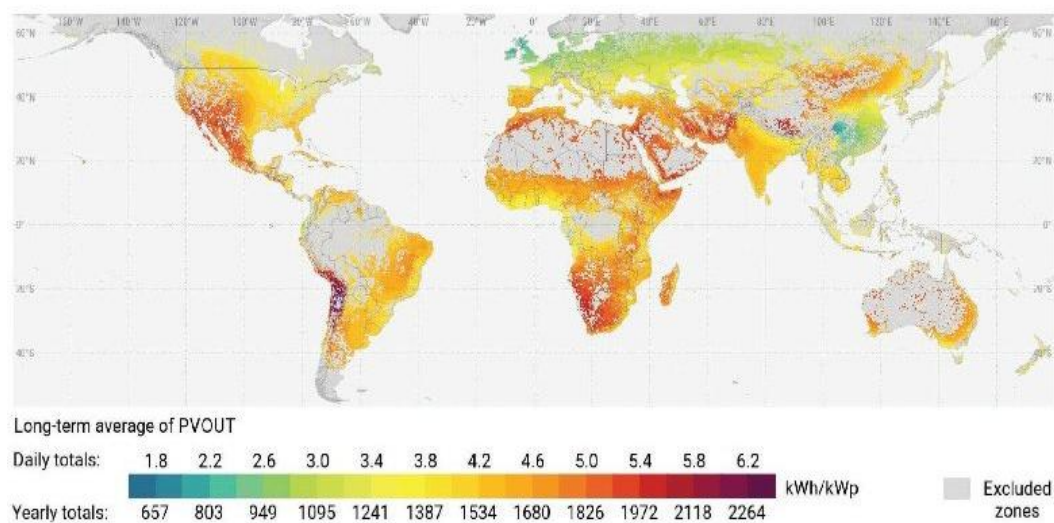


Figure 2.7: Global solar energy potential (Global Solar Atlas, 2024).

The Global Solar Atlas from the World Bank reveals that Africa holds the greatest potential for solar energy globally, showcasing an impressive long-term practical yield of 4.51 kWh/kWp/day for utility-scale solar installations, the highest yield of any region. Although the continent possesses 60% of the world's prime solar resources, it contributes a mere 1% to the global solar generation capacity (*Solar Resource Maps and GIS Data for 200+ Countries*

| *Solargis*, 2024). To fulfill its energy and climate targets, Africa will need to secure an annual investment of \$190 billion from 2026 to 2030, with a significant share directed toward clean energy, as reported by the International Energy Agency (IEA).

As of 2023, South Africa tops the continent in solar energy capacity, exceeding 6 GW, followed by Egypt with 1.9 GW and Morocco at 934 MW, as depicted in Figure 2.8 (*Africa: Solar Energy Capacity by Country 2023* | *Statista*, 2023). The IEA's Sustainable Africa Scenario (SAS) predicts that by 2030, solar PV will surpass all other energy sources in competitiveness across the continent. Renewable energy sources, including solar, wind, hydropower, and geothermal, are expected to constitute over 80% of new power generation capacity. This emphasizes solar energy's ability to provide cost-effective, reliable, and sustainable electricity, especially in regions that require improved economic opportunities and enhanced quality of life.

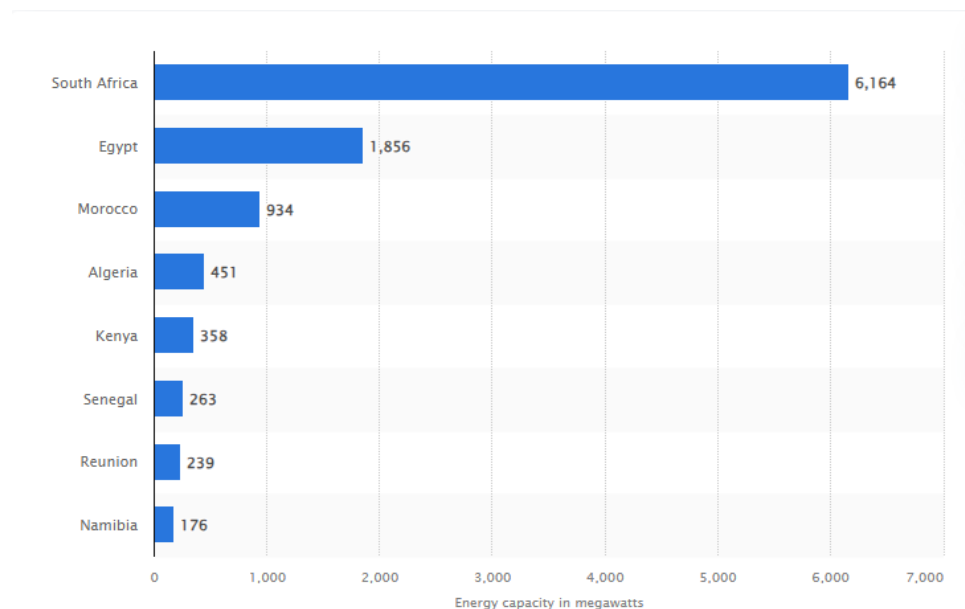


Figure 2.8: 2023 solar energy capacity by country in Africa (Africa: Solar Energy Capacity by Country 2023 | Statista, 2023).

2.2.4 Solar resource in Kenya

Situated along the equator in East Africa, Kenya benefits from a conducive solar resource, with an mean of 4-6 kWh/m²/day as visually represented by Figure 2.9, making it highly suitable for solar power generation (KIPPRA, 2022). The estimated solar energy potential for the country is reported to be 15,000 MW according to KIPPRA in 2022 (KIPPRA, 2022).

Kenya's solar energy potential varies across regions due to differences in climate, altitude, and geographic location. The northern and northeastern regions, such as Garissa and Mandera, have the highest solar irradiance, often exceeding 6 kWh/m²/day, making them suitable for large-scale solar projects like the Garissa Solar Power Plant. Coastal areas and parts of the Rift Valley also have good solar potential, while the central highlands and western regions have lower solar irradiance due to increased cloud cover and rainfall (*Kenya's Clean Energy Transition Gets a Boost from Solar Power - Kleinman Center for Energy Policy*, n.d.). Despite its advantageous location, the country still heavily relies on traditional sources of energy such as fossil fuel. However, Kenya has made significant progress in recent years in diversifying its energy sources and reducing its reliance on fossil fuels.

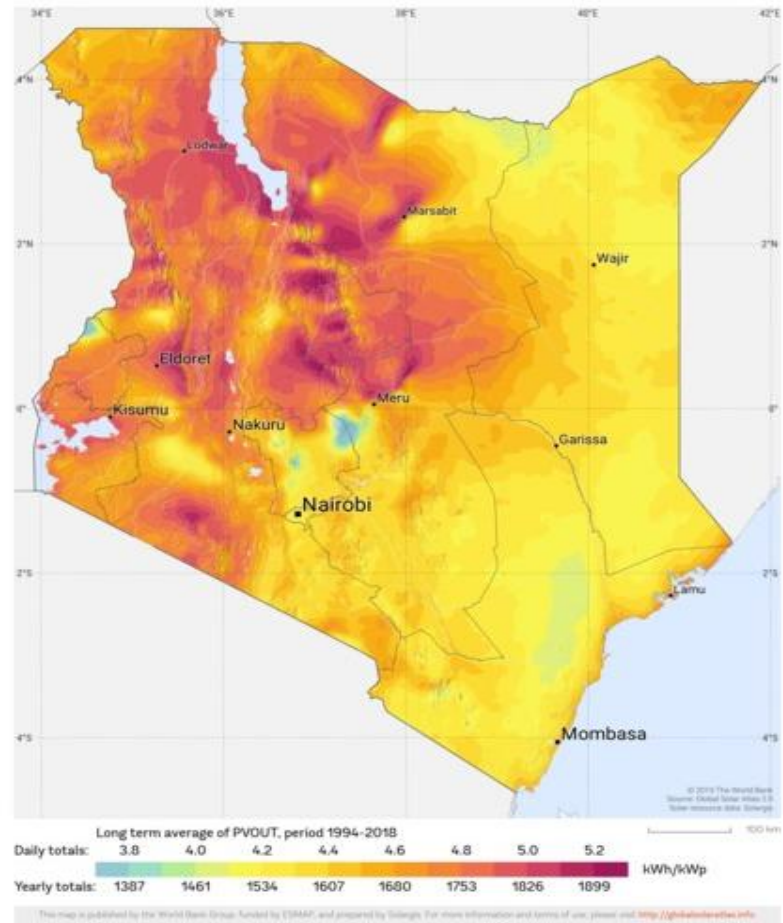


Figure 2.9: Kenya's solar energy potential (KIPPRA, 2022)

Kenya has several key solar PV installations, as shown in *Table 2.2*, that contribute a significant amount of energy to the national grid, supporting the country's clean energy targets by diversifying the energy mix. (*Solar Projects in Kenya: 10 Largest Solar Power Plants in MW - Solar Financed*, 2024)(KIPPRA, 2022).

Table 2.2: Kenya's Large solar PV installations

Project	Installed capacity (MWp)	Location	Commissioning year	Developer/owner
Garissa Solar Power Plant	54.65	Garissa	2018	Rural Electrification and Renewable Energy Corporation (REREC)
Eldosol solar Power plant	40	Eldoret	2021	Frontier Energy
Malindi Solar Plant	52	Malindi, Kilifi	2021	Globeleq, Africa Energy Development Corp. (AEDC)
Selenkei Radiant solar power plant	40	Uasin Gishu	2021	Frontier Energy
Kesses 1 (Alten)	40	Eldoret	2023	Alten Energias Renovables
Others small scale solar installations	41.35	-	-	-
Total (MW)	268	-	-	-

According to (EPRA, 2023), solar PV power contributed about 3.5 % of the cumulative installed power capacity of 6805 MW in Kenya as demonstrated by Figure 2.10. This indicates there is room for improvement. The Kenyan government's focus is on expanding renewable energy generation in the country; solar energy is projected to contribute about 852 MW to national power mix by 2037 (KIPPRA, 2022). This will account for about 25% of the total cumulative power.

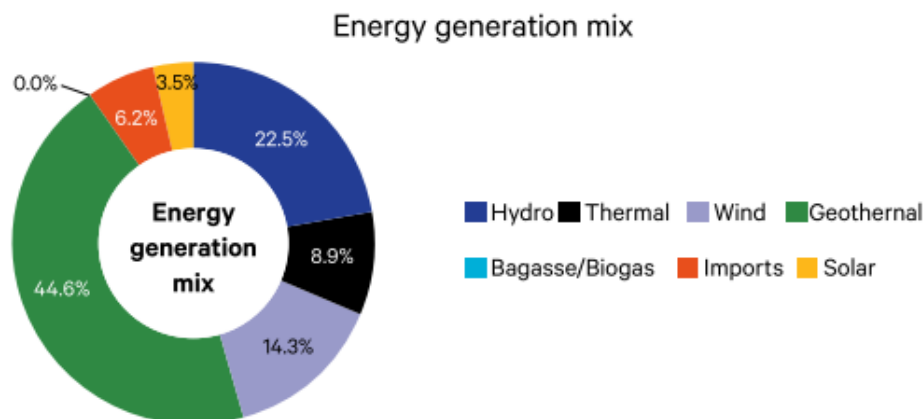


Figure 2.10: Distribution of energy mix in 2023 (EPRA, 2023)

2.2.5 Garissa Solar Power Plant

The Garissa Solar Power Plant, situated in northeastern Kenya, stands as a major renewable energy initiative in East and Central Africa. As the largest grid-connected solar facility in the region, it boasts a capacity of 54.65 MW (*Rural Electrification and Renewable Energy Corporation, 2024a*)(*Kenyan: Mixed Expectations as a 50MW Garissa Solar Power Plant Project Is Carried out - ACRP, 2024*). The plant was established to capitalize on Kenya's vast solar energy potential, enhance the diversity of the country's power generation sources, and lower electricity costs.

While the Garissa Solar Power Plant represents a crucial step towards Kenya's renewable energy goals, there is limited detailed analysis on its operational performance and efficiency. Studies on solar power plants generally highlight the potential for enhanced power generation and reduced CO² emissions (*Kenyan: Mixed Expectations as a 50MW Garissa Solar Power Plant Project Is Carried out - ACRP, 2024*)(Makkiabadi et al., 2021). However, specific performance evaluations of the Garissa plant are scarce. Various studies have highlighted its strategic location, technological advancements, and role in Kenya's renewable energy

transition (Case et al., 2023). (Case et al., 2023), conducted research focused on its design, potential, and predictive modeling using machine learning, but limited empirical data is available on how the plant has performed since commissioning.

Key areas requiring further study include energy yield versus initial projections, performance degradation over time, and effects of environmental factors such as dust accumulation and high temperatures on output. Additionally, while the plant was designed to provide stable grid support, its real contribution to grid reliability and voltage stability remains largely undocumented. There is also a need to examine operation and maintenance (O&M) challenges, including inverter failures, module degradation, and cleaning schedules, which impact efficiency. Addressing these gaps would provide data-driven recommendations for optimizing the plant's output, improving Kenya's future solar projects, and ensuring maximum return on investment for large-scale PV installations.

2.3 PERFORMANCE OF DIFFERENT SOLAR PV SYSTEMS ACROSS THE WORLD

The performance of different solar photovoltaic (PV) systems globally varies significantly due to factors such as system configuration, technology, and environmental conditions (B. S. Kumar & Sudhakar, 2015). Table 2.3 illustrates the performance of select few solar PV systems globally. The performance ratio (PR), which measures actual energy output compared to the theoretical maximum, ranges from 60% to 90% depending on these factors. The capacity factor (CF), representing the actual energy produced as a percentage of the maximum possible, typically ranges from 10% to 30%. Specific yield (SY), reflecting energy output per unit of installed capacity, generally ranges from 1000 kWh/kWp to 2000

kWh/kWp. Overall system efficiency (SE) varies from 10% to 20%. Solar module technology also significantly impacts performance, with monocrystalline silicon modules often outperforming polycrystalline silicon modules.

Table 2.3: Performance of different systems globally

Location	Technology	Size	PR (%)	CF (%)	SY (kWh/kWp)	η (%)	References
Uganda	Monocrystalline	10 MW	75.84	19.07	1670.2	-	(Oloya et al., 2021)
Mauritania	Thin film	15 MW	67.9	16.14	1558.6	-	(Elhadj Sidi et al., 2016)
Ghana	Polycrystalline	2.5 MW	70.4	16.2	1419.1	-	(Mensah et al., 2019)
Kuwait	Thin film	5.5 MW	80	20.58	1805	-	(AL-Rasheedi et al., 2020)
Kuwait	Polycrystalline	5.6 MW	80.2	20.58	1810	-	(AL-Rasheedi et al., 2020)
Kenya	Monocrystalline	54 kW	78	17.3	1434	-	(Ngure et al., 2023)
Iraq	-	4 MW	79.2	19.4	1715.5	15.5	(Samah et al., 2017)
India	Polycrystalline	10 MW	78	17.29	1514.8	11.9	(M. Kumar et al., 2020)
France	-	4.5 MW	87.18	-	1215.45	-	(El et al., 2021)
India	Polycrystalline	10 MW	86.12	17.68	1560.6	-	(B. S. Kumar & Sudhakar, 2015)
Ghana	Thin film	50 MW	77	15.75	11022.3	-	(Obeng et al., 2020)
Ghana	Polycrystalline	50 MW	75.7	15.41	974.55	-	(Obeng et al., 2020)
Ghana	Monocrystalline	50 MW	67.9	15.37	970.9	-	(Obeng et al., 2020)
Louisiana	Copper Indium Gallium Selenide (CIGS)	1.1 MW	79	16.08	1392	9.5	(Veerendra Kumar et al., 2022)
Louisiana	Monocrystalline	1.1 MW	77	15.68	1356	13.5	(Veerendra Kumar et al., 2022)
Louisiana	Polycrystalline	1.1 MW	73	14.78	1279	12.2	(Veerendra Kumar et al., 2022)

System configuration, including the number and type of modules, inverters, and mounting systems, is crucial, with more modules typically generating more energy. Low PR and CF in utility solar power plants can have significant effects on energy output, costs, and efficiency. It is essential to ensure that solar power plants are designed, installed, and maintained properly to maximize their performance and efficiency.

2.3.1 Efficiency of Solar Modules

The conversion efficiency of solar modules represents the portion of solar energy striking the modules that gets transformed into direct current (DC) electricity. This efficiency is affected by several factors, including the type and quality of the solar cells, temperature, irradiance, spectral distribution, and shading effects. Table 2.3 shows that the efficiency of solar cells can vary between 10% and 25%, depending on the specific technology employed. In essence, this percentage reflects how effectively the solar cells within the modules can convert sunlight into usable electrical power, and this efficiency range underscores the diverse technologies available in the solar energy landscape (Rashid et al., 2019).

An experiment was conducted on the impact of various operating parameters on PV module performance by addressing factors which impact the efficiency of PV modules (Rahman et al., 2015). The research showed that factors such as humidity and dust accumulation have a direct effect on the efficiency of PV modules. It was observed that as the temperature of the solar cells increased, both power and efficiency decreased. The study underscores the necessity of regulating conditions, particularly temperature, to enhance the functioning of PV modules. The application of water cooling proved effective in enhancing output power and efficiency, emphasizing the significance of thermal management in PV systems.

The soiling effect, also known as dust is defined as the contamination of PV modules' optical surfaces by fine particles of dirt. The surface of PV modules can become contaminated by various substances, including bird droppings and nests, microorganisms, mineral deposits, smoke residue, and vegetation (Babatunde et al., 2018). This study observed that an average difference of 2.5% was observed in specific yield after implementing a cleaning procedure.

According to (Veerendra Kumar et al., 2022), the system efficiencies of various solar PV technologies in differ as Copper Indium Gallium Selenide (CIGS) at 9.5%, reflecting its flexibility and cost-effectiveness despite lower overall efficiency compared to other technologies. Monocrystalline silicon exhibits the highest system efficiency at 13.5%, emphasizing its superior performance in converting solar energy into electricity and its suitability for maximizing power output in limited space scenarios. Polycrystalline silicon follows closely with a system efficiency of 12.2%, offering a balance between efficiency and cost-effectiveness in large-scale solar installations. These efficiency figures highlight the technological diversity in solar PV systems, where the choice of technology impacts both performance and economic considerations depending on specific project requirements and environmental conditions.

The efficiency of PV panels can be impacted by shading from vegetation, the movement of clouds, adjacent constructions, or any other obstructive factors. (Ballal et al., 2015) performed a systematic investigation of the effect of shading on the solar panel's power yield, fill factor, and efficiency. The research indicated that under consistent shading conditions, the short circuit current was directly correlated with solar irradiation. However, the performance varied under non-uniform shading conditions. Fill factor and efficiency

remained unaffected by shading. The degree of shading on specific cells influenced their performance, acting as loads and resulting in a reduction in current, power, and efficiency. To improve the performance of solar panels, non-uniform shading should be prevented.

Enhancing the efficiency of PV modules is achievable through the utilization of high-quality materials and components, strategic optimization of system design and configuration, systematic cleaning and maintenance practices, and the incorporation of advanced technologies like self-cleaning coatings, robots, or drones. The efficiency of PV modules holds a significant role in maximizing the output and benefits of solar energy systems, especially in regions with restricted space or limited solar resources.

2.3.2 Inverter Efficiency

Inverter efficiency is influenced by input power, input voltage, and design features like single or multistage configurations. This source provides an overview of inverter efficiency, highlighting the importance of these factors in determining overall performance (Pearsall, 2017). The efficiency of an inverter can range from 85% to 99%, and this variation is influenced by both technological factors and operating conditions. High-quality pure sine wave inverters typically exhibit efficiencies ranging from 90% to 95%, whereas the typical efficiency of lower-quality modified sine wave inverters ranges from 75% to 85%.

In grid-connected PV systems, the inverter plays a crucial role, and its efficiency is influenced by various factors (Ketjoy et al., 2021). This paper analyzed the duration of inverter operations, showing that over four years of operation, the yearly average efficiency of the inverter remained at 0.90, close to the value dictated by the manufacturer of 0.91. This

stability was attributed to maintaining a cool temperature in the inverter storage room. The study also examined the influence of power input from various PV module technologies, finding that while p-Si PV modules attained a top efficiency of 0.91, the specific type of PV module had little effect on inverter efficiency. The research concentrated on the power input provided by the PV modules. Additionally, it investigated how irradiance distribution affected inverter efficiency, showing that the inverter achieved its peak efficiency of 0.90 when irradiance at 350 W/m² and higher.

2.4 ENVIRONMENTAL EFFECTS ON PERFORMANCE OF SOLAR POWER PLANTS

Environmental conditions such as irradiance, temperature and humidity profoundly affect system performance, with high temperatures potentially reducing efficiency and high irradiance increasing energy output (Mustafa et al., 2020). The environmental effects on the performance of solar power plants can be significant and varied. High temperatures can lower the solar panels efficiency, while low temperatures can increase it, with the optimal temperature range being between 25°C and 35°C. High humidity can reduce efficiency by increasing the risk of corrosion and diminishing the effectiveness of the panels' cooling systems (Das, 2019).

Temperature and irradiance are significant factors in the deviation of PV modules from STC. High temperatures can reduce the solar modules efficiency, while low irradiance levels can reduce power output, Table 2.4. A study on the impact of wind speed and ambient temperature on the performance of solar modules found that the deviation in performance was more pronounced at higher temperatures and lower irradiance levels.

Wind can improve the performance of PV modules by reducing the temperature of the modules and increasing convective heat transfer from the module surface to the surrounding air, Table 2.4. This is particularly important in hot and sunny climates where the module temperature can be high, leading to reduced efficiency (Ansori et al., 2022) (Tahir et al., 2022). Similarly, high wind speeds can damage panels and impair cooling efficiency. However, high wind speeds can also reduce the power output of PV modules due to increased energy losses (Ansori et al., 2022).

Light intensity plays a crucial role, with optimal performance achieved between 1000 and 2000 W/m², while low light intensity reduces efficiency (Mustafa et al., 2020). High altitudes can also negatively impact efficiency due to lower air pressure and temperatures. Air pressure variations affect panel efficiency by increasing the risk of damage and hindering cooling. Dust and pollution are detrimental, as they increase corrosion risk and reduce cooling effectiveness (Das, 2019). Understanding these environmental factors is essential for optimizing the efficiency and longevity of solar PV systems.

Various studies have investigated the impact of irradiance intensity on the performance of PV systems, shedding light on how changes in solar irradiance levels influence power generation. Solar irradiance affects the energy output of PV systems directly by changing the current-voltage (IV) and power-voltage (PV) curves. Higher solar insolation lead to increased output power as they enhance the I_{sc} and V_{oc} of PV modules (Al-bashir et al., 2020). Conversely, a decrease in solar irradiance intensity results in reduced power output due to the changes in the IV and PV curves (Musanga et al., 2018). *Table 2.4* displays some of the key parameters and their effects on solar PV systems according to different authors.

Table 2.4: Different parameters and their effect on solar PV systems

Parameter	Findings	Reference
Temperature	An increase in temperature leads to low power output.	(Ayadi et al., 2019) (Das, 2019)
Ambient temperature and irradiance	High irradiance increases power output, but associated with high temperatures reduces the efficiency.	(Salimi et al., 2020) (Rahman et al., 2015) (Shaik et al., 2023)
Humidity	High humidity leads to low power output and rusting solar cells.	(Das, 2019) (Rahman et al., 2015)
Wind	High wind speeds cause low cell temperatures which in turn increases power output	(Das, 2019) (Salimi et al., 2020) (Tahir et al., 2022)
Ground Coverage Ratio (GCR)	A low GCR ratio increases the efficiency of a solar plant. The recommended GCR is 0.3 – 0.5.	(Mustafa et al., 2020) (Dupraz, 2023)
Rainfall / Water	Water provides a cooling effect to the cell temperature which increases power output	(Mustafa et al., 2020) (Rahman et al., 2015)
Dust	Dust accumulation on solar panels leads to significant power losses, with studies showing a linear relationship between dust density and energy reduction—ranging from 1.7% per g/m ² in the UAE to 34% per g/m ² in Kuwait.	(Mustafa et al., 2020) (Babatunde et al., 2018) (Abuzaid et al., 2022)
Wind speed and temperature	An increase in wind speed helps dissipate heat from the solar module, reducing cell temperature and thereby improving energy output by minimizing thermal losses.	(Naveed, 2017) (Tahir et al., 2022)

2.4.1 Module deviation from STC

The deviation of PV modules from STC is primarily due to changes in solar irradiance, wind speed and temperature. These environmental factors can significantly impact the output of PV modules, leading to deviations from their expected performance under STC (Siddiqui &

Bajpai, 2012). The PV module temperature has a sizable impact on its efficiency. As the temperature increases, the efficiency of the module decreases due to the reduced V_{OC} and the increase in the series resistance. This is because the high temperature causes the material properties of the module to degrade, leading to a decrease in the conversion efficiency of the solar energy into electrical energy (Rahman et al., 2015) (Naveed, 2017).

Studies have shown that the energy output of PV modules can deviate significantly from their STC values. For instance, a paper on the performance of crystalline silicon-wafer based PV modules found that the mean STC power output was lower than the rated value by 5.5%, with a 2% standard deviation. Another study observed that the power deviation in relation to the nominal value for generators with similar characteristics was around 1%, while the mean power output varied according to the module model, ranging from 92% to 97% of the nominal power (García et al., 2012).

In conclusion, the deviation of PV modules from STC is a complex phenomenon influenced by various environmental factors, including temperature, irradiance, and wind speed (*Table 2.4*). Understanding these factors is essential for improving the performance of solar energy systems and warranting maximum energy gain from available solar radiation. The power output deviation from STC can be significant, ranging from 1% to 5.5% depending on the module model and environmental conditions. By accounting for these deviations, solar energy system designers and operators can better predict and manage the performance of their systems.

captured and the energy output generated. For fixed-tilt systems, the tilt angle is set during the installation process and remains fixed throughout the year. Alternatively, some solar PV systems utilize adjustable tilt mounts, allowing for manual or automated adjustment of the tilt angle to optimize energy production based on seasonal variations in the sun's path.

The ideal tilt angle for solar installations varies depending on factors such as specific energy needs, seasonal sun angles, the sun path and geographic location. In general, the inclination angle is set to maximize the amount of sunlight falling on the panels throughout the year, thereby optimizing energy production. A study in Saudi Arabia emphasized the significance of optimizing the tilt angle for solar panels to increase energy generation. The study found that the ideal tilt angle differs depending on the location and time of year, with an annual average tilt angle of 23.5° corresponding to the latitude of the site (Benghanem, 2011).

In regions closer to the equator, where the sun's path is more direct, solar panels are typically installed at a tilt angle close to the latitude of the location (Krishna et al., 2021). This allows the panels to capture the maximum amount of sunlight year-round. However, in regions further from the equator, where the sun's path varies more significantly throughout the year, modifying the inclination angle seasonally may be beneficial to optimize energy production. A study in Cameroon found out that the optimal tilt for system in this region ranged from 10° – 20° corresponding to the general latitude of the country (Ekoe A Akata et al., 2022).

The inclination angle has a sizable impact on energy generation. A study by (Gomes et al., 2023) found that the energy output of a PV panel decreases by around 8% when the tilt angle is not adjusted seasonally.

2.4.4 Effect of orientation on energy generation

Panel orientation is the direction in which solar modules are installed to receive the highest exposure to the sun and optimize energy production. For fixed-tilt solar PV systems, the panel orientation is set during installation and remains fixed throughout the year. However, some systems may utilize tracking mounts that allow panels to adjust their orientation throughout the day to follow the sun's movement. This tracking capability can further enhance energy production by ensuring panels are always positioned optimally relative to the position of the sun in the sky (The Best Solar Panel Angle and Orientation for Installation, 2023).

The optimal orientation angle for a solar system is a crucial factor in maximizing energy production. The latitude of the location is a primary determinant, with solar panels located in the Northern Hemisphere typically facing south and those in the Southern Hemisphere facing north. However, the optimal angle can vary seasonally, as a steeper tilt is often preferred in the winter to capture more sunlight, while a shallower angle may be better suited for the summer to prevent overheating (How to Optimize Solar Panel Orientation and Tilt for Maximum Efficiency, 2023).

The pitch and orientation of the roof must be considered, as a flat roof may require a larger tilt angle compared to a pitched roof. Shading from nearby obstructions can also significantly impact energy production, necessitating the careful placement of solar panels to minimize shading. Furthermore, the efficiency and power output of the solar panels themselves can influence the optimal orientation angle, with high-efficiency panels potentially requiring a lower tilt angle to maximize energy output. By carefully considering these factors, solar

system designers can optimize the orientation angle to achieve maximum energy generation and system performance (Alhaidari, 2017). This orientation ensures that the panels receive sunlight when the sun is at its highest point in the sky, maximizing energy generation. Conversely, in the southern hemisphere, solar panels are often oriented to face true north for optimal sunlight exposure. The goal is to position the panels perpendicular to the sun's rays to capture sunlight most effectively.

The optimal orientation for solar panels around the equator is typically between 90° and 270° azimuths, as the sun passes from east to west during the day. However, this can vary depending on the time of year and the location's latitude (Ekoe A Akata et al., 2022). In Douala, Cameroon, which is located near the equator, the optimal orientation for a photovoltaic thermal (PVT) system is between 180° and 225° azimuth (Ekoe A Akata et al., 2022). While facing true south or true north is ideal for maximizing energy production, slight deviations from these directions may be acceptable depending on specific site conditions and energy requirements. Factors such as shading from nearby structures or trees, roof orientation, and available space for panel installation can influence the optimal panel orientation.

The azimuth angle of a solar collector is the compass direction it faces, measured in degrees from true north, and it is crucial for optimizing solar energy capture, system efficiency, and adapting to seasonal variations. The orientation of a solar collector is directly related to this azimuth angle. Typically, in the northern hemisphere, the optimal orientation for maximum energy capture is due south, corresponding to an azimuth angle of 180° . Conversely, in the southern hemisphere, the optimal orientation is due north, with an azimuth angle of 0° .

(Handoyo et al., 2013). Properly determining and adjusting the azimuth angle involves considering the geographical location, site constraints such as physical obstructions, local climate conditions, and the specific purpose of the solar installation. This ensures that the solar collector is positioned to receive the most direct sunlight throughout the year, maximizing its efficiency and energy output (N'Tsoukpoe, 2022).

2.5 DESIGN AND OPTIMIZATION OF SOLAR POWER PLANTS

Designing and optimizing solar power plants is crucial for maximizing energy generation efficiency and sustainability. Recent studies have focused on several aspects of solar power plant design, optimization strategies, and challenges in the renewable energy sector. A study by the Electrical Engineering Department at Mehran University, and other collaborating institutions explored solar PV energy optimization approaches and the associated challenges. The research delved into strategies for optimizing solar energy systems, addressing obstacles, and enhancing system performance. The study emphasized the importance of optimization tactics in improving system reliability, efficiency, and reducing costs (Soomar et al., 2022).

Research conducted by National Renewable Energy Laboratory (NREL) in collaboration with the Colorado School of Mines focused on the optimized design of hybrid solar power plants with storage capabilities. The study highlighted the flexibility of dispatching renewable energy to the grid and the trade-offs involved in plant performance and optimal sizing. The research demonstrated the profitability of hybrid solar system designs under specific assumptions and the significant energy production potential of Concentrated Solar Power (CSP) systems. The study also discussed the direct relationship between CSP field

solar multiple and storage hours, emphasizing the impact of various inputs on plant performance and sizing decisions (Cox et al., 2023).

A study conducted in Iraq (Aziz et al., 2022), investigated the design and optimization of a grid-connected solar energy system. The research aimed to address the load requirements of a residential home using a hybrid solar energy system. The study focused on optimizing system parameters to enhance energy efficiency, reduce emissions, and improve system reliability. The research findings provided insights into the design and operation planning of solar energy systems, emphasizing the importance of efficient dispatch strategies for hybrid energy systems.

2.6 SIMULATED VERSUS MEASURED DATA ON SOLAR SYSTEMS

Table 2.5 provides an overview of the capabilities of each software tool, facilitating the selection of the most appropriate tool for specific PV system design requirements and performance assessments.

Table 2.5: Simulation software

Design software	Types of systems designed	Features	Reference
PVsyst	Grid-connected, Standalone, Hybrid, BIPV (Building Integrated PV)	Detailed system design, performance analysis, shading analysis, financial analysis.	(Mermoud & Wittmer, 2014)
Homer	Hybrid, Off-grid, Grid-connected	Optimization of microgrids, renewable integration, economic analysis, sensitivity analysis.	(Deshmukh & Deshmukh, 2008)
System Advisor Model (SAM)	Grid-connected, Standalone, Hybrid	Detailed performance modeling, financial analysis, incentives, and policy impact.	(Blair et al., 2014)
PV Sol	Grid-connected, Off-grid, Hybrid, BIPV	3D visualization, shading analysis, financial analysis, energy balance.	(Sharma & Gidwani, 2017)
Helioscope	Grid-connected, Commercial, Residential	Design and performance simulations, 3D modeling, shading analysis, bankability analysis.	(Guittet & Freeman, 2018)
SolarPro	Grid-connected, Off-grid, Hybrid	Detailed system design, energy yield calculation, financial analysis.	(Thula et al., 2017)
Polysun	Grid-connected, Off-grid, Hybrid, BIPV	Detailed simulations, economic analysis, thermal and electrical system design.	(Milosavljević et al., 2022)
Archelios Suite	Grid-connected, Commercial, Residential, BIPV	Complete PV project design, yield forecasts, financial analysis, shading analysis.	(Archelios Suite, 2024)
Retscreen	Grid-connected, Off-grid, Hybrid	Feasibility analysis, energy performance analysis, risk analysis, GHG emission reduction.	(Samu & Fahrioglu, 2017)
EnergyPlus	BIPV, Grid-connected	Energy modeling for buildings, integration of PV systems with building energy systems.	(Doe, 2013)
Blue Sol	Grid-connected PV systems	CAD-based design and simulation tool for PV systems	(Kut & Nowak, 2019)

Comparing the performance of solar photovoltaic (PV) systems based on simulated and measured data is essential for understanding the precision of predictive models and the real-world behavior of solar installations. Simulations are often used during the planning and design phases to estimate the projected energy output, efficiency, and financial returns of a

PV system. However, actual performance can vary due to several factors. A study by (Ngure et al., 2023) indicates that utilizing actual data offers accurate estimates and aids in creating dependable models for assessing the real-world performance, reliability, and economic advantages of the system within the specific climatic conditions of the region.

Table 2.6 presents the deviations observed in various simulation software. As reported by (Najibhamisu Umar et al., 2018), Helioscope exhibited the largest deviation at -15.77%, while Solarius had the smallest deviation at 0.8% when comparing the performance ratio to the actual performance ratio. A study by (Ezeanya et al., 2018) highlights the effectiveness of SAM software, which showed a deviation of 3% from actual results. Another study by (Omar et al., 2024) found that PVsyst had a performance ratio that was 13.4% higher than actual data, influenced by several parameters including the degree of dust and shading.

In conclusion, comparative studies of simulation software for solar PV systems reveal significant discrepancies between predicted and actual performance, largely due to how each tool models site-specific conditions such as dust accumulation, shading, and local climate variations. For example, while Helioscope and PVsyst have shown deviations as high as -15.77% and +13.4% respectively, SAM stands out with a deviation of only about 3%, making it the most reliable among those evaluated. These differences can be attributed to varying modeling approaches, calibration needs, and the degree to which long-term degradation and maintenance factors are incorporated. Ultimately, these gaps highlight the necessity for improved integration of local data and enhanced calibration methodologies in simulation software to ensure more accurate performance predictions for solar PV installations.

Table 2.6: Different Simulation software deviation from actual data

Simulation Software	Considered parameters	Deviation	Possible Explanation	Reference
SAM	Power output	SAM had a higher result by 3%	-	(Ezeanya et al., 2018)
PVsyst	Performance ratio	PVsyst was 13.4% higher than actual data	Several parameters including degree of dust and shading	(Omar et al., 2024)
PVGIS PVWatts PVSyst	Energy yield	PVGIS reported less energy by 5.33%, PVWatts by 12.33% and PVSyst by 30.64%	The study only considered India (tropical wet and dry areas)	(Thotakura et al., 2020)
PVSyst, Helioscope	Annual yield	PVSyst: +9.2% Helioscope: +14.75%	Data sources for the two software are different	(Goel & Sharma, 2021)
Homer Solarius PV SAM PV F-chart PVsol PVsyst Retscreen Solar Pro Helioscope	Performance ratio (PR)	The deviation from the actual PR is: 2.07%, 0.8%, -1.74%, -2.08%, 1.51%, 4.08%, 3.27%, 6.45%, -8.27% and -15.77% respectively.	-	(Najibhamisu Umar et al., 2018)

2.7 OPERATION AND MAINTENANCE OF SOLAR PV PLANTS

Operation and Maintenance (O&M) of solar PV plants involve a range of activities essential for ensuring optimal performance and longevity of the system. These include remote monitoring and performance analysis to detect inefficiencies, regular preventive maintenance such as inspections, cleaning, and vegetation management to prevent shading, and corrective maintenance to repair or replace faulty components. Predictive maintenance uses data to anticipate and address potential issues proactively. Effective O&M maximizes energy production, extends the plant's lifespan, reduces downtime, ensures safety, and maintains regulatory compliance, ultimately ensuring the profitability and efficiency of utility-scale solar PV installations (Haney, 2013).

Utility-scale solar PV plants are essential for achieving renewable energy targets. While investment costs for various PV configurations are well-documented, O&M costs for vegetation management at low-impact solar sites are less understood, specifically in comparison to conventional ground cover practices. A study by (Mccall et al., 2023) provides a comprehensive assessment of PV vegetation O&M costs. The research found that while the costs per acre and per kilowatt DC for specific activities like mowing, trimming, and applying herbicides to native or pollinator-friendly ground covers were lower than those for turfgrass sites, the overall vegetation O&M costs were slightly higher.

Proper O&M practices are crucial for maximizing energy production, extending equipment lifespan, maintaining safety, and optimizing financial performance. O&M costs vary based on factors like plant size, technology type, location, and provider. Industry benchmarks indicate that utility-scale solar O&M costs typically range from \$5/kWDC per year to

\$8/kWDC per year, with a general trend of decreasing costs due to improved technology and economies of scale (Ryan, 2020).

Figure 2.12 illustrates the components of O&M costs for a solar PV plant, divided into several categories. Fixed costs include expenses that remain constant regardless of the plant's output, such as administrative tasks, insurance, and monitoring systems. Fixed cost components cover the costs associated with these ongoing obligations. Large components refer to significant infrastructure parts like inverters and transformers, which incur substantial costs when maintained or replaced. Maintenance costs encompass regular activities required to keep the plant operating efficiently, such as cleaning, inspections, and minor repairs. Maintenance components detail the specific activities and materials involved in these routine tasks. Lastly, replacement costs account for the expenses associated with replacing worn-out or malfunctioning parts to restore the plant's functionality. Understanding these components helps in planning and budgeting for effective O&M practices, ensuring the efficient and profitable operation of the solar PV plant (Feldman et al., 2021).

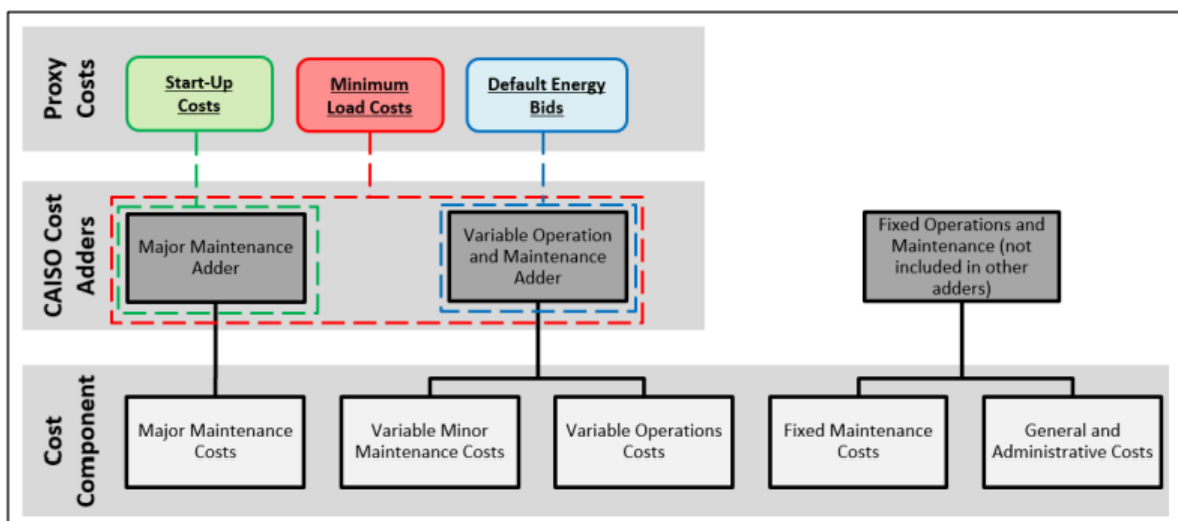


Figure 2.12: Components of O&M costs (California Independent System Operator, 2020)

2.8 CONCLUSION

A review of Kenya's energy mix revealed that despite the country having a solar energy potential of 15,000 MW, it lagged in its utilization, with solar contributing only 3.5% as of 2023. This highlighted the substantial untapped potential for solar energy deployment. The chapter explored the environmental effects on solar energy output and the significant influence of module tilt and orientation on energy generation efficiency, emphasizing the need for optimization to maximize energy yield from solar installations.

Various studies reviewed in this chapter established essential performance indicators for assessing solar power plant performance, including a performance ratio of 60% to 90%, a capacity factor of 10% to 30%, system efficiencies of 10% to 20%, and specific yields of 1000 to 2000 kWh/kWp. The chapter also underscored the importance of operation and maintenance (O&M) practices in optimizing solar PV performance. Additionally, it evaluated different solar simulation and design software, highlighting significant discrepancies between simulated outputs and actual performance. This research identified gaps in modeling site-specific variables and stressed the need for actual meteorological data to minimize deviations. Among the reviewed tools, SAM demonstrated the highest reliability, with minimal deviation from real-world performance, providing a robust framework for this study.

Despite the importance of performance assessment in ensuring the long-term efficiency of solar power plants, there was a notable lack of empirical technical performance data on the Garissa Solar Power Plant. Existing research primarily focused on its design, theoretical potential, and predictive modeling using machine learning. However, limited studies

examined its real-world performance since commissioning. Key parameters such as actual energy yield, degradation rates, seasonal performance variations, and system losses remained largely undocumented in publicly available literature. This gap in empirical data presented a challenge for optimizing plant efficiency and developing informed O&M strategies.

Addressing this data limitation was essential for improving solar power plant management, refining predictive models, and ensuring that large-scale solar projects achieved their intended performance. Future research should focus on systematic performance monitoring using real-time operational data and environmental impact assessments to enhance the reliability and sustainability of Kenya's solar energy infrastructure.

CHAPTER 3: METHODOLOGY

3.1 INTRODUCTION

This chapter highlights the approach employed in conducting the study. The data obtained was presented, analyzed and discussed in Chapter 4.

3.2 SUNS POSITION

The position of the sun can be explained using its azimuth and altitude angles, which directly influence the quantity of solar radiation received by PV modules. This, in turn, impacts the efficiency and energy output of the PV modules. Understanding and accurately modeling the position of the sun is fundamental to evaluating the technical performance of the solar power plant, as it allows for precise analysis of solar irradiance patterns and their effect on energy generation.

The sun's position differs all through the day and across different seasons due to the Earth's axial tilt and orbital mechanics. These variations affect the angle at which solar rays strike the PV panels, known as the angle of incidence, which in turn influences the amount of solar energy converted into electrical energy. This section provides insights on the position of the sun relative to solar modules in a solar installation, exploring different aspects including the azimuth angle of the sun, declination angle, and altitude angle. Figure 3.1 illustrates the azimuth and altitude angles of the position of the sun (Gjølstad Røhnebaek, 2017)(Awasthi et al., 2020).

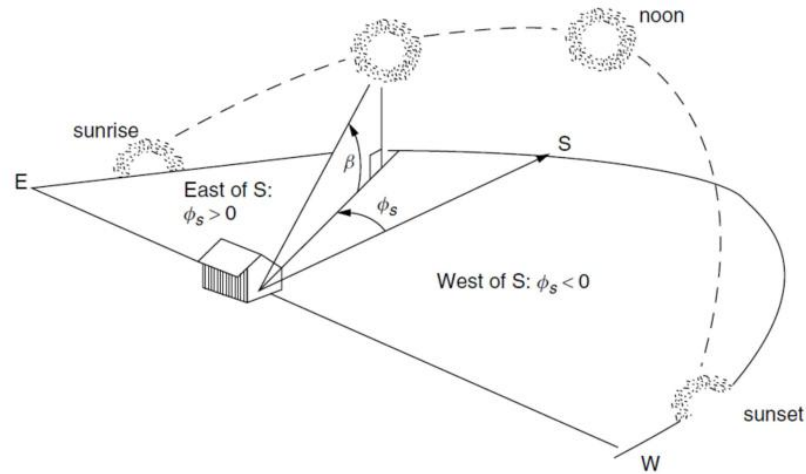


Figure 3.1: Illustration of the sun's azimuth angle and altitude angle (Gjølstad Røhnebaek, 2017)

3.2.1 Declination angle

The declination angle, denoted by δ , is a crucial parameter in solar energy systems as it represents the tilt of the Earth's axis relative to the plane of its orbit around the Sun. Figure 3.2 illustrates this parameter (Awasthi et al., 2020). This angle varies seasonally and plays a significant role in determining the position of the Sun in the sky, which in turn affects the performance of solar energy systems.

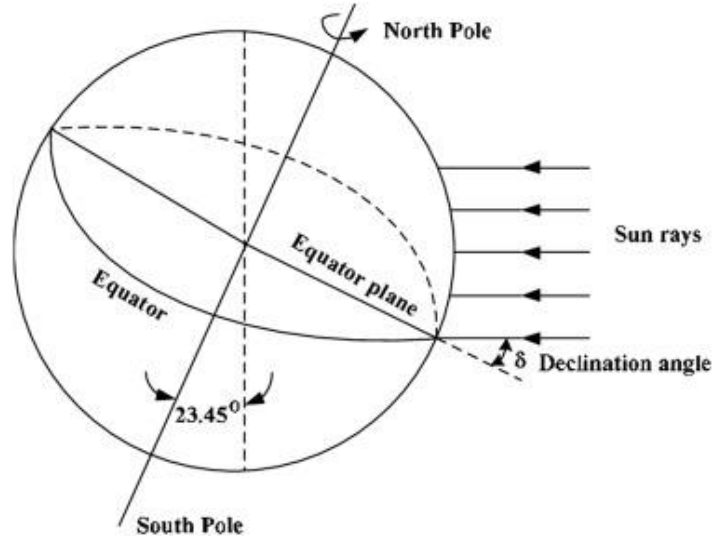


Figure 3.2: Illustration of declination angle (Awasthi et al., 2020)

The declination angle can be computed using equation (3.1) where N is the days number in the year (Yassir et al., 2019).

$$\delta = 23.45 \times \sin \frac{360}{365} (284 + N) \quad (3.1)$$

3.2.2 Azimuth angle

The azimuth angle in solar energy systems denotes the compass direction to which solar panels are aligned, measured in degrees clockwise from true north in the northern hemisphere and from true south in the southern hemisphere (Yunus Khan et al., 2020). It is denoted by Φ_s and is illustrated on Figure 3.1.

To maximize energy generation, solar panels are typically directed to the south in the northern hemisphere and to the north in the southern hemisphere. The ideal azimuth angle may vary based on factors like location, season, and specific energy needs. Site-specific elements such as nearby obstructions, roof orientation, and available installation space also impact the optimal azimuth angle (Nwankwo, 2021).

In fixed-tilt solar PV setups, the azimuth angle is predetermined during installation and remains constant throughout the year. Alternatively, systems may employ tracking mounts that enable panels to adjust their azimuth angle dynamically to track the sun's movement. This tracking feature optimizes energy output by ensuring panels are continuously positioned optimally relative to the position of the sun in the sky (Al Garni et al., 2019).

To compute the azimuth angle, equation (3.2) may be applied, where Φ_s is the azimuth angle, β is the altitude angle, δ is the angle of declination and H is the hour angle.

$$\sin \Phi_s = \frac{\cos \delta \sin H}{\cos \beta} \quad (3.2)$$

3.2.3 Altitude angle

The altitude angle, denoted by β , is the angle between the sun and the local horizon directly beneath it, as illustrated by Figure 3.1. This angle is key for solar energy systems as it directly affects the amount of solar radiation that PV modules receive. The altitude angle changes throughout the day and is influenced by the observer's latitude and the time of year. Equation (3.3) expresses the formula for calculating the altitude angle β , of the sun (Gjølstad Røhnebaek, 2017).

$$\sin \beta = \cos L \cos \delta \cos H + \sin L \sin \delta \quad (3.3)$$

Where L is the latitude angle.

3.2.4 Hour angle

The hour angle is a crucial concept in solar energy systems representing the angular distance of the sun from the local solar noon (Bhatia, 2014). Measured in degrees, it changes throughout the day as the sun traverses the sky. Solar noon refers to the point when the sun

reaches its peak position in the sky for a specific location, with the hour angle being zero at the moment. Before solar noon, the hour angle is negative, indicating the number of degrees the sun is behind the local solar noon. After solar noon, the hour angle becomes positive, indicating the number of degrees the sun is ahead of the local solar noon. Equation (3.4) provides the formula for calculating the hour angle.

$$H = 15^{\circ} \times (12 - ST) \quad (3.4)$$

3.3 PV MODULE POSITION

The positioning of PV modules is a critical factor in maximizing the efficiency and energy output of solar energy systems. Optimal placement involves careful consideration of several elements, including orientation, tilt angle and shading. By aligning PV modules correctly relative to the sun's path and adjusting their tilt to match the latitude and seasonal variations, significant gains in energy capture can be achieved. Moreover, minimizing shading from nearby obstructions and ensuring structural suitability are essential for maintaining consistent performance (Gjølstad Røhnebaek, 2017).

3.3.1 Panel Tilt Angle

The panel tilt angle (θ), also known as the inclination angle, is the angle at which solar panels are mounted in relation to the horizontal plane. The inclination angle is important when determining the efficiency and performance of a solar PV system by influencing the amount of sunlight captured and the energy output generated (Bhatia, 2014).

To get the ideal inclination angle of a solar module, the altitude angle of the sun at noon must be calculated using equation (3.5), where L is the latitude angle and δ is the declination angle.

$$\beta_N = 90 - L + \delta \quad (3.5)$$

Using the altitude angle of the sun at noon, β_N is utilized to calculate the optimum tilt angle of the module that will have the sun's rays vertical to the module at noon. The formula is expressed by equation (3.6).

$$\theta = 90 - \beta_N \rightarrow L - \delta \quad (3.6)$$

3.3.2 Panel Orientation

Panel orientation is the direction the solar modules are installed to receive maximum sunlight and optimize energy production. The ideal orientation depends on the geographic site of the solar PV system and the path of the sun throughout the day.

Around the equator, the optimal orientation for solar panels is typically between 90° and 270° azimuths, as the sun passes from east to west during the day. However, this can vary depending on the time of year and the location's latitude (Ekoe A Akata et al., 2022).

3.3.3 Shading Analysis

Proper shadow analysis is essential for optimizing solar panel performance. By calculating shadow lengths and understanding how objects cast shadows on solar arrays, designers can minimize shading and maximize energy production. Trigonometric formulas help determine the optimal inter-row spacing, considering factors like panel tilt angle, width, and solar position. Figure 3.3 illustrates the key elements for computing the row spacing including the height difference between modules, solar elevation angle, and azimuth correction angle (Gjølstad Røhnebaek, 2017).

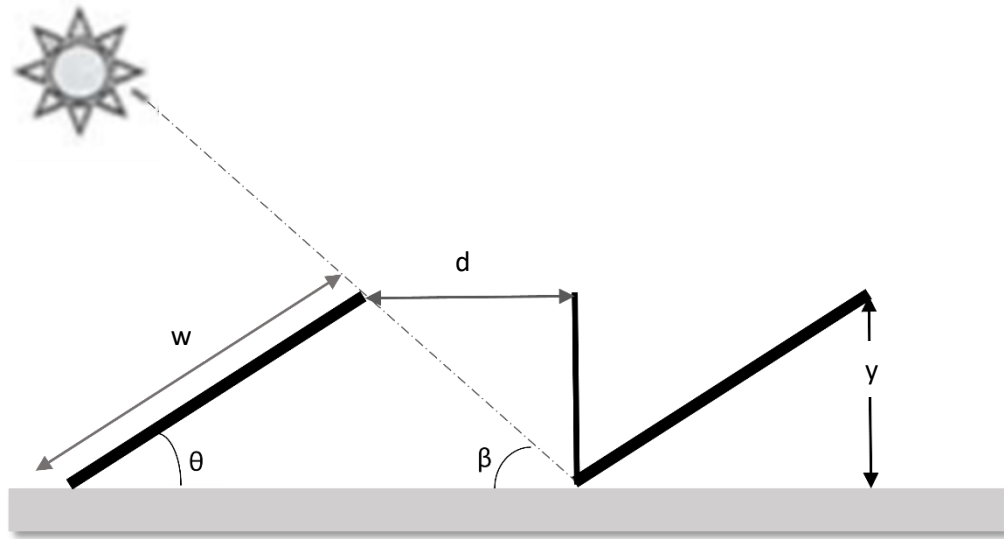


Figure 3.3: Module row spacing (Gjølstad Røhnebaek, 2017)

To determine the optimal inter-row spacing of solar panels, start by calculating the height difference (Y) based on the tilt angle (θ) of the installation and the width of the panel (w). This height difference can be found using the formula represented by equation (3.7).

$$Y = w \times \sin \theta \quad (3.7)$$

Using the height difference and the solar elevation angle (β), the length of the shadow, L_s can further be calculated using equation (3.8).

$$L_s = \frac{Y}{\tan \beta} \quad (3.8)$$

Finally, the module row spacing was adjusted by considering the azimuth correction angle (φ), which accounts for the orientation of the panels relative to true south or north. This adjustment ensured that the spacing was optimized for the actual sun path across the sky. The adjusted row spacing, d was calculated using equation (3.9).

$$d = L_s \times \cos \varphi \quad (3.9)$$

3.3.4 Ground Coverage Ratio (GCR)

GCR is the ratio of the panel width to the inter row spacing (Dupraz, 2023). The formula for computing the GCR is expressed by Equation (3.10), where x is the total row spacing.

$$\text{GCR} = \frac{w}{x} \quad (3.10)$$

3.3.5 Solar radiation on an inclined surface

Solar radiation is the energy produced by the sun, which hits the Earth in the form of electromagnetic waves. Inclined surfaces, such as tilted solar panels, receive solar radiation differently than horizontal surfaces. The angle of inclination and orientation of these surfaces can significantly affect the amount of solar energy they capture (Gjølstad Røhnebaek, 2017).

Figure 3.4 illustrates the different components of solar radiation, direct, diffuse, and reflected which affect how much energy a tilted solar panel can capture (Gualla, 2015). Direct radiation comes straight from the sun and is maximized when hitting the surface perpendicularly. Diffuse radiation, scattered by the atmosphere, reaches the panel from all directions and is significant on cloudy days. Reflected radiation bounces off surrounding surfaces and reaches the panel, influenced by the reflectivity of those surfaces. Optimizing solar radiation capture involves adjusting the tilt angle and orientation of the panels, minimizing shading, and considering the effects of reflective surroundings to enhance energy production and system performance.

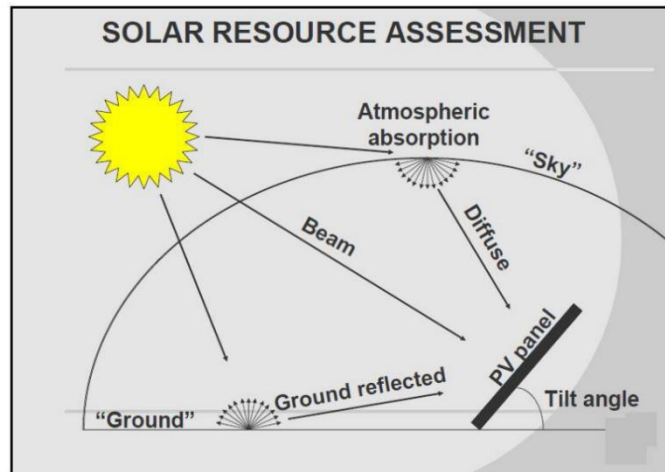


Figure 3.4: Solar radiation components (Ansori et al., 2022)

3.3.6 Sun Peak Hours

Sun peak hours, also known as solar peak hours or solar insolation hours, refer to the times of day when a location receives the most intense sunlight, similar to when the sun is shining at its brightest. These hours are crucial for solar panels because they represent the period when panels can generate the maximum amount of electricity. Factors like where you are on the globe, the time of year, weather, and how clear the atmosphere is all affect how long these peak hours last and how strong they are.

Around the equator, where the sun shines directly throughout the year, sun peak hours tend to be longer and more consistent. In contrast, areas farther from the equator may have shorter peak hours, especially during winter when the sun's angle is lower in the sky. To make the most of these peak hours, solar energy systems are designed to position solar panels to capture as much sunlight as possible. This optimization helps maximize energy production and efficiency. Equation (3.11) expresses the formula for calculating the sun hours of a region

where H_c is the total in-plane radiation ($\text{kWh/m}^2/\text{day}$) and 1 is the reference irradiance of 1 kW/m^2 . (Ramanan et al., 2019).

$$S_h = \frac{H_c}{1} \quad (3.11)$$

3.4 THE GARISSA SOLAR POWER PLANT

The Garissa Solar PV Plant has an installed capacity of 54.65 MWp, the maximum power output that the plant can generate under ideal conditions (Jan March Newsletter Quater 3, 2021). With a latitude 0.34°S and longitude 39.60°E , the solar power plant is located in Mbalambala Constituency, Garissa County, about 20 kilometers from Garissa town in Kenya.

Figure 3.5 illustrates the aerial view of the Garissa solar power plant.



Figure 3.5: Garissa solar power plant (Jan March Newsletter Quater 3, 2021)

3.4.1 Technical Data of the System

This solar facility is under the ownership and operation of REREC and Kenya Electricity Generating Company (KenGen). Data was collected from REREC and KenGen using a

checklist to attain general information on the power plant (APPENDIX I). The technical specifications of the solar farm are as presented by

Table 3.1.

Table 3.1: Technical specification of the Garissa solar power plant

Parameter	Description
System capacity	54.65 MW
Number of panels	206, 272
Number of inverters	1172
Year of commissioning	November 2018
Model type	Jinko 265W polycrystalline
Inverter type and model	Huawei SUN2000-42KTL
Module spacing	2 meters
System tilt	4 ⁰
Orientation	140 ⁰ SE
Cost of installation	Ksh. 13.7 billion

Table 3.2 outlines the technical specifications of the Jinko 265 polycrystalline solar module used in the solar farm. The system is panel layout is configured such that 22 panels are connected in series to form in string which goes into the inverter (APPENDIX II). The panel has a power rating of 265W under Standard Test Conditions (STC) and 198W under Normal Operating Cell Temperature (NOCT). The table details various performance parameters under both STC and NOCT, including maximum and rated current, as well as maximum and open circuit voltage.

Table 3.2: PV module technical specification

Jinko - JKM265PP	STC	NOCT
Power (W)	265	198
Current Imp (A)	8.44	6.91
Current Isc (A)	9.03	7.31
Voltage Vmp (V)	31.4	28.7
Voltage Voc (V)	38.6	35.3
Voltage coefficient	-0.30%	
Power coefficient	-0.40%	
Current Coefficient	0.06%	
Efficiency	16.19%	
Temp (°C)	25	45+/-2

The power plant utilizes the Huawei SUN2000-42KTL smart string inverter with the technical specification outline in Table 3.3. The maximum input voltage of the inverter is 1100V and the maximum input current per Maximum Power Point Tracker (MPPT) is 22A with a short circuit current of 30A. One string inverter can handle 8 inputs with a rated voltage of 720V and a maximum active power input of 42000W.

Table 3.3: Inverter specification

Technical Specification	SUN2000-42KTL
	<i>Efficiency</i>
Max. Efficiency	98.8%
European Efficiency	98.6%
	<i>Input</i>
Max. Input Voltage	1100 V
Max Current per MPPT	22 A
Max Short Circuit Current per MPPT	30 A
Start Voltage	250 V
MPPT Operating Voltage Range	200 V ~ 1000 V
Rated Input Voltage	720 V
Number of Inputs	8
Number of MPP Trackers	4
	<i>Output</i>
Rated AC Active Power	42,000 W
Max AC Apparent Power	47,000 VA
Max AC Active Power ($\cos\Phi=1$)	Default 47,000W; 42,000W optional in settings
Rated Output Voltage	480 V, 3W + PE
Rated AC Grid Frequency	50 Hz/60 Hz
Rated Output Current	50.6 A
Max. Output Current	56.6 A
Adjustable Power Factor Range	0.8 LG ... 0.8 LD
Max. Total Harmonic Distortion	< 3%

3.4.2 Framework of Performance Assessment of the Solar Power Plant

Figure 3.6 provides a detailed illustration of the methodological framework employed for this research. The stages include data collection, data preparation, data analysis, simulation, and finally, results interpretation and discussion.

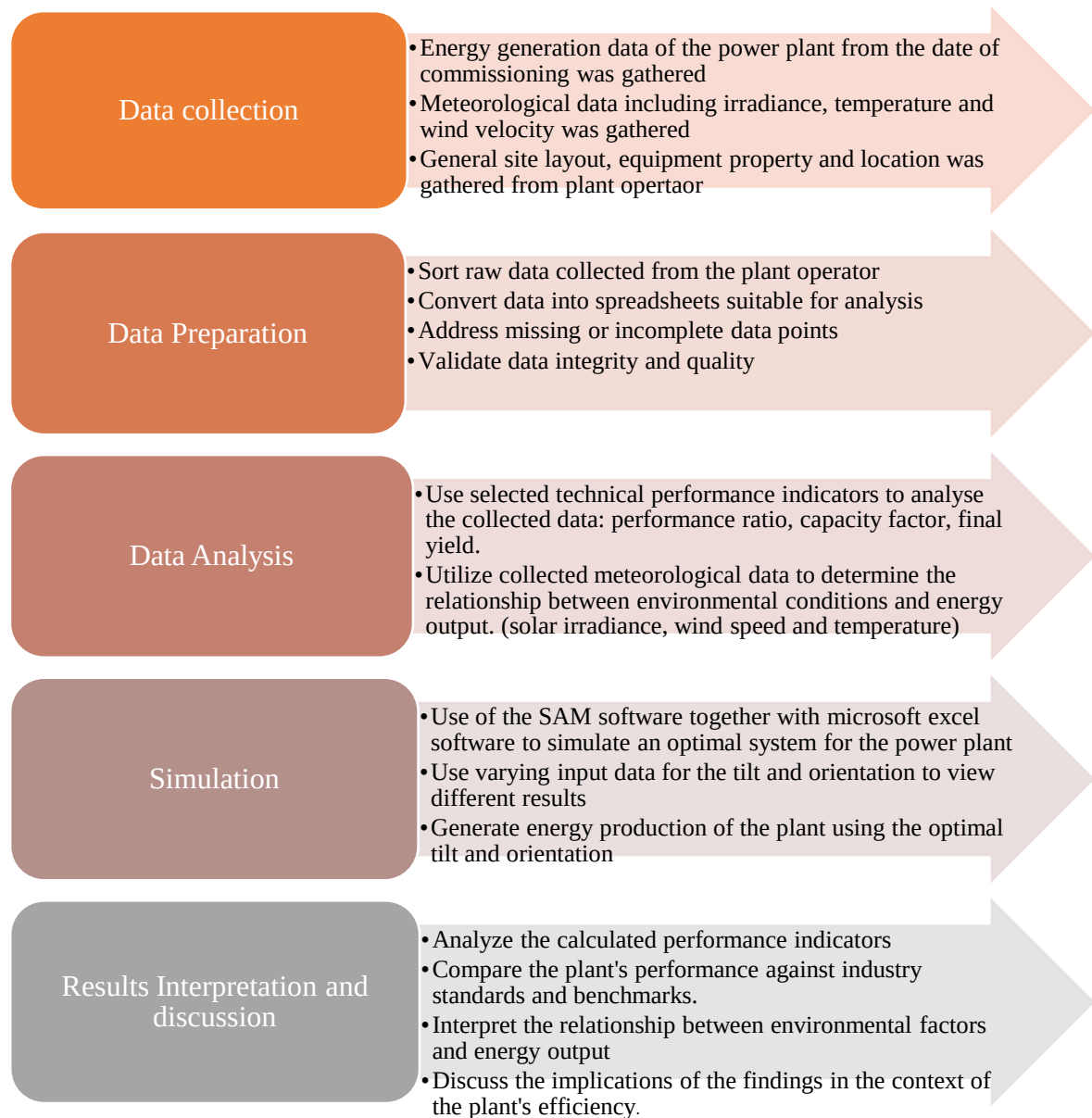


Figure 3.6: Methodology framework

3.5 EXAMINATION OF PLANT PERFORMANCE

3.5.1 Performance Ratio

The Performance Ratio (PR) indicates the difference between the ideal and the real performance of a solar PV system. It reflects the losses resulting from the environmental conditions, the installation components, and the installation angles of the system (Oloya et al., 2021). Equation (3.12) expresses the formula for computing the PR of a solar PV system (Ramanan et al., 2019).

$$PR = \frac{100 \times Y_F}{Y_R} (\%) \quad (3.12)$$

3.5.2 Capacity Utilization Factor

The Capacity Utilization Factor (CUF) is the ratio of the actual AC energy produced by the system during a specified period (monthly or annually) to the potential energy output (kWh) if the system were operating at full capacity throughout that period, and is expressed by equation (3.13) (Ramanan et al., 2019). This metric reveals the proportion of time the system operates at its maximum rated capacity each day. CUF serves as a tool for estimating the expected power output in specific climatic conditions and can also be utilized to assess the economic feasibility of a solar PV power plant project (Ngure et al., 2023). The CUF can range from 10% to 25%, contingent on factors such as geographical location, season, weather conditions, and system operation.

$$CUF = \frac{100 \times E_a}{P_c \times 8760} (\%) \quad (3.13)$$

3.5.3 Array Yield

The array yield is to the efficiency or productivity of the solar array. It is computed by taking the ratio of the generated DC energy to the rated capacity of the PV power plant system. This

measure provides insights into how effectively the solar array is converting sunlight into usable electrical energy (Singh et al., 2022). The mathematical expression for this is demonstrated by equation (3.14) (Ramanan et al., 2019).

$$Y_A = \frac{E_{DC}}{P_c} \quad (3.14)$$

3.5.4 Reference Yield

Reference yield refers to the expected or calculated amount of energy that a solar PV system is anticipated to generate under specific conditions. It serves as a benchmark or reference point for estimating the potential energy output of a solar installation (Ngure et al., 2023). It takes into account factors such as solar irradiance, climate conditions, tilt and orientation of solar panels, shading, and other environmental variables. It provides a baseline for comparing the actual performance of a solar PV system to its expected output under optimal conditions. Reference yield can be computed using equation (3.15) (Ramanan et al., 2019).

$$Y_R = \frac{I_T}{I_R} \quad (3.15)$$

3.5.5 Final Yield

This is the overall energy output or efficiency of the plant over a specified period. It represents the total amount of electricity generated by the solar PV system during its operational lifetime. The final yield is influenced by factors such as the quality of the solar panels, the efficiency of the inverter, the solar irradiance at the location, system design, maintenance practices, and any potential losses due to shading or other environmental factors (Singh et al., 2022). It is represented by equation (3.16).

$$Y_F = \frac{E_{AC}}{P_c} \quad (3.16)$$

3.5.6 System Efficiency

The system efficiency denoted by η , is the percentage of incident solar energy that is converted into usable electrical energy. It takes into account factors such as the efficiency of the solar panels, inverters, and other components of the system (Ngure et al., 2022). This is expressed by equation (3.17). Where E_{AC} is the AC energy generated, H_C is the total in plane irradiance and A_M is the area of the module.

$$\eta = \frac{100 \times E_{AC}}{A_M \times H_C} (\%) \quad (3.17)$$

3.5.7 Economic Analysis of the power plant

Using an Excel sheet, the annual average data of the power plant over a period of 5 years was analyzed to compute the average revenue generated by the plant. This calculation was based on the Power Purchase Agreement (PPA) rate of Ksh. 5.49 per unit, as per the agreement with KPLC, and a proposed new rate of Ksh. 12 per unit for electricity sales. The initial investment cost of Ksh. 13.7 billion (135.7 million) was also considered in this analysis.

Equation (3.18) shows the expression used to compute the Annual Revenue Generated (AR_t).

$$AR_t = E_{a,t} \times P_t \quad (3.18)$$

Where, $E_{a,t}$ is the annual energy generated (kWh) and P_t is the PPA price (Ksh/kWh)

The annual net cash flow (CF_a) is determined by deducting the plant's operational costs (O&M) from the total annual revenue generated, which is expressed by equation (3.19).

$$CF_a = AR_t - O\&M \quad (3.19)$$

Leveled Cost of Electricity (LCOE) is a metric used to compare the cost-effectiveness of different energy generation methods. It represents the average cost of generating one unit of electricity (usually a megawatt-hour or kilowatt-hour) over the lifetime of a power plant,

accounting for all costs incurred, including initial investment, operation, maintenance, fuel, and financing (Mensah et al., 2019). The expression for calculating LCOE is expressed by equation (3.20).

$$LCOE = \frac{Cost_{lifetime}}{E_{lifetime}} \quad (3.20)$$

The net present value is a measure used to determine the value of an investment by calculating the difference between the present value of its expected cash inflows and outflows which is represented by equation (3.21). Where C_o is the initial cost of investment.

$$NPV = -C_o + \sum_{t=1}^n \frac{NCF_t}{(1+i)^t} \quad (3.21)$$

3.6 STANDARD TEST OPERATING CONDITIONS

Standard Testing Conditions (STC) refer to the set of standardized parameters under which the performance of solar PV modules is measured. The STC of solar power plants, as defined by manufacturers, typically include irradiance set at 1000 W/m², temperature maintained at 25°C, and air mass assumed to be 1.5. The temperature data for Mbalambala, Garissa was gathered from the PVGIS database and subsequently organized using Microsoft Excel to ensure its appropriateness for analysis.

3.6.1 Effect of ambient temperature on the module cell temperature

Ambient temperature data from PVGIS, System Advisor Model, NSRDB database for Mbalambala, Garissa was downloaded. The cell temperature was computed using equation (3.22) assuming a wind speed of 1m/s. Where T_a is ambient temperature and G_c is the reference irradiance.

$$T_{cell} = T_a + \left(\frac{(NOCT - 20^{\circ}C)}{800} \right) \times G_c \quad (3.22)$$

3.6.2 Effect of temperature and wind speed on power output

Wind speed data was collected from SAM database, NSRDB and organized using Microsoft excel tool. The data was presented as average, minimum and maximum values.

The collected wind speed data from the PVGIS data was employed to the cell temperature equation (3.23) and the new cell temperature values were computed (Al-bashir et al., 2020).

$$T_{cell} = T_a + \left(\frac{9.5}{5.7 + 3.8 + V_f} \right) \times \left(\frac{NOCT - 20^{\circ}C}{800} \right) \times G_c \quad (3.23)$$

Where V_f is the wind speed, T_a is ambient temperature and G_c is the reference irradiance.

The computed cell temperature was used to compute the effect of both the wind speed and ambient temperature on the power output of the modules employing equation (3.24) where the ϵ is the temperature coefficient as defined by the manufacturer on the module datasheet (Das, 2019).

$$P_C = P_{STC} \times \left(1 + \frac{\epsilon}{100} \right) \times (T_{CELL} - T_{STC}) \quad (3.24)$$

3.7 SYSTEM ADVISOR MODEL

The SAM software is a performance and economic model devised to assess the cost of energy for grid-connected power projects based on various renewable energy technologies. SAM is a comprehensive tool that provides a consistent framework for studying and contrasting power system costs and performance across the range of solar technologies and markets (Blair et al., 2014). SAM is a free desktop application developed by NREL for techno-economic evaluation of energy technologies.

To model the ideal energy production and efficiency of the Garissa power plant using SAM software, a structured approach was followed. On launching the SAM software, users engage with the interface shown in Figure 3.7 . Here, they choose a performance model that aligns best with their system, along with selecting a financial model if desired. In this study, the photovoltaic performance model, incorporating a detailed PV model and a Power Purchase Agreement (PPA) for a single owner, was employed, as illustrated in Figure 3.7. This model was chosen for the study because the economic information available for the power plant was insufficient but adequate for this particular model type.

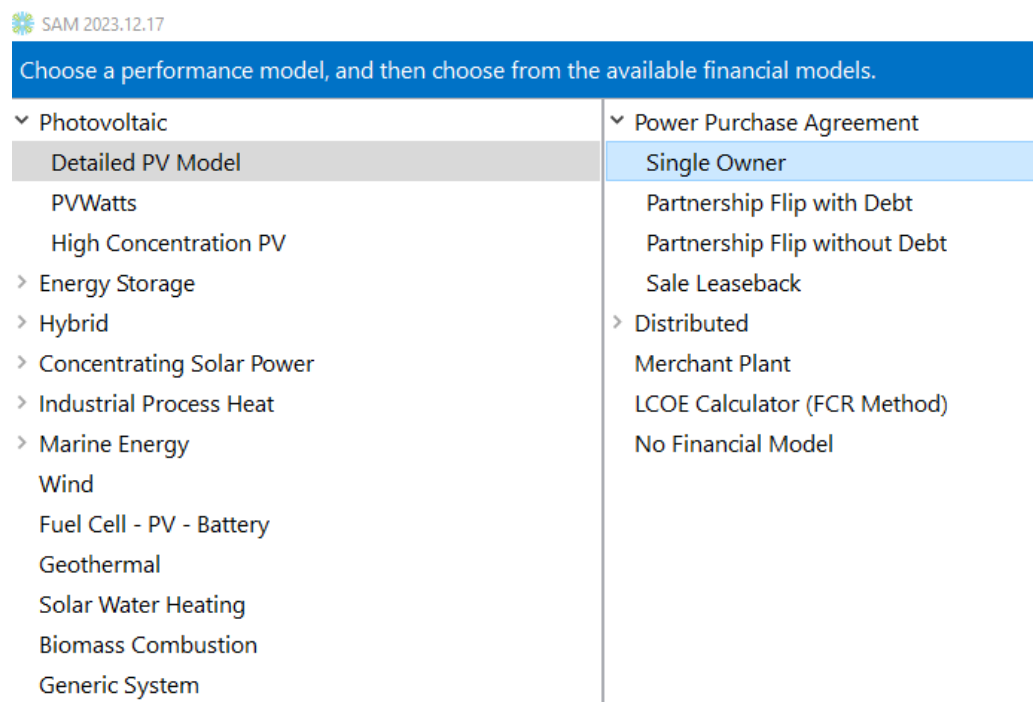


Figure 3.7: SAM software interface

SAM software utilizes various metrological data sources that have been compared to achieve the most accurate estimates possible. The data primarily relies on satellite data and nearby weather stations including Meteocontrol, PVGIS, and NASA SSE among other sources (Blair et al., 2014). To allow SAM to accurately model the solar resource and sun path

diagram for the site, the meteorological data for Mbalabala Garissa was obtained under the location and resource as displayed by Figure 3.8.

Download Weather Files

The NSRDB is a database of thousands of weather files that you can download and add to your solar resource library. Download a default typical-year (TMY) file for most long-term cash flow analyses, or choose files to download for single-year or uncertainty (P50/P90) analyses. See Help for details.

☒ One location ☐ Multiple locations ☐ Advanced download

Type a location name, street address, or lat,lon in decimal degrees

[For locations not covered by the NSRDB, visit the SAM website Weather Page for links to other data sources.](#)

Weather Data Information

The following information describes the data in the highlighted weather file from the Solar Resource library above. This is the file SAM will use when you click Simulate.

Weather file:

-Header Data from Weather File

Latitude	-0.35 degrees	Location	2115890
Longitude	39.62 degrees	Data Source	NSRDB
Time zone	GMT 3	For NSRDB data, the latitude and longitude shown here from the weather file header are the coordinates of the NSRDB grid cell and may be different from the values in the file name, which are the coordinates of the requested location.	
Elevation	152 m		
Time step	60 minutes		

-Annual Averages Calculated from Weather File Data

Global horizontal	6.19 kWh/m ² /day	-Optional Data
Direct normal (beam)	5.70 kWh/m ² /day	Maximum snow depth NaN cm
Diffuse horizontal	2.10 kWh/m ² /day	Annual albedo 0.239
Average temperature	28.6 °C	
Average wind speed	4.2 m/s	

*NaN indicates missing data.

Figure 3.8: Location and resource selection

The software enables the user to select the system components including solar modules and inverters from a diverse range of products. The specifications of the system components collected for the Garissa solar power plant were input into SAM. While the module Jinko 265 polycrystalline was available on the software, the Huawei inverters available in the software did not match the specifications of the inverter used in the Garissa power plant. The software allows the user to input inverter specification on the inverter datasheet option which was utilized on this research. The Huawei 42KTL inverter specifications were accurately input as illustrated on Figure 3.9.

Inverter Datasheet ▼

Power Ratings

Maximum AC output power

42000

Wac

☐ Weighted efficiency
☒ Manufacturer efficiency

98.8

%

98.6

%

Maximum DC input power

42596.349

Wdc

You can specify either a weighted or nominal efficiency. The weighted efficiency can be either CEC or European. The manufacturer efficiency can be either peak or nominal. See Help for details.

Operating Ranges

Nominal AC voltage

480

Vac

Maximum DC voltage

1100

Vdc

Maximum DC current

22

Adc

Minimum MPPT DC voltage

200

Vdc

Nominal DC voltage

720

Vdc

Maximum MPPT DC voltage

1000

Vdc

Number of MPPT inputs

1

Losses

Power consumption during operation

0

Wdc

Power consumption at night

1

Wac

Suggested value

336.000

10.500

If the datasheet does not specify loss values, you can use the suggested values to approximate the losses. See Help for details.

If you are modeling a system with microinverters or DC power optimizers, see the Losses page to adjust the system losses accordingly.

Copy Inverter Specifications from Current Library Selection

Click Copy Specifications to copy inverter data from the inverter currently selected for the Inverter CEC Database option.

Copy specifications

Figure 3.9: Inverter datasheet

Figure 3.10 depicts the system sizing process for configuring the desired capacity of the solar energy system, specified in kilowatts (kW) or megawatts (MW). At this stage, the type of installation, azimuth angle, and tilt angle are also input. For the Garissa solar power plant, a tilt angle of 4° and an azimuth of 140° SE were applied, matching the installation's actual orientation.

AC Sizing

Number of inverters

DC to AC ratio

Size the system using modules per string and strings in parallel inputs below.

☐ Estimate Subarray 1 configuration

Sizing Summary

Nameplate DC capacity	54,665.380 kWdc	Number of modules	206,272
Total AC capacity	49,224.000 kWac	Number of strings	9,376
Total inverter DC capacity	49,922.921 kWdc	Total module area	337,667.264 m ²

System and subarray capacity and voltage ratings are at module reference conditions shown on the Module page.

DC Sizing and Configuration

To model a system with one array, specify properties for Subarray 1 and disable Subarrays 2, 3, and 4. To model a system with up to four subarrays connected in parallel to a single bank of inverters, for each subarray, check Enable and specify a number of strings and other properties.

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
-Electrical Configuration-				
	(always enabled)	☒ Enable	☒ Enable	☒ Enable
Modules per string in subarray	22	22	22	22
Strings in parallel in subarray	2,344	2,344	2,344	2,344
Number of modules in subarray	51,568	51,568	51,568	51,568
String Voc at reference conditions (V)	849.2	849.2	849.2	849.2
String Vmp at reference conditions (V)	690.8	690.8	690.8	690.8
-Multiple MPPT Inputs-				
Set MPPT inputs	1	1	1	1
Set MPPT inputs when Number of MPPT Inputs on the Inverter page is greater than 1.				
-Tracking & Orientation-				
	☒ Fixed ☐ 1 Axis ☐ 2 Axis ☐ Azimuth Axis ☐ Seasonal Tilt	☒ Fixed ☐ 1 Axis ☐ 2 Axis ☐ Azimuth Axis ☐ Seasonal Tilt	☒ Fixed ☐ 1 Axis ☐ 2 Axis ☐ Azimuth Axis ☐ Seasonal Tilt	☒ Fixed ☐ 1 Axis ☐ 2 Axis ☐ Azimuth Axis ☐ Seasonal Tilt
	☐ Tilt=latitude	☐ Tilt=latitude	☐ Tilt=latitude	☐ Tilt=latitude

Figure 3.10: System sizing

SAM software utilizes all the inputs and runs a simulation for the estimated energy generation for the specified system offering comprehensive results. Utilizing its models and algorithms, SAM computes the optimal energy output and efficiency of the plant. Detailed outputs and visualizations are generated, showcasing metrics like annual energy production and capacity factor. These results include an annual energy generation graph, illustrating expected output month by month, and a loss diagram outlining environmental and component-related losses. Multiple simulations were executed for the Garissa solar power plant using different azimuth and tilt angles including the calculated optimal tilt and azimuth to optimize system performance.

3.8 CONCLUSION

This chapter presents a thorough overview of the methodologies applied to attain the objectives of this study, focusing on assessing the performance of solar PV plants, particularly at the Garissa solar power plant. The chapter begins with a detailed examination of essential frameworks for evaluating solar PV plant performance, emphasizing factors such as the sun's position relative to Earth and the optimal positioning of solar modules to maximize energy output. Methodologies for calculating the sun's position and determining the optimal orientation of solar modules are thoroughly explored. Technical specifications of the Garissa solar power plant and its components are also presented and analyzed within the chapter. Methodologies utilized to assess plant performance, including key performance indicators such as performance ratio, capacity factor, system efficiency, and specific yield, are thoroughly detailed. These assessments were conducted using Microsoft Excel tools, ensuring precision and reliability in data analysis. The chapter introduces SAM, a powerful software tool employed for simulation and performance prediction of solar energy systems. The methodology for utilizing SAM in this study is comprehensively described, focusing specifically on its application to optimize the operational efficiency of the Garissa solar power plant. The subsequent chapter will present the findings derived from these methodologies, offering an in-depth analysis and interpretation of their implications for enhancing the operational efficiency of the Garissa solar power plant and informing future research endeavors in the field of renewable energy.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 CHAPTER OVERVIEW

This chapter presents the study's results using methodologies outlined in previous chapters. SAM software and Microsoft Excel were used to collect and analyze data, focusing on the performance assessment of the Garissa Solar Power Plant.

The analysis covered key performance indicators, including performance ratio, capacity factor, array yield, and final yield from 2019 to 2023. The yearly data presented was the monthly average. Trends and variations in these metrics were examined, with visual representations such as graphs and tables. The impact of environmental factors, including wind speed and temperature, on plant performance was also analyzed to identify site-specific challenges and optimization opportunities.

Additionally, simulation results from SAM software were compared with actual performance data to assess accuracy and identify discrepancies. The economic feasibility of the plant was evaluated based on financial metrics from the simulations. The findings provided insights into solar energy development, informing future investments and best practices. The chapter concluded with a summary of key outcomes and their implications for improving the efficiency and sustainability of solar power projects.

4.2 TECHNICAL PERFORMANCE OF THE PLANT

4.2.1 Meteorological data and Energy generation data

Historical data on energy production and meteorological conditions from the Garissa solar PV plant was obtained directly from the plant operator. The irradiance data was collected from PVGIS database for Mbalambala, Garissa and for the inclined tilt of 4° (APPENDIX III). The data presented by Figure 4.1 illustrated the relationship of the monthly average, minimum and maximum values of the collected data. GHI is the irradiation on horizontal surface ($\text{kWh/m}^2/\text{month}$), I at 4° is the irradiation on a surface at the angle ($\text{kWh/m}^2/\text{month}$) and DNI is the direct beam irradiation on a surface normal to sun rays per month ($\text{kWh/m}^2/\text{month}$).

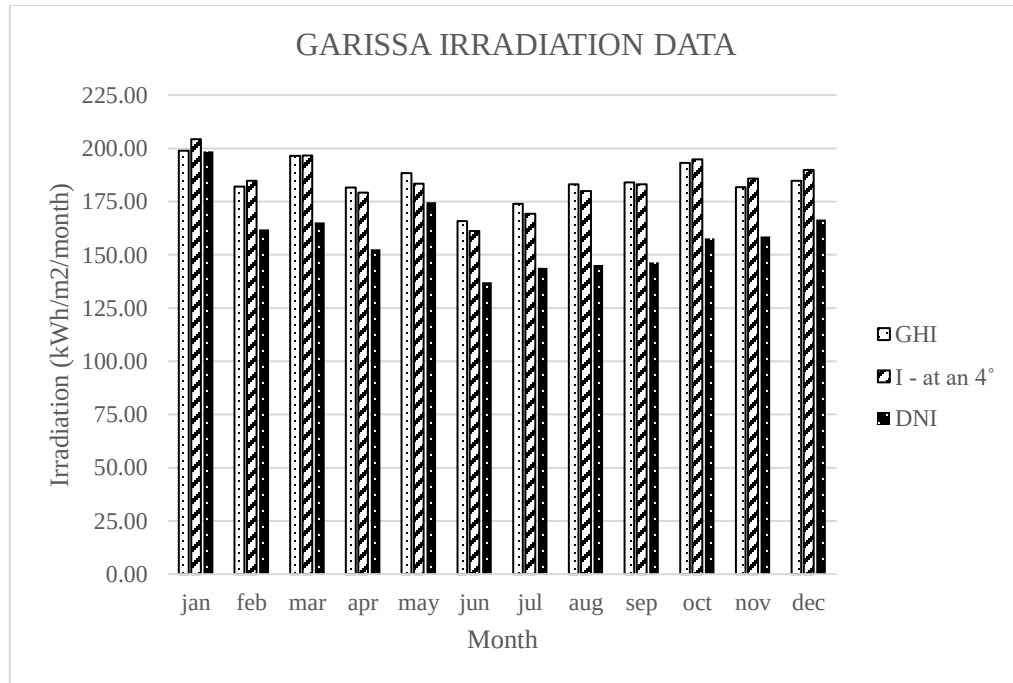


Figure 4.1: Garissa irradiation data

4.2.2 Annual PR and CUF

Figure 4.2, a graph showing the yearly average PR and CUF of the solar power plant for the years 2019, 2020, 2021, 2022 and 2023. The values were computed using equation (3.13)

and (3.12) and the results were 76.22%, 72.8%, 68.43%, 69.07% and 72.48% for the PR and 19.22%, 18.36%, 17.29%, 17.45% and 18.24% for the CUF for the respective years. From the data, there was a general decline in the PR from 2019 to 2021, with the lowest value recorded in 2021 at 68.43%. However, an upward trend was noticed in 2022 and 2023, with the PR increasing to 69.07% and 72.48%, respectively. Similarly, the CUF showed a decreasing trend from 2019 to 2021, dropping from 19.22% to 17.29%. In 2022 and 2023, there was a slight increase, with the CUF rising to 17.45% and 18.24%. This trend was attributed to the COVID-19 pandemic in 2020 and 2021, during which strict measures were implemented to enforce social distancing and limit the spread of the virus. The PF and CUF increased in 2022 and 2023 following the easing of restrictions and the post-pandemic recovery.

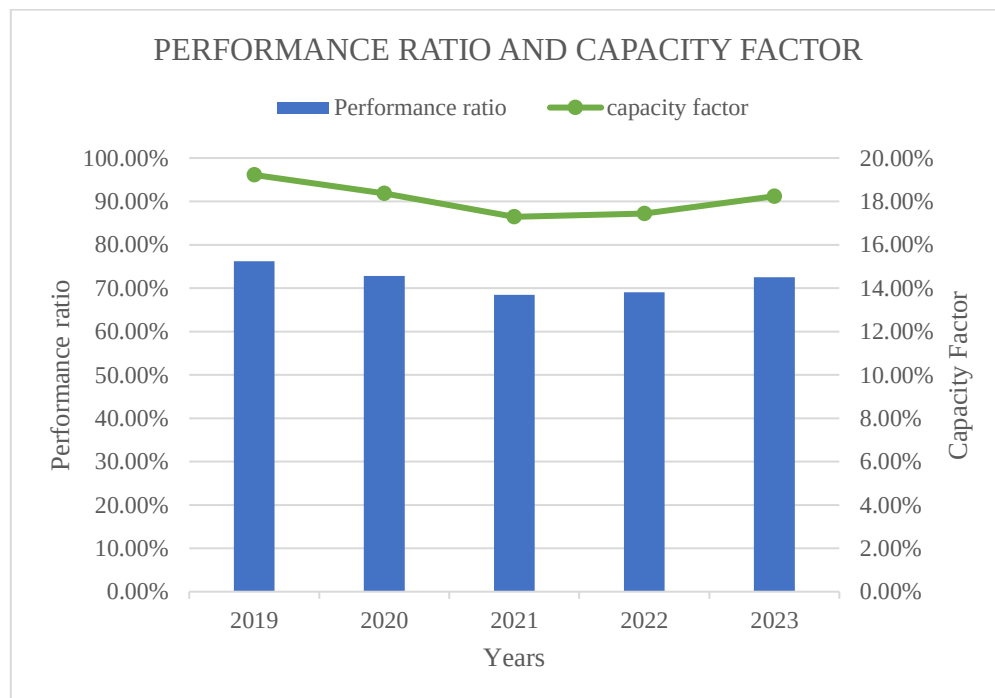


Figure 4.2: Performance Ratio & Capacity Factor

4.2.3 Average annual performance of the power plant

Table 4.1 showed the computed annual average performance ratio, capacity factor, reference yield and specific yield of the power plant over the five years. The results were 71.8%, 18.09%, 6.06 h/day and 1586 kWh/kWp for each performance indicator respectively.

The monthly average energy output of the power plant was 7213.47 MWh. As of December 2023, the power plant produced a total of 447001.1 MWh of energy.

Table 4.1: Average annual performance

Parameter	Output
Performance Ratio	71.80%
Capacity factor	18.11%
Reference yield (h/day)	6.06
Specific Yield/Final Yield (kWh/kWp)	1586.09
System efficiency	11.62%

4.2.4 Quarterly annual performance ratio of the power plant

Figure 4.3 illustrated the quarterly performance of the power plant based on the performance ratio. The power plant achieved its highest performance ratio in the second quarter of 2019, reaching 80.86%. Overall, the plant's performance ratio was notably high throughout 2019, with the second quarter marking the peak performance period for the year. This indicated that during this quarter, the plant operated most efficiently, converting the available solar energy into usable electricity with minimal losses.

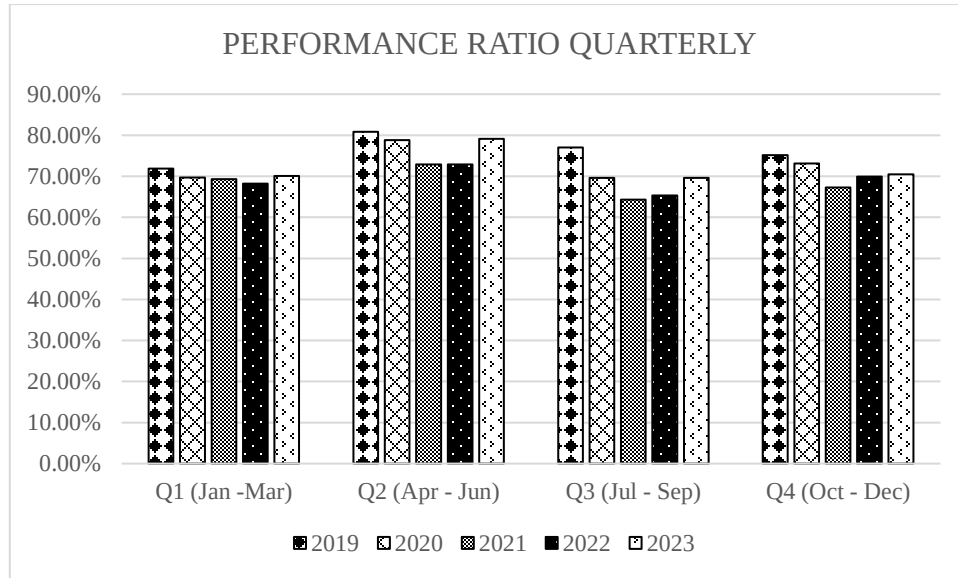


Figure 4.3: Quarterly Performance ratios

4.2.5 Quarterly annual capacity factor

Figure 4.4 illustrated the computed capacity factor of the power plant on a quarterly basis over a five-year period. The highest capacity factor, observed in January 2019, reached 19.5%. On average, quarter 3 consistently recorded the lowest capacity factor, while quarter 1 consistently exhibited the highest capacity factor throughout the analyzed period.

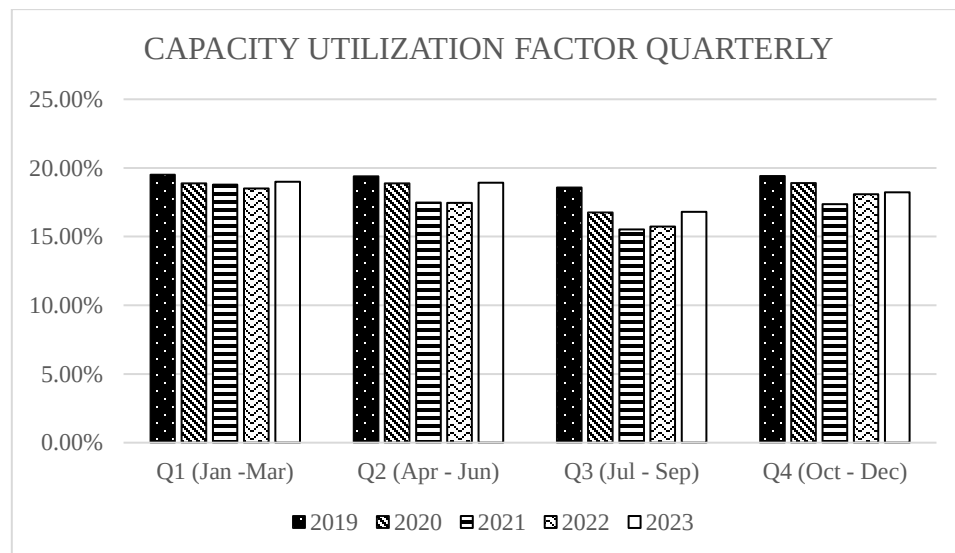


Figure 4.4: Quarterly CUF of the power plant

4.2.6 Final Yield

Figure 4.5 illustrated the annual average final yield, or specific yield, of the power plant for the years 2019, 2020, 2021, 2022, and 2023. Equation (3.16) was used to compute the values for the final yield and the results were 1683.46, 1608.08, 1513.68, 1527.76, and 1597.48 kWh/kWp, for the respective years.

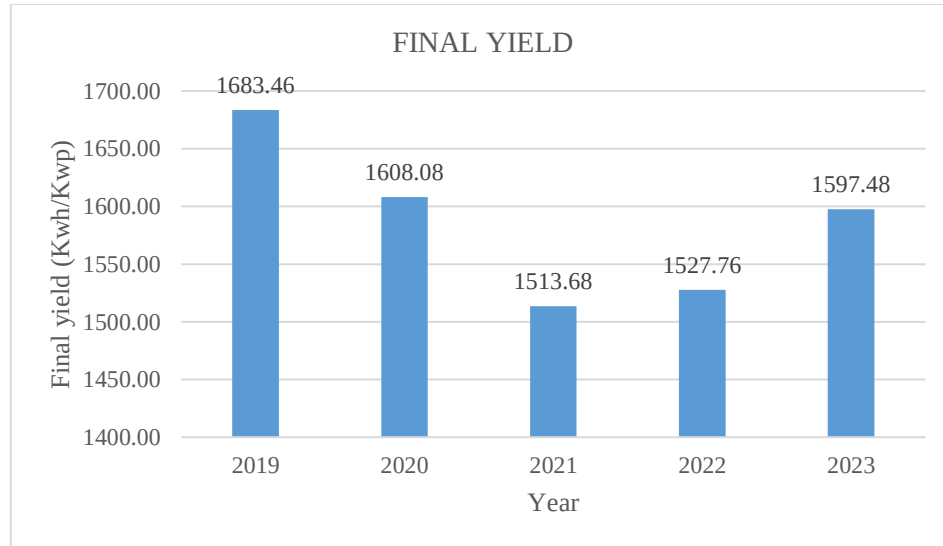


Figure 4.5: Annual average specific yield

4.2.7 System Efficiency

Figure 4.6 illustrated the computed system efficiency for each quarter of the year over a five-year period. Equation (3.17) was used to compute these values. The highest efficiency was observed in the second quarter of 2019, reaching a value of 13.09%. Across the analyzed period, the power plant consistently exhibited higher efficiency during the second quarter of each year.

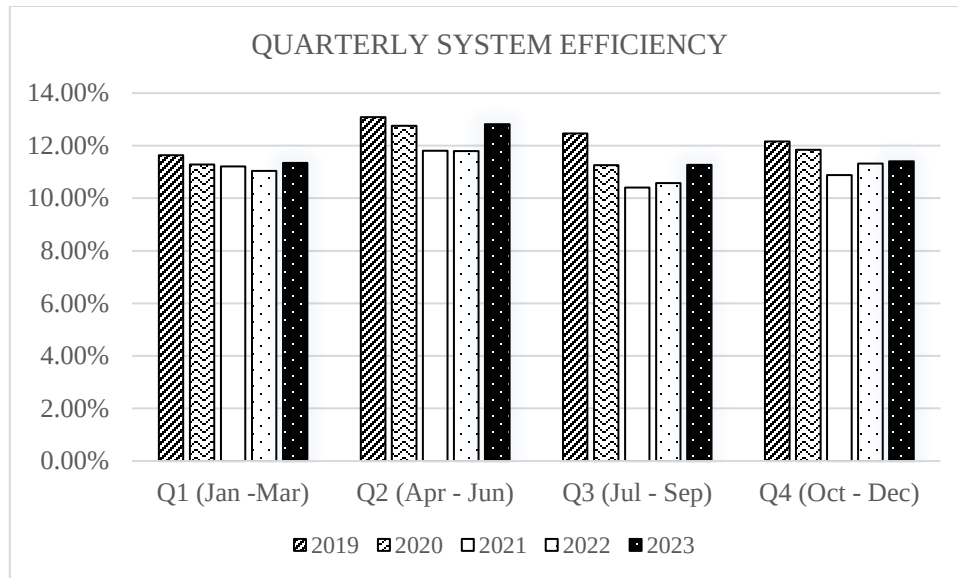


Figure 4.6: Quarterly system efficiency

Figure 4.7 showed the annual system efficiency of the power plant. The highest efficiency was observed in 2019 with a value of 12.34%. The lowest was observed in 2021 with a value of 11.08%. Generally, the power plant had a decreasing trend from 2019 to 2021 and picked up in 2022 and 2023.

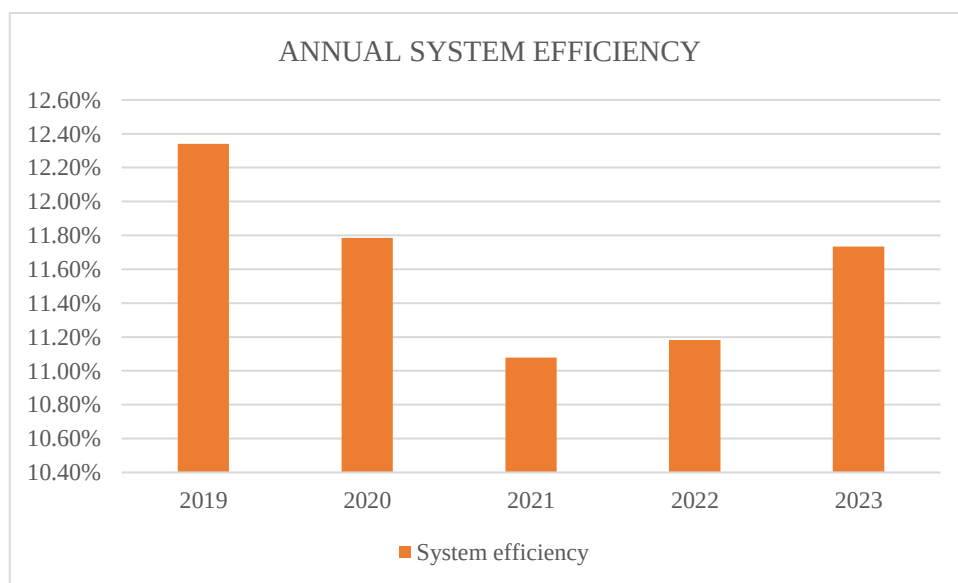


Figure 4.7: Annual system efficiency

4.2.8 Discussion

Analysis of the performance trends of the solar power plant over the five-year period revealed distinct patterns in both PR and CUF. PR exhibited a significant decline from 76.22% in 2019 to its lowest point of 68.43% in 2021, attributed to various factors including maintenance and operational inefficiencies, equipment degradation over time, and environmental influences such as dust accumulation and shading. In 2020 and 2021, energy consumption in Kenya declined due to the COVID-19 pandemic. EPRA reported that Kenya Power's earnings were expected to drop by at least 25% in the year ending June 2020, reaching a sixteen-year low, primarily due to reduced industrial and commercial power demand (*Kenya Power Stares at Profit Drop as Covid-19 Affects Power Uptake*, n.d.). This decrease in energy consumption was largely attributed to reduced industrial and commercial activity resulting from COVID-19 restrictions. Additionally, the pandemic led to reduced frequency of operations and maintenance (O&M) activities within the energy sector. Social distancing protocols and inter-county movement restrictions hindered routine maintenance schedules, potentially affecting the reliability and efficiency of energy infrastructure.

A positive trend emerged in 2022 and 2023, with PR values increasing to 69.07% and 72.48% respectively. This improvement can be attributed to reduced energy curtailments, as reported by EPRA, following the full resumption of commercial and industrial activities. With businesses operating at full capacity post-pandemic, electricity demand increased, leading to better grid absorption of solar (ENERGY & PETROLEUM REGULATION AUTHORITY, 2023). Similarly, the CUF followed a comparable trajectory, decreasing from 19.22% in 2019 to 17.29% in 2021, likely due to increased operational downtime and reduced system efficiency. In contrast, there was a slight recovery noted in 2022 and 2023, with CUF rising

to 17.45% and 18.24% respectively, possibly attributed to refined operational strategies and performance optimizations such as cleaning and minor repairs. These trends underscore the dynamic nature of solar plant performance influenced by both operational management and environmental conditions.

The average performance indicators of the power plant, as detailed in Table 4.1, indicate overall satisfactory performance compared to global research on solar PV plants. The PR of the plant falls within the typical range of 60% to 90%, aligning with findings from various researchers illustrated in Table 2.3. Similarly, the CUF of the power plant also falls within the expected range of 10% to 30%, indicating acceptable operational utilization. The system efficiency, falling within the bracket of 10% to 20%, further reflects standard efficiency levels observed in similar solar installations globally. Lastly, the specific yield of the plant, falling between 1000 kWh/kWp and 2000 kWh/kWp, denotes a satisfactory energy output relative to installed capacity. These findings suggest that the power plant's performance metrics are consistent with established benchmarks and norms observed across diverse solar PV installations worldwide.

4.3 EFFECT OF ENVIRONMENTAL FACTORS ON POWER GENERATION

4.3.1 Relationship between irradiance on energy generation

Analysis of the relationship between monthly energy generation and collected irradiance data revealed a direct proportionality, as depicted in Figure 4.88. This graph illustrates that energy generation increased with higher irradiance levels (Gopi et al., 2021). The annual average energy production was calculated to be 86,695.81 MWh.

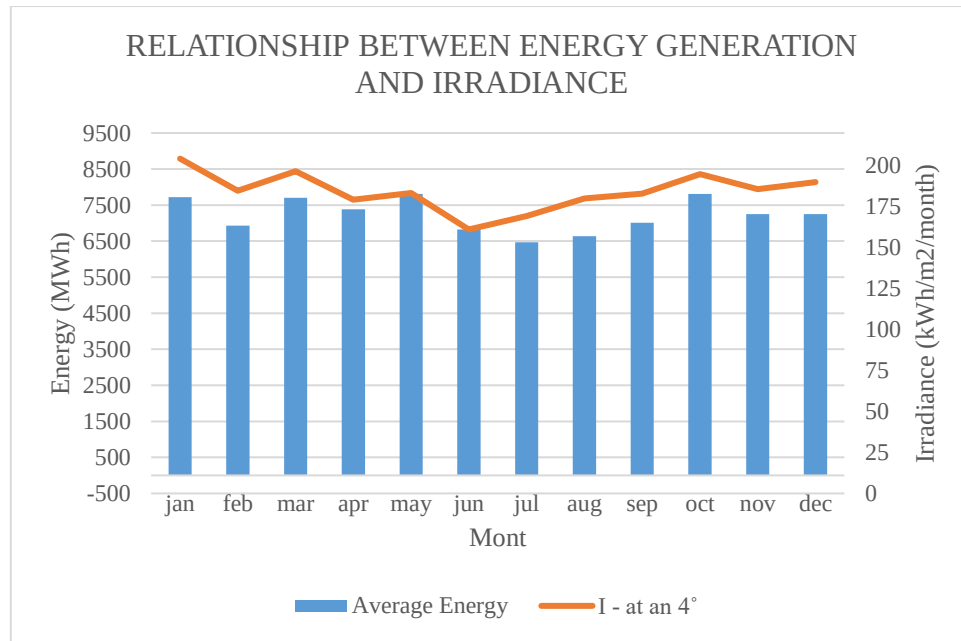


Figure 4.8: Energy generated and irradiance relationship

4.3.2 Relationship between temperature and energy output at a wind-speed of 1 m/s

The temperature data for Mbalambala, Garissa was gathered from the PVGIS database and organized using Microsoft Excel. The resulting dataset was presented on Table 4.2 which categorizes the data into average, minimum and maximum average values for every month.

Table 4.2: Wind Speed data for Mbalambala

Monthly Temperature(°C)	Average Temperature(°C)	Minimum Temperature(°C)	Maximum Temperature(°C)
January	29.67	28.70	30.30
February	30.50	29.90	30.90
March	30.33	29.00	31.30
April	29.13	27.20	31.10
May	28.30	27.50	28.80
June	27.80	27.20	28.40
July	26.97	26.60	27.40
August	26.80	26.40	27.30
September	27.63	27.50	27.90
October	28.57	27.90	29.30
November	28.20	27.10	29.20
December	27.87	27.50	28.10

Using this data, the impact of temperature was analyzed for the specific location. The temperature at this location ranges between 26 °C around the month of August and 31 °C in the month of March. The data provided critical insights into how temperature variations affect the performance and efficiency of solar energy systems in the region throughout different seasons. The cell temperature assuming a windspeed of 1m/s was calculated using equation (3.22). The cell monthly cell temperature was analyzed and categorized into average, minimum and maximum monthly values as presented by Table 4.3.

Table 4.3: Monthly module cell temperature

Month	Average Temperature (°C)	Minimum Temperature (°C)	Maximum Temperature (°C)
January	60.92	59.95	61.55
February	61.75	61.15	62.15
March	61.58	60.25	62.55
April	60.38	58.45	62.35
May	59.55	58.75	60.05
June	59.05	58.45	59.65
July	58.22	57.85	58.65
August	58.05	57.65	58.55
September	58.88	58.75	59.15
October	59.82	59.15	60.55
November	59.45	58.35	60.45
December	59.12	58.75	59.35

Using the calculated cell temperature and the module power coefficient of $-0.4\% / ^\circ\text{C}$, the effect of different cell temperatures on the power output was calculated using equation (3.24). Figure 4.9 illustrates how the calculated cell temperatures with an assumed windspeed of 1 m/s related with the average monthly energy output of the power plant.

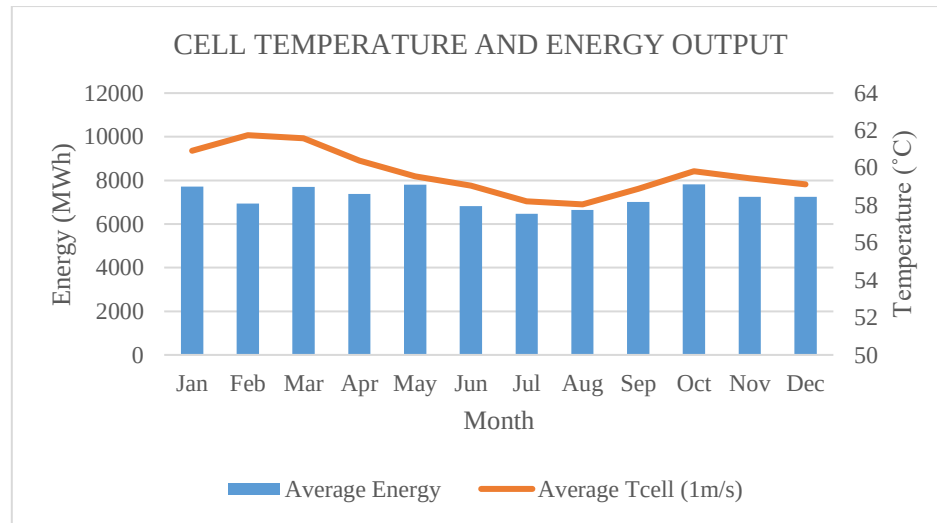


Figure 4.9: Relationship between ambient temperature and energy output

4.3.3 Combined wind speed and temperature on energy output

Table 4.4 shows data from the NSRDB database highlighting the monthly average, minimum and maximum wind speeds were calculated.

Table 4.4: Monthly windspeed data

Monthly Wind speed (m/s)	Average Wind speed (m/s)	Minimum Wind speed (m/s)	Maximum Wind speed (m/s)
January	2.52	1.95	2.97
February	3.20	2.39	3.90
March	3.39	2.29	4.52
April	3.44	1.85	4.75
May	4.58	3.52	5.38
June	5.42	4.68	6.29
July	6.25	4.88	7.35
August	6.18	5.18	7.16
September	5.95	5.00	6.76
October	4.70	3.95	5.80
November	2.69	1.48	3.67
December	2.25	1.45	3.19

The cell temperature was calculated using equation (3.23) resulting to the values presented by Table 4.5.

Table 4.5 Effect of wind speed on cell temperature

Month	Average (°C)	Maximum (°C)	Minimum (°C)
January	49.11	51.37	47.77
February	47.13	50.00	45.36
March	46.32	49.63	44.28
April	44.94	50.55	43.61
May	41.14	43.06	40.16
June	39.09	39.84	38.43
July	37.05	38.84	36.23
August	36.97	38.09	36.32
September	38.12	39.51	37.36
October	41.17	42.25	40.01
November	46.86	53.32	44.32
December	48.71	53.95	44.75

Applying the effect of wind speed on the cell temperature, a relation graph was formulated to analyze the relationship between the resulting cell temperature and the energy output of the power plant. This was illustrated by Figure 4.10. Despite the known fact that the combined effect of wind speed and temperature influences the performance of a solar cell, the figure showed that an increase in the resulting cell temperature led to an increase in resulting energy output. This relationship was not conclusive, as other factors, such as humidity, dust cover and panel degradation, affecting the energy output of the power plant were not considered in this study (Bamisile et al., 2025) (Dewi et al., 2019).

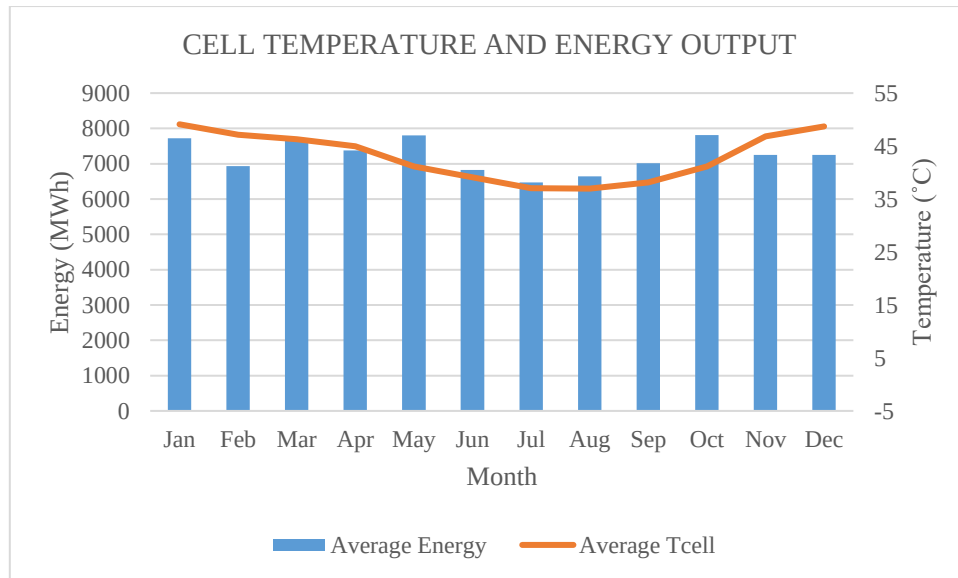


Figure 4.10: Relationship between cell temperature and energy output

4.3.4 Discussion

As observed from Figure 4.8, Figure 4.9 and Figure 4.10, the influence of irradiance, ambient temperature, and the combined effect of wind speed and temperature on energy generation showed variability. Figure 4.8 demonstrated that higher irradiance levels correlate with increased energy output, consistent with the actual average energy production of the power plant studied. This relationship was supported by (Gopi et al., 2021), who also found similar results regarding irradiance and energy output.

However, Figure 4.9 and Figure 4.10 present contrasting findings regarding the impact of temperature and wind speed on energy generation. Figure 4.9, which examined the effect of temperature at a wind speed of 1 m/s, and Figure 4.10, which explored the combined effect of temperature and wind speed on energy output, did not provide conclusive evidence on their influence on the power plant's actual performance. Specifically, for February, an increase in cell temperature resulted in lower energy output, whereas decreased temperatures

showed slightly higher energy output. Such contradictory results across different months suggest that the relationship between temperature, wind speed, and energy output was complex and varied depending on specific environmental conditions and operational factors.

It was notable that these figures only considered a limited set of factors influencing solar power plant output. Numerous other variables, such as humidity, dust accumulation, and panel orientation, also significantly impact performance but were not addressed in this study (Shaik et al., 2023). Therefore, while these findings provide insights into the relationships studied, a comprehensive understanding of all factors affecting solar power plant performance would require further investigation and consideration of a broader range of variables.

4.4 OPTIMIZATION, SIMULATION AND MODELLING OF THE SOLAR POWER PLANT

4.4.1 Sun Path Diagram

This section presented the analysis of the sun path for the Garissa solar power plant. The sun path diagram provided a visual representation of the sun's trajectory across the sky at this specific location, helping to optimize the orientation and tilt of solar panels for maximum energy capture. Using the latitude of the power plant (-0.34), and considering different days of the year, the altitude angle and the angle of declination of the sun were calculated using equations (3.1) and (3.3). These calculations were performed for solar time H ranging from 7 am to 5 pm.

Figure 4.11 illustrates the computed sun path diagram for the Garissa solar power plant. The numbers on the diagram (21, 52, 80, 111, 141, and 172) correspond to the following dates: January 21st, February 21st, March 21st, April 21st, May 21st and June 21st. The azimuth angle of the sun was calculated using the equation (3.2). These dates were significant for understanding solar positions around the equator where the sun is highest during the equinoxes (March 21st and September 21st) and lowest during the solstices (June 21st and December 21st). January 21st and February 21st capture the sun's increasing altitude post-December solstice. March 21st marks the equinox with the sun directly overhead, while April 21st and May 21st show increasing daylight towards the June solstice. These dates helped optimize solar panel orientation and tilt to maximize energy capture throughout the year.

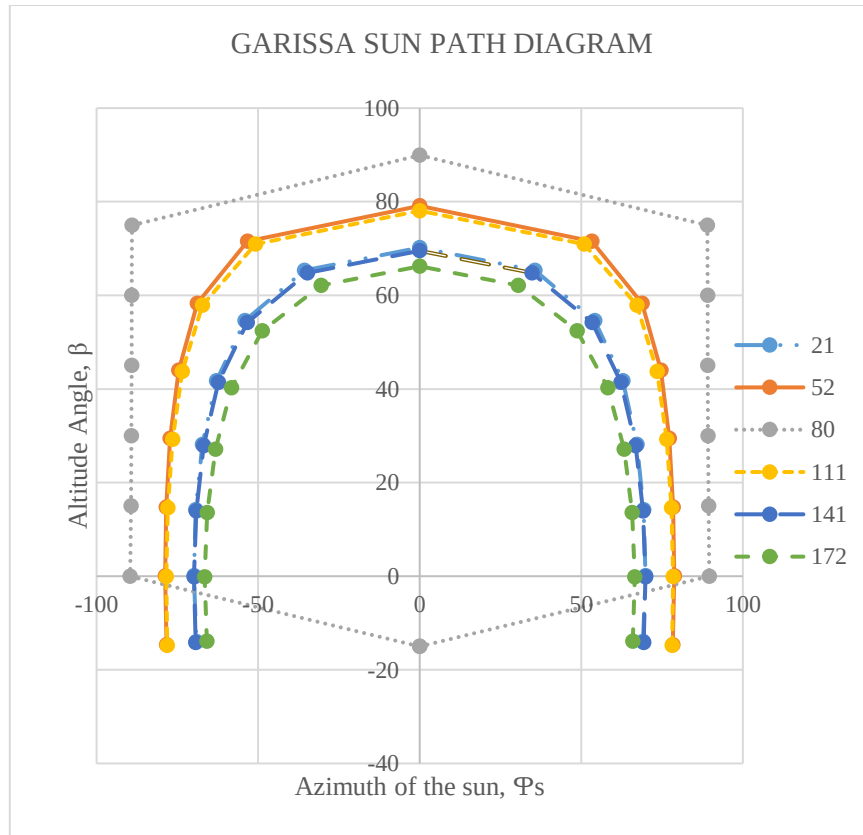


Figure 4.11: Garissa sun Path diagram

4.4.2 Inter row Spacing

Using the same input parameters as those used in generating the sun path diagram, the shadow length was calculated by incorporating the height of the solar installation from the ground. The shadow was observed to be the longest on June 21st (day 172), the winter solstice. Based on these calculations, the minimum allowable distance between the rows of solar panels was computed to ensure there is no shading throughout the day. This distance was critical for maintaining optimal performance and preventing shading losses. The results in Figure 4.12 displays the minimum distance required between the rows of panels throughout the day, ensuring maximum solar efficiency.

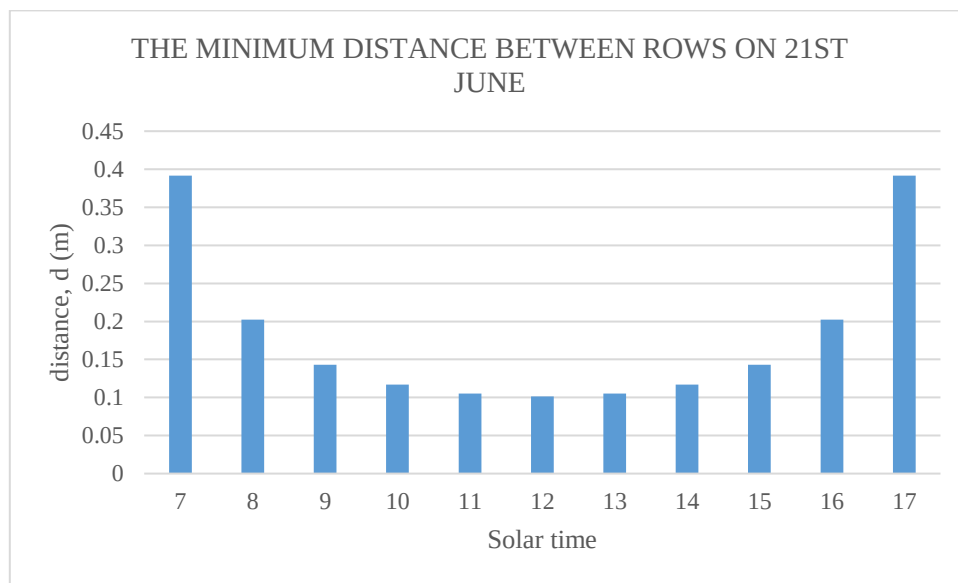


Figure 4.12: Minimum allowable inter row spacing

The longest minimum allowable distance was figured to be 0.39 m at 7 am in the morning and 5pm in the evening. This makes the total row spacing a summation of 3.29 and 0.39 making it 3.68m. This meant that reducing inter-row spacing from 2 meters to 0.4 meters would to accommodate more solar arrays without shading.

Figure 4.13 displays the minimum allowable inter row spacing for the latitude of Garissa at noon. The longest shadow at noon was seen on June 21st and was 0.05m. In the equinox, the shadow at noon was the shortest and the minimum allowable distance was found to be 0.0013.

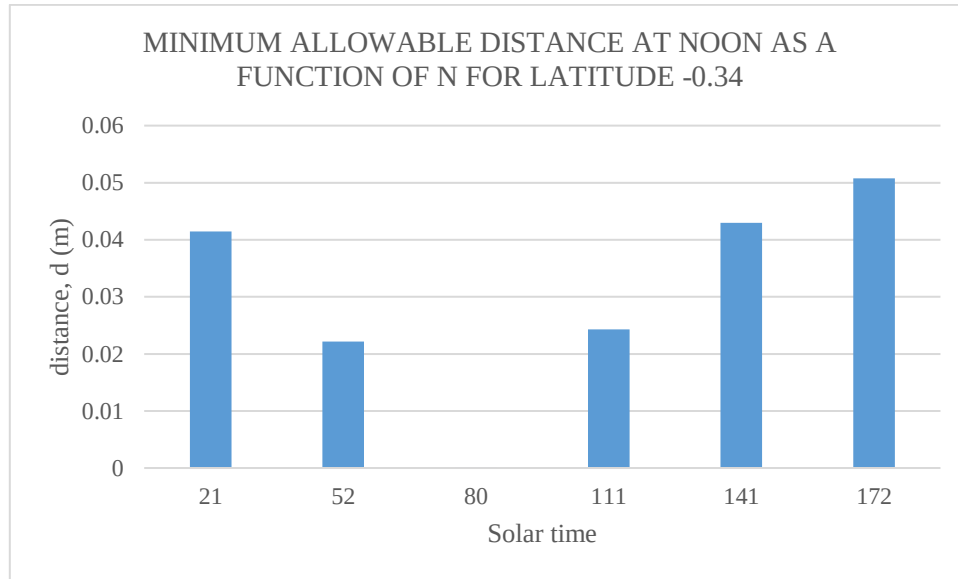


Figure 4.13: Minimum allowable inter row distance at noon

4.4.3 Ground Coverage Ratio

Applying equation (3.10) the GCR was computed using calculation on equation (4.1).

$$\text{GCR} = \frac{\text{Panel width}}{\text{Total row spacing}} = \frac{3.3}{3.29 + 2} = 0.625 \quad (4.1)$$

4.4.4 Simulation Results

The simulation was carried out for different scenarios:

1. Using the actual plant configuration (tilt 4, azimuth 140, GCR of 0.625) for the PPA of 0.0549 and 0.12 US cents per unit. The simulation results are presented on Table 4.6

Table 4.6: Simulation results for azimuth 140 degrees

Metric	Results 1	Results 2
Annual AC energy in Year 1	97,829,416 kWh	97,829,416 kWh
DC capacity factor in Year 1	20.40%	20.40%
Energy yield in Year 1	1,790 kWh/kW	1,790 kWh/kW
Performance ratio in Year 1	0.79	0.79
PPA price in Year 1	5.49 ¢/kWh	12.00 ¢/kWh
PPA price escalation	0.00 %/year	0.00 %/year
LPPA Levelized PPA price nominal	5.49 ¢/kWh	12.00 ¢/kWh
LPPA Levelized PPA price real	4.38 ¢/kWh	9.58 ¢/kWh
LCOE Levelized cost of energy nominal	14.67 ¢/kWh	14.68 ¢/kWh
LCOE Levelized cost of energy real	11.72 ¢/kWh	11.72 ¢/kWh
NPV Net present value	\$-84,408,128	\$-24,584,870
IRR Internal rate of return	-3.08%	5.53%
Year IRR is achieved	20	20
IRR at end of project	-1.23%	6.59%

2. Using the computed optimal values (tilt 4, azimuth 0, GCR of 0.4) for the PPA of 0.0549 and 0.12 US per unit. The results are depicted on Table 4.7.

Table 4.7: Simulation results with an azimuth of 0 degrees

Metric	Results 1	Results 2
Annual AC energy in Year 1	98,233,672 kWh	98,233,672 kWh
DC capacity factor in Year 1	20.50%	20.50%
Energy yield in Year 1	1,797 kWh/kW	1,797 kWh/kW
Performance ratio in Year 1	0.8	0.8
PPA price in Year 1	12.00 ¢/kWh	5.49 ¢/kWh
PPA price escalation	0.00 %/year	0.00 %/year
LPPA Levelized PPA price nominal	12.00 ¢/kWh	5.49 ¢/kWh
LPPA Levelized PPA price real	9.58 ¢/kWh	4.38 ¢/kWh
LCOE Levelized cost of energy nominal	17.19 ¢/kWh	17.19 ¢/kWh
LCOE Levelized cost of energy real	13.72 ¢/kWh	13.72 ¢/kWh
NPV Net present value	\$-47,858,724	\$-107,929,192
IRR Internal rate of return	3.16%	-5.69%
Year IRR is achieved	20	20
IRR at end of project	4.55%	-3.25%

4.4.5 System loss flow chart

Figure 4.14 illustrates the distribution of system losses, offering a comprehensive overview of the factors affecting power generation. It summarized the impact of these losses on the overall power generated by the system. This irradiance value was influenced by various factors, including shading (0.038%), soiling (5%), and reflection (IAM, 1.628%).

The nominal DC electricity generated by the system was calculated at 115,282,056 kWh. Several factors contribute to the deviation from the STC performance, including module

deviation (8.829%), module mismatch (2%), diodes and connections (0.5%), and DC wiring losses (2%).

The system's tracking error and nameplate specifications had negligible impacts on performance, with losses recorded at 0%. Similarly, losses attributed to snow coverage, inverter MPPT clipping, and DC power optimizer are minimal or non-existent. On the AC side, gross electricity generated totaled 100,436,634 kWh, factoring in losses from AC wiring (1%), transformer loss, and transmission loss. However, lifetime daily losses in year one for AC electricity were negligible, with an overall availability and curtailment rate of 0%.

Ultimately, the net AC electricity fed into the grid was calculated at 98,233,672 kWh. Despite minor losses attributed to inverter efficiency (1.2%) and inverter nighttime consumption (0.005%), the system demonstrated a robust performance with minimal losses impacting overall output.

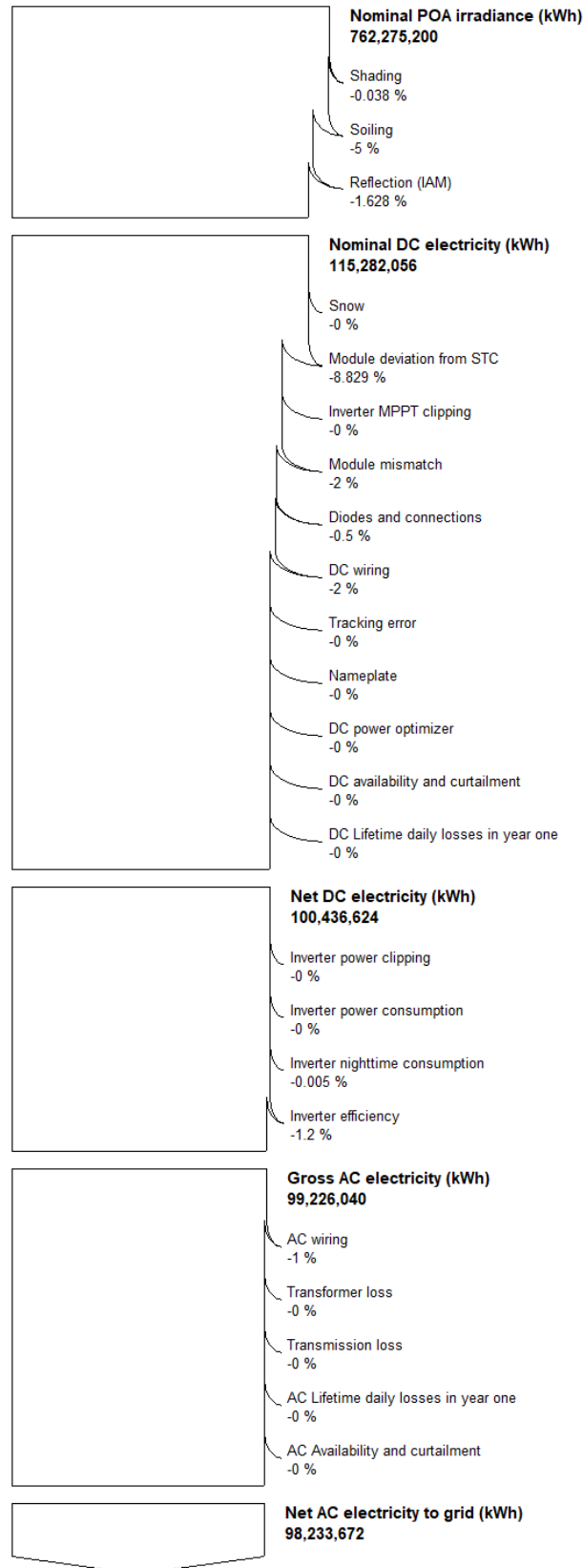


Figure 4.14: System loss diagram

4.4.6 Comparison of actual to the simulated energy generation results

Figure 4.15 illustrated the relationship between simulated energy generation results of the optimal design of the system and actual annual energy results of the power plant. While the general trend in performance between the two data sets was similar, a significant discrepancy was observed in the month of August, where the difference amounts to 1903 MWh. Overall, the simulated results closely followed the actual results despite the notable deviation.

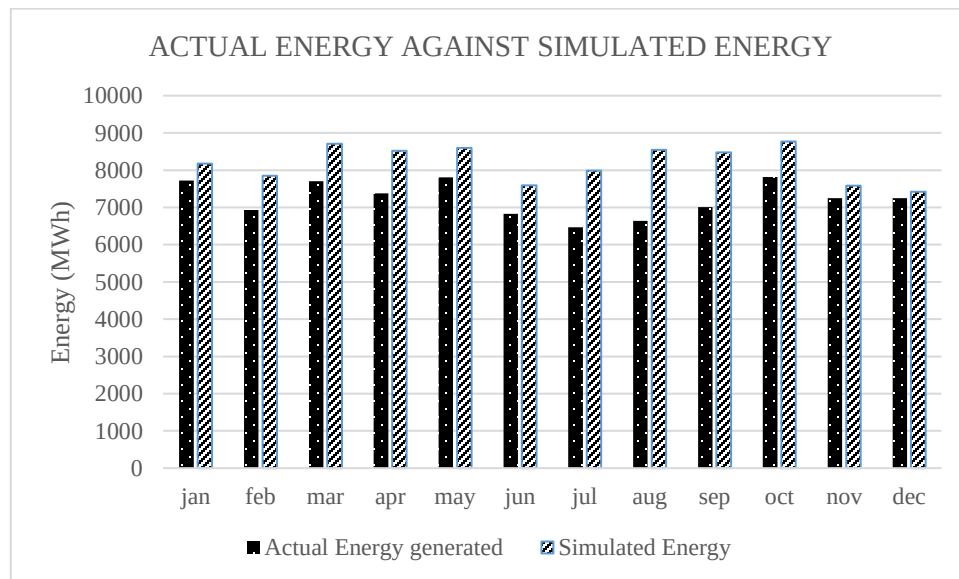


Figure 4.15: Simulated results against actual results

Figure 4.16 illustrated the relationship between the energy generation of the power plant under two different simulation inputs and the actual energy generated. The first set of simulation inputs included the actual parameters of the plant: an azimuth of 140°, a tilt of 4°, and a Ground Coverage Ratio (GCR) of 0.625. The second set used optimized computed parameters: an azimuth of 0°, a tilt of 4°, and a GCR of 0.4. The results showed that with the optimized design parameters, the energy generation was slightly increased compared to the simulation using the plant's actual input parameters. This indicated that optimizing design parameters enhanced the performance and energy output of the solar power plant.

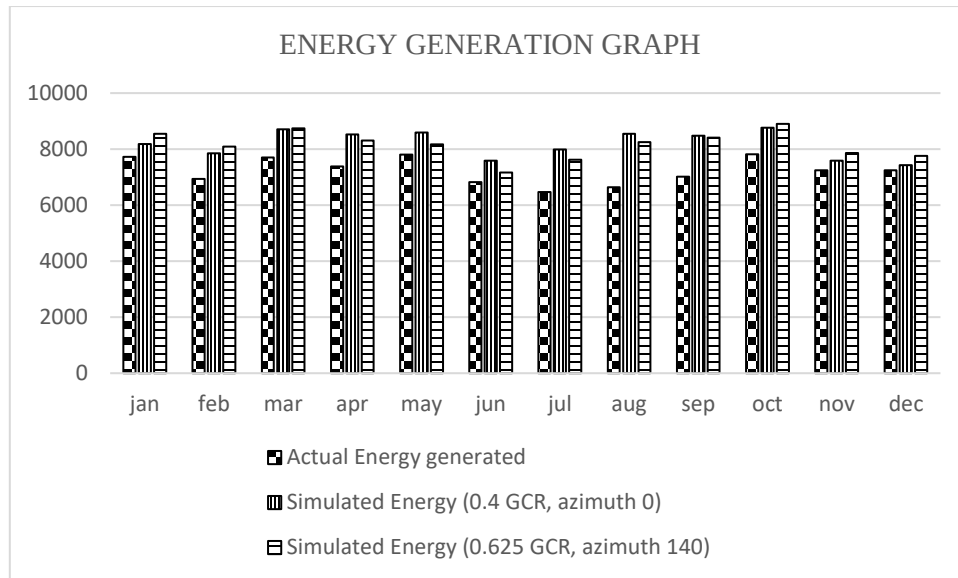


Figure 4.16: Energy generation graph for 3 different scenarios

The performance of the photovoltaic power plant was evaluated over a five-year period, and the key metrics were summarized in Table 4.8. The plant exhibited an annual average performance ratio of 71.8%, indicating that the actual energy output was 71.8% of the theoretical maximum output under standard test conditions. The capacity factor, which represents the ratio of the actual energy output to the maximum possible output, was measured at 18.09% over the five-year period.

The reference yield, defined as the theoretical energy output per unit of installed capacity, was 6.06 hours per day on average. This metric provided insights into the available solar resource at the plant's location. The specific yield, which is the actual energy output per unit of installed capacity, was measured at 1586 kWh/kWp over the five-year period.

Simulated results for the power plant's performance yielded higher values compared to the actual measurements. The simulated performance ratio was 80%, the capacity factor was 20.5%, and the specific energy yield was 1797 kWh/kWp. These simulated values suggested

that the plant's performance could potentially be optimized to achieve higher efficiency and energy output.

Table 4.8: Simulated vs Actual performance of the plant

Performance Indicator	Actual Values	Simulated Values
Performance ratio (%)	71.8	80
Capacity factor, CUF (%)	18.09	20.5
Specific yield (kWh/kWp)	1586	1797
Annual energy generated (MWh)	86695.81	98233.67
System Efficiency (η)	11.62%	13.17%

4.4.7 Discussion

The optimal design for the Garissa solar power plant incorporated specific input parameters: an azimuth angle of 0° for optimal orientation towards the equator, a tilt angle of 4° which aligns well with optimal tilt angles near the equator, and a GCR ratio of 0.4, falling within the recommended range of 0.3 to 0.5 for efficient solar PV systems (Mustafa et al., 2020). According to research by (Alhaidari, 2017), solar systems are ideally oriented towards the equator. In the northern hemisphere, an azimuth angle of 180° (due south) is recommended, while in the southern hemisphere, an azimuth angle of 0° (due north) is advised. (Krishna et al., 2021) found that the tilt angle of solar PV systems should closely match the latitude angle of the location. The tilt angle of 4° was chosen to facilitate self-cleaning of the solar panels during rainfall. The azimuth of 0° as chosen based on the latitude of the Garissa solar power plant, which is approximately -0.34° .

Using these optimized parameters in simulation, the energy output increased from 97,829,416 kWh to 98,233,672 kWh. The initial energy output of 97,829,416 kWh was

achieved using actual input parameters of the Garissa solar power plant; a computed GCR of 0.625, a tilt angle of 4° , and an azimuth angle of 140° . The selection of SAM for simulation was validated by (Ezeanya et al., 2018), affirming its accuracy with only a 3% deviation compared to actual solar power plant performance.

From Table 4.8, the data presented revealed that the simulated values for all key performance indicators (KPIs) were higher than the actual values. This discrepancy suggested that the Garissa Solar power plant was not performing as efficiently as the simulations predict. The performance ratio (PR) in simulations was based on ideal conditions with optimized parameters and consistent performance. The actual PR, calculated over an average of five years, reflected real-world challenges such as varying maintenance quality, equipment degradation, and environmental factors. Maintenance practices over the five-year period might not have been optimal, leading to lower efficiency and reduced PR. Simulated CUF was derived from historical and predicted solar irradiance data, often under ideal conditions. Actual CUF was influenced by operational issues, maintenance downtime, and unpredictable weather patterns.

Over the five-year period, operational disruptions and maintenance lapses likely contributed to the lower CUF observed in actual data. Simulations assumed consistent optimal operation and regular maintenance. In reality, specific yield is affected by factors such as equipment aging, variability in installation quality, and operational inefficiencies. The five-year average performance reflected these practical challenges and deviations, resulting in lower specific yield compared to simulations. Simulated annual energy generation was based on idealized input data and optimal performance assumptions. Actual annual energy generation, averaged

over five years, was reduced due to maintenance issues, unexpected outages, and local climate variations not fully captured in simulations. These real-world factors, including potential maintenance inadequacies over the years, contributed to the lower actual energy generation.

The simulated results provided a useful benchmark based on ideal and optimal conditions, offering insights into the potential maximum performance of the solar power plant. The discrepancies between simulated and actual values, particularly the lower actual PR averaged over five years, highlighted the importance of considering real-world factors such as maintenance quality, equipment degradation, and environmental impacts. Understanding these differences can guide improvements in operational strategies, maintenance practices, and model refinements to bridge the gap between expected and actual performance.

4.5 CONCLUSION

The study examined the performance of the Garissa solar power plant over a period of 5 years, spanning from 2019 to 2023. Although the plant became operational in November 2018, data used for assessing its performance pertained to years with complete data availability. Information was gathered from the plant operator, REREC, encompassing energy generation data for the specified timeframe, supplemented by meteorological data sourced from PVGIS. Additionally, a checklist was employed to collect supplementary data, including details on plant orientation, tilt angle, solar PV module specifications, inverter details, and plant location.

Data on local weather conditions was obtained from both the SAM NSRDB and PVGIS databases and was used to analyze the relationship between irradiance, windspeed and temperature on energy output of the solar power plant. Key performance indicators were calculated using Microsoft Excel, while SAM software was utilized to simulate the optimal solar system based on the technical specifications of the Garissa solar power plant.

On an annual average, the technical performance of the power plant was determined as follows: a performance ratio of 71.8%, capacity factor of 18.09%, reference yield of 6.06 hours per day, and specific yield of 1586 kWh/kWp over the five-year period. Conversely, simulated results revealed technical performance indicators of 80% for the performance ratio, 20.5% for the capacity factor, and a specific energy yield of 1797 kWh/kWp. These findings indicated that the Garissa solar power plant was operating below optimal efficiency, despite the tilt angle being deemed appropriate. The study concluded that the azimuth angle of 140° and the GCR ratio of 0.625 were suboptimal. Ideally, the azimuth angle should have been 0° to better align with the plant's latitude, while the recommended GCR for optimal performance was found to be 0.4.

The study also highlighted that the influence of weather conditions on energy output cannot be fully attributed solely to ambient temperature and wind speed. However, it clearly demonstrated that irradiance directly impacts energy output, with higher irradiance levels correlating with increased energy generation.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The aim of this study was to evaluate the performance of the Garissa Solar power plant utilizing selected performance indicators, and subsequently, to simulate an optimal system informed by diverse calculations for optimal design. The study conducted a comprehensive review of literature on the performance evaluation of solar PV plants globally. This literature review revealed that common performance indicators for solar power plants include the performance ratio, capacity utilization factor, specific yield, and reference yield and typical results for these performance indicators. Utilizing various technical formulas and collected data, the study then determined these performance indicators for the case study of the Garissa solar power plant. The results obtained from this study offer valuable information to guide investors and other stakeholders in making informed decisions regarding solar energy development projects. By highlighting the factors influencing the plant's performance, this research contributes to increasing solar PV penetration in Kenya. Some of the conclusions drawn include:

1. The study revealed that the overall performance of the plant was acceptable compared to global research on solar PV plants, with a performance ratio of 71.80%, a capacity factor of 18.11%, a reference yield of 6.06 hours per day, a specific yield of 1586.09 kWh/kWp, and a system efficiency of 11.62%. These metrics align well with benchmarks observed in similar solar installations globally, indicating that the Garissa Solar Power Plant is performing averagely within the industry standards for solar energy generation efficiency.

2. The study underscored that the energy output of a solar power plant is influenced by a multitude of factors beyond just ambient temperature, solar irradiance and wind speed. While these variables play a role, other critical factors such as, panel orientation, tilt angle, and the efficiency of components like inverters and solar panels also significantly impact energy generation.
3. The comparison between simulated and actual performance of the Garissa Solar Power Plant revealed notable discrepancies, with simulated values indicating higher efficiency metrics than observed in practice. Specifically, the simulated performance indicators were 10.03% higher for performance ratio, 12.17% higher for capacity factor, and 12.01% higher for specific energy yield over the 5-year period. This disparity highlighted opportunities for optimization to enhance the plant's operational efficiency
4. The research findings revealed that while a panel tilt of 4° fell within the optimal range for the location in Mbalambala, Garissa, the orientation of 140° SE and the GCR of 0.625 were found to be suboptimal. The study highlights that future solar power plants in similar regions should consider a GCR between 0.3 and 0.5, with panel orientation to the north for locations in the southern hemisphere and to the south for those in the northern hemisphere. These adjustments are expected to enhance energy yield and optimize system performance in alignment with geographical factors.
5. There is a need to address operational challenges such as vegetation cover, dust accumulation, grid losses, and frequent corrective maintenance, as they significantly impact the efficiency and energy output of solar power plants. These factors lead to energy wastage during grid outages, when solar PV modules continue to generate

power that cannot be utilized, and contribute to reduced efficiency during normal operations, ultimately affecting the overall performance of the plants.

5.2 RECOMMENDATIONS

This research examined the performance of the Garissa solar PV system in terms of technical parameters. Based on the conclusions drawn from the study's findings, several recommendations emerge to address the identified challenges and optimize the performance of solar power plants like the Garissa Solar Power Plant. These recommendations aim to enhance efficiency, mitigate operational issues, and maximize energy generation in the context of grid-tie solar PV systems. By implementing these measures, stakeholders can improve the overall sustainability and effectiveness of solar energy production in Kenya.

The recommendations include:

1. Implement comprehensive O&M practices to ensure the optimal performance of the solar power plant. This includes planning and executing regular maintenance schedules that encompass preventive, corrective, and reactive maintenance activities
2. Implement effective vegetation management strategies to minimize shading caused by weeds and other vegetation beneath the solar panels, as shading can significantly reduce solar panel efficiency. Regularly trim or remove vegetation to prevent it from affecting the cell temperature of the modules, thereby optimizing energy generation and overall plant efficiency.
3. Introduction of battery systems and implement battery management systems to store excess solar power during periods of grid loss. This stored energy can be utilized for self-consumption in the facility for lighting and other purposes, reducing reliance on the grid and minimizing energy wastage.

4. Enhancing the precision of techno-economic performance assessments requires the collection of local meteorological data, specifically irradiance, wind speed, and temperature, to minimize reliance on online sources and ensure more accurate results for the specific area of interest.

5.3 FUTURE WORKS

Building upon the findings and methodologies of the performance assessment of the Garissa Solar Power Plant, future research endeavors can further explore and optimize various aspects of the plant's performance to maximize energy generation and sustainability. Some of the recommended future works include:

1. There is need for extensive economic analysis of the power plant.
2. Design exploration for a tracking system which optimizes the amount of sunlight captured hence higher energy generation
3. Assess the integration of energy storage systems for enhanced flexibility and reliability.

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APPENDICES

APPENDIX I: CHECKLIST

GENERAL INFORMATION

Date of commissioning – 07//11/2018

Physical location (latitude) – Garissa County

PLANT DESIGN AND COMPONENTS

- Description of the power plant design
- Plant layout (schematic diagram)
- Overview of the major components of the system

ON MODULES

1. Module model/manufacturer and size. (polycrystalline, monocrystalline, amorphous silicon, etc.) jkm265pp-60 from jinko, polycrystalline,
2. How many modules in total? 206,272
3. Installation type (fixed, tracking, ground mount etc) and spacing of modules structures to minimize shading fixed, 2m wide
4. Modules arrangement 22 panels are connected in series to form in string
5. Cleaning mode (operation and maintenance frequency) semi-automatic cleaning
6. Tilt angle and orientation tilt angle 4° azimuth 140° SE

ON INVERTER

1. Inverter(s) model/manufacturer. (quantity, capacity, rated power) SUN2000-42KTL, Huawei, 42kW, 1172 in number
2. Inverter configuration and arrangement

ON THE BATTERIES/STORAGE (If any)

1. Battery model/manufacture. (quantity, capacity rated power) **N/A**

ON THE TRANSFORMER/GRID CONNECTIVITY

1. Transformer model/manufacturer **ABB,**
2. Grid connection line

ON PLANT CAPACITY

1. What is the installed capacity of the power plant? **54.6MWp**
2. What is the land area occupied? **210 acres**
3. Plant installation cost, average annual operation and maintenance cost and any other related annual costs? (including; cost of modules, batteries, inverters, transformers, installation, land purchased or leased (if lease, payment arrangement?) etc).
 - Are there any government financial supports? **Ksh 13.7 billion**
 - Any other incentives from government and/or elsewhere? If yes, how much?
 - What is interest on loan and loan duration for any portion of the investment cost that is borrowed (from international or domestic banks)?

ON IRRADIATION

1. What is the average daily solar irradiation?
2. When do you have the highest and lowest irradiation (months)? **Highest in Jan, lowest in July**

ON ENERGY OUTPUT

1. Plants daily/monthly energy output from installation to date if available. (Is there an online portal for data monitoring? If yes, can you give access? or data recorded on excel sheets) **no online portal**

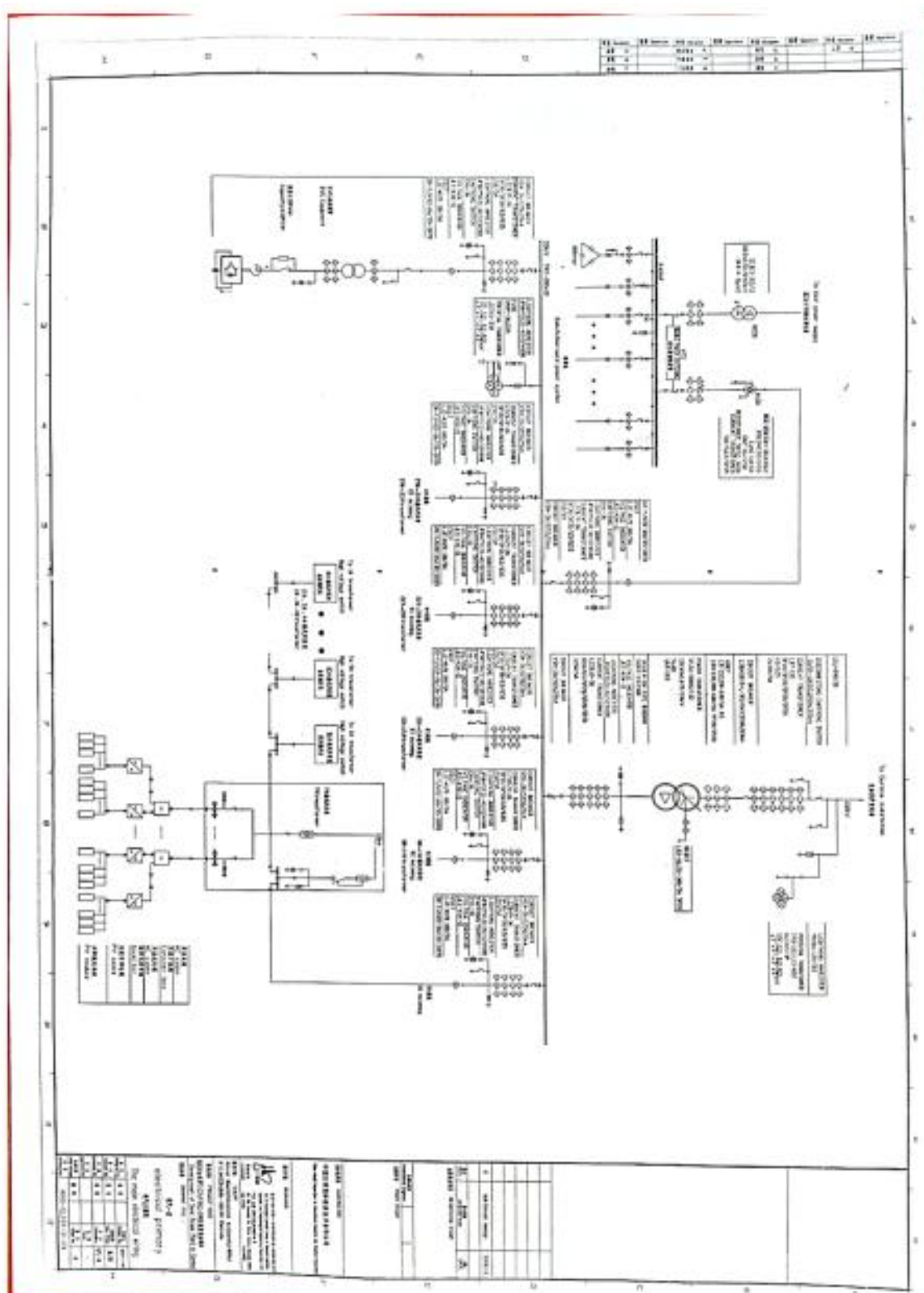
2. Expected energy output of the power plant.
3. What is the total annual energy generated from the plant?
3. What is the total annual energy delivered to the grid? (energy used by site from installation to date if available) **Average 86GWh sent to the grid annually**
4. Is there a system interface with the PV systems, may be Bluetooth or WIFI to collect and store data from the PV systems, what are the intervals for recording? **We use SCADA system for recording, Bluetooth is just used during inverter parameterization**
5. Hourly, daily and monthly weather-related data such as irradiance, ambient temperature, wind speed, rain and other conditions measured? (minimum, maximum and average temperature)

CHALLENGES

Any challenges experienced from the design phase to operation.

Dust and vegetation growth.

APPENDIX II: WIRING DIAGRAM FOR GARISSA SOLAR POWER PLANT



APPENDIX III: METEOROLOGICAL DATA FROM PVGIS

[illegible]

APPENDIX IV: PLAGIARISM REPORT



SR714

ISO 9001:2019 Certified Institution

THESIS WRITING COURSE

PLAGIARISM AWARENESS CERTIFICATE

This certificate is awarded to

MAINA, NELIUS WAITHIRA

ENG/MS/SEA/4819/23

In recognition for passing the University's plagiarism

Awareness test for Thesis **entitled: TECHNICAL PERFORMANCE ASSESSMENT OF THE GARISSA SOLAR POWER PLANT IN KENYA** with similarity index of 2% and striving to maintain academic integrity.

Word count: 20517

Awarded by

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

APPENDIX V: IMAGES OF THE GARISSA SOLAR POWER PLANT

