

Ramarothole Solar PV Plant Technical Performance Analysis

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ABSTRACT

Despite the country's persistent energy deficit and reliance on imports, access to reliable data on the technical performance of commercial solar photovoltaic (PV) plants in Lesotho remains limited. This study evaluates the performance of the 30 MWp grid-connected Ramarothole Solar PV Plant to determine its efficiency, reliability and long-term sustainability. The analysis applies International Energy Agency (IEA)-recommended performance indicators, namely Performance Ratio (PR), Capacity Factor (CF) and Final Yield (Y_F). Plant operational data measured at 30minute intervals from January to December 2024 was assessed. The results show that the plant generated a total of 59,326.40 MWh of electricity, achieving an annual average PR of 94.8%, CF of 21%, and Y_F of 1884.3 hours. These values indicate that the plant operates with higher efficiency compared to similar plants in the region, where PR typically ranges between 70% and 82%. The findings demonstrate that the Ramarothole Solar PV Plant performs well under the local conditions, though seasonal fluctuations highlight the influence of irradiance variability and potential technical inefficiencies. It is concluded that regular preventive maintenance, improved monitoring of solar irradiance data and better alignment with national energy planning are necessary to sustain high performance and to optimize future solar PV projects in Lesotho.

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ABBREVIATIONS

| | |
|---------|--|
| CF | Capacity Factor |
| CUF | Capacity Utilization Factor |
| DC | Direct Current |
| GW | Gigawatt |
| IEC | International Energy Agency |
| IRENA | International Renewable Energy Agency |
| KPI | Key Performance Indicator |
| kWh | kilowatt-hour |
| LEGCO | Lesotho Electricity Generation Company |
| MLPE | Module-Level Power Electronics |
| MPPT | Maximum Power Point Tracking. |
| MVA | Megavolt-Amperes |
| kV | Kilo volt |
| kW | Kilowatt |
| MW | Megawatt |
| PR | Performance Ratio |
| PV | Photovoltaic |
| REIPPPP | Renewable Energy Independent Power Producer Procurement Programmed |
| SCADA | Supervisory Control and Data Acquisition |
| STC | Standard Test Condition |
| V | Volt |
| Wh | Watt hour |

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1.0 INTRODUCTION

1.1 Background

Solar energy is, without a doubt, the world's most plentiful resource. Solar photovoltaic (PV) technology has emerged as a promising alternative for electricity generation, harnessing solar irradiance to produce clean energy [1]. It sets the stage for a bright future in the next decades for the production of clean, reasonably priced and sustainable energy [2]. The growing global demand for sustainable energy solutions has accelerated the adoption of solar PV technology as a reliable alternative to fossil fuels. Solar energy is abundant, renewable and increasingly cost-effective, making it a viable solution for addressing energy security challenges, particularly in developing countries [3]. In 2022, solar PV represented two-thirds of the whole newly installed renewable energy capacity, and it is expected to surpass three terawatt capacity globally by 2027 after it reached its first terawatt in 2022 [3]. The global annual installed capacity of solar PV in 2023 was 1632GW [4].

Large-scale solar PV plants have been deployed across various regions to harness solar energy efficiently, but their long-term performance and technical reliability remain a critical area of analysis [4]. Assessing the technical performance of these plants is essential to optimizing energy output, improving efficiency and ensuring economic viability [5].

Due to the inherent unpredictability of solar systems, integrating storage and distributed generation into the grid has both technical and economic implications for the active distribution network [6]. Usually, energy devices are used to minimise grid power interchange and even out fluctuations in distributed power generation [7]. PV technology has emerged as one of the most promising sources of renewable energy due to its scalability, modularity and decreasing costs over the past decade [8].

In view of the importance of PV technology, the Lesotho government has built the Ramarothole Solar PV Plant, with an installed capacity of 30 MWp. Lesotho is one of the countries that have potential for solar generation, and it has an average horizontal global radiation of 5.5–7.2 kWh/m² [5]. The Ramarothole solar PV plant has set an example with a generation that makes it possible to harness solar energy for electricity. The renewable energy sources, particularly, have been identified as the primary means for meeting the growing energy demand [6]. However,

Lesotho continues to face a significant shortfall in electricity supply. In 2023/24, the country's annual electricity demand was approximately 970 GWh, while the installed generation capacity could only supply about 532 GWh. This resulted in a deficit of nearly 438 GWh, which is equivalent to 50% of the country's total demand [7], which was met through electricity imports [8] as indicated in Table 1.

Table 1: Lesotho Maximum electricity demand profile (MW) 2012-13-2023/24[8]

| Year | Maximum Demand (MW) | Installed Capacity (MW) | Imported Capacity (MW) | Capacity Deficit (%) |
|-------------|----------------------------|--------------------------------|-------------------------------|-----------------------------|
| 2012/13 | 147.63 | 74.7 | 72.93 | 49 |
| 2013/14 | 143 | 74.7 | 68.3 | 48 |
| 2014/15 | 149 | 74.7 | 74.3 | 50 |
| 2015/16 | 152.98 | 74.7 | 78.28 | 51 |
| 2016/17 | 161.84 | 74.7 | 87.14 | 54 |
| 2017/18 | 166.91 | 74.7 | 92.21 | 55 |
| 2018/19 | 177.31 | 74.7 | 102.61 | 58 |
| 2019/20 | 196.41 | 74.7 | 121.71 | 62 |
| 2020/21 | 180.57 | 74.7 | 105.87 | 58 |
| 2021/22 | 203.48 | 74.7 | 128.78 | 63 |
| 2022/23 | 222.12 | 74.7 | 147.42 | 66 |
| 2023/24 | 209.62 | 104.7 | 104.92 | 50 |

1.2 Statement of the problem

There is a lack of ground data and analysis of performance for commercial solar PV plants in Lesotho. Despite the importance of the Ramarothole Solar PV Plant, there is a shortage of studies that focus on the technical performance aspect of this important plant. Therefore, a detailed analysis of the plant's technical performance is necessary to determine its effectiveness and to identify opportunities for optimisation.

1.3 Aim and objectives of the study

The study aims to analyze the technical performance of the Ramarothole Solar PV Plant by evaluating the Key Performance Indicators (KPIs) to determine its efficiency, reliability and long-term sustainability.

The specific objectives are to:

1. Assess the technical performance of the plant using internationally recognized KPIs such as Performance Ratio (PR), Capacity Factor (CF) and Final Yield (Y_F).
2. Identify environmental and operational factors that influence the efficiency of the plant.
3. Derive lessons learned to inform the design, operation and management of future utility-scale of solar projects in Lesotho.

1.4 Research Questions

1. What is the average monthly and annual energy output and how does it compare to its rated capacity?
2. How do temperature, solar irradiance and seasonal variation affect the plant's PR and efficiency?
3. How accurate and reliable is the plant's monitoring system in providing data, detecting faults and performance anomalies?
4. What recommendations can be made to improve the plant's performance and inform stakeholders?

1.5 Justification

This study provides the first systematic technical assessment of the Ramarothole Solar PV Plant. The findings may inform policymakers, investors, developers, engineers and other stakeholders on the operational performance of the plant and guide evidence-based decisions for scaling up renewable energy deployment in Lesotho. Beyond national relevance, the study contributes to regional knowledge on solar PV performance in sub-Saharan Africa, where utility-scale plants are expanding rapidly [13].

1.6 Dissertation Structure

The dissertation is structured in five chapters. Chapter 1 presents the background, problem statement, aim and objectives. Chapter 2 reviews the existing literature on utility-scale PV systems, their components, performance factors and performance evaluation methodologies. Chapter 3 outlines the research methodology, the data collection procedures and the analysis

framework. Chapter 4 presents and discusses the results, while Chapter 5 draws conclusions and provides some recommendations.

2.0 LITERATURE REVIEW

2.1 Overview of literature

The literature review centers on solar PV energy systems, exploring the fundamental aspects of solar irradiance, PV components and the various factors that influence the performance of PV

systems. It delves into the technical performance of PV systems which are determined by a complex mix of factors including environmental conditions, design choices, materials used and operational/maintenance practices. The review covers a range of topics from the materials used in photovoltaic[9] and the effects of irradiation on semiconductors [10] to comprehensive evaluations of solar cell technologies, their loss mechanisms and efficiency enhancement strategies [11].

Studies also investigate specific issues, such as the effect of dust on system efficiency and mitigation techniques [12],[13], partial shading scenarios [14],[15] and moisture ingress in modules [16]. The literature reviews hybrid systems, such as combining solar PV with wind energy [17].

Progress in technology, the monitoring systems and predictive modeling have significantly enhanced the capability to optimise PV system performance. However, the field faces evolving challenges such as adapting to climate change and managing material degradation, necessitating continuous innovation and adaptation.

2.2 Solar energy systems Fundamentals of a PV system

A solar PV system is a system which captures the sun's energy and converts it into electrical energy using the photovoltaic effect. The photovoltaic effect is defined as the physical and chemical phenomenon responsible for converting solar radiation into voltage and electric current. A PV system employs energy conversion devices called solar cells, which are composed of atoms, just like every other physical substance [18],[19].The photoelectric effect seen in its solar cells is the only source of power for this technology. Sunlight is composed of photons or bundles of radiant energy; when the photons strike a PV cell, they may be reflected or absorbed. Electricity is generated only by the absorbed photons. When the photons are absorbed, their energy is transferred to electrons in the atoms of the solar cell [20].

PV is the most common form of solar energy. It uses solar panels made of photovoltaic cells to convert sunlight directly into electricity (see figure 1). Silicon is the most widely used material for solar cells [1]. The electricity generated can be used immediately or stored in batteries for later use.

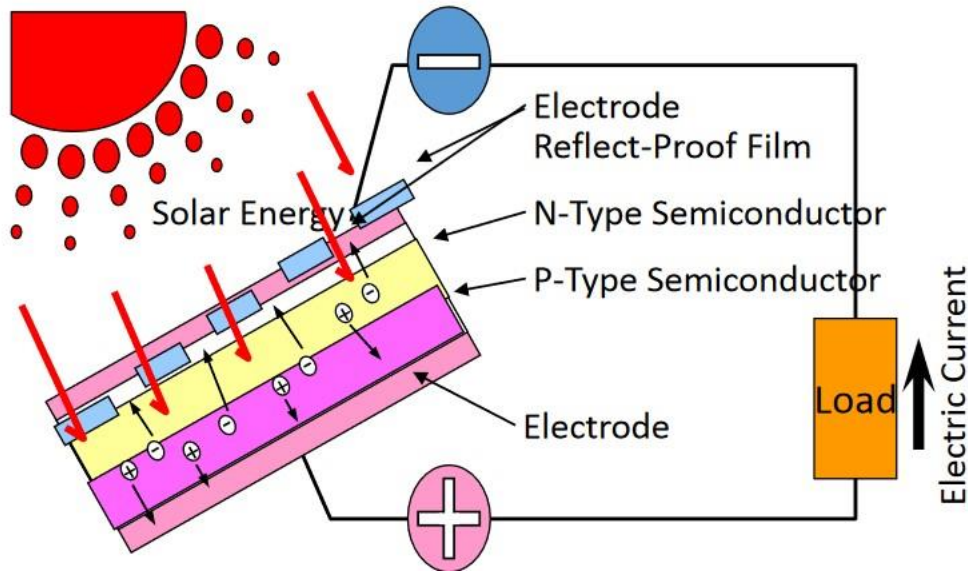


Figure 1: Photovoltaic cell [21].

There are three major types of PV solar cells, namely Monocrystalline, Polycrystalline and ThinFilm. They are made from silicon, which is the second most abundant element on Earth after oxygen. One of the silicon benefits is that it is a semiconductor; it has specific electrical properties.

The crystalline silicones are the oldest cells and are the mostly used PV. They are based on crystalline silicon wafers (small slices of silicon). There are two types of crystalline silicone (cSi), namely Monocrystalline and Polycrystalline, and they are referred to as first generation [23]. The monocrystalline and polycrystalline are known for their energy conversion efficiency and reliability. Their efficiency ranges are 16-22% and 15-18% respectively [23],[24] [25],[26]. Efficiency refers to the rate at which the solar cell converts sunlight into electricity.

Thin-film PV cells are also known as second generation and are more flexible than crystalline silicon. They are suitable for a wide range of applications. However, they generally have lower efficiencies than c-Si cells. [24]. They are made from very thin layers of semiconductor materials such as cadmium telluride, Amorphous silicon or copper indium gallium diSelenide. Amorphous Silicon (A-Si) and Cadmium Telluride (Cd-Te) are the two most popular forms [22].

2.3 Components of the PV system

A PV solar system typically consists of basic components such as PV array, inverters, batteries, inverter charge controller and cabling [27]. PV systems use a collection of components to create electrical energy, as seen in Figure 2.

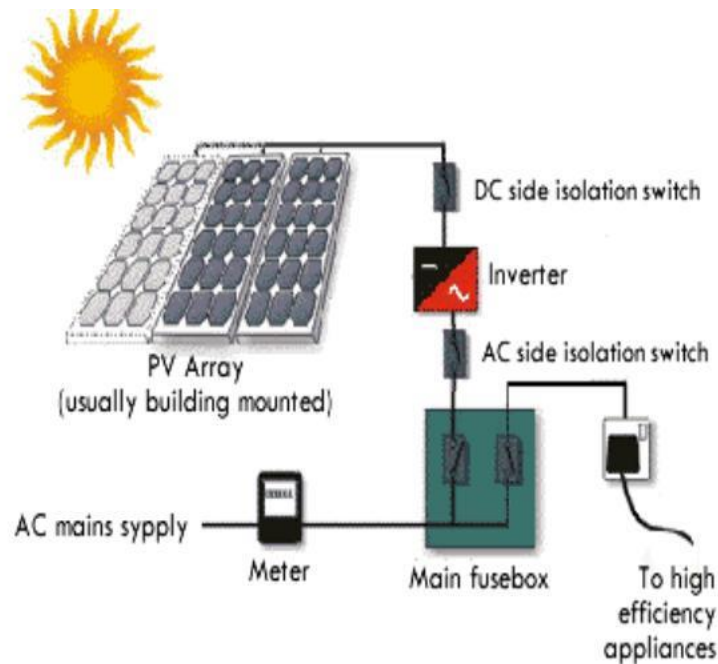


Figure 2: Basic PV system components.

2.3.1 PV array

PV cells absorb solar radiation and convert it into direct current (DC) electricity [12]. To increase capacity, individual cells are connected in a series and parallel to form modules, which are then grouped into arrays [13]. Although modules vary in size, material and the rated wattage, their common purpose is to transform solar energy into DC electricity. When combined into arrays, they provide the required electrical output for large-scale solar installations [14]. Figure 3 shows the PV array. Recent technological innovations have introduced bifacial PV modules, which capture sunlight from both the front and rear surfaces. This dual-surface absorption increases energy yield, particularly in environments with reflective surfaces such as snow or sand. Hayibo et al. [28] reported that bifacial modules achieved 15–20% higher energy gains compared to monofacial

modules in snowy environments, thus attributing this improvement to enhanced ground reflectivity [15]. The most common commercial modules have a series connection of 32 to 36 silicon cells to make it capable of charging a 12-V battery [29]. Several solar modules are connected in serial/parallel combinations in a frame to form solar panel. This is to increase the voltage/current ratings of the modules. When modules are connected in parallel, it is desirable to have each module maximum power production occur at the same voltage.



Figure 3: PV array

2.3.2 Inverter

Inverters play a critical role in PV systems by converting the DC generated by solar modules into AC suitable for grid integration. Their efficiency directly influences overall system performance [26]. Comparative studies of centralized and string inverters in large-scale PV plants have shown that string inverters perform better under partial shading and uneven irradiance conditions, achieving efficiency gains of up to 5% [17]. This demonstrates that inverter selection is central to ensuring a high performance in utility-scale PV systems [14].

2.3.3 Batteries

The intermittent nature of solar irradiance necessitates the integration of energy storage systems to ensure a stable energy supply. The battery plays an important role in the off-grid PV systems by storing excess electricity production. The excess electricity acts as backup electricity during limited sunlight so as to ensure a continuous supply of power [30]. According to Tripathi et al., batteries should normally be able to store enough electric energy for use at night and during nonsunny hours [31].

There are a few types of batteries that can be used in an off-grid solar system. They include:

- Lithium batteries – a battery type that can be stored without ventilation; they are safe to use, low maintenance, and have a long lifespan. These advantages make lithium batteries a popular choice for off-grid solar systems.
- Flooded lead acid batteries – a type of lead acid battery that requires maintenance, including adding distilled water monthly to replenish water lost during the normal charging process and continuous water level checking is critical. However, it is a more budget-friendly solution than lithium batteries.
- Sealed lead acid batteries – a lead acid battery type that does not require maintenance but offers a shorter lifespan than lithium batteries. It is usually more expensive than flooded batteries but still cheaper than lithium.

The choice of a battery depends on the energy needs and budget. Lead-acid batteries are commonly used in a solar PV system for residential applications because of their low cost. While lead-acid batteries are cheaper, lithium batteries can be more cost-effective in the long run [29]. A study which was conducted in the United States by Dorel et al. compared the performance of lead-acid and lithium-ion batteries in off-grid solar PV systems. The results indicated that lithium-ion batteries had higher charging efficiency and a longer lifespan compared to lead-acid batteries [32]. The choice of a battery is dependent on various factors such as battery type, charging rate, battery capacity and temperature management.

2.3.4 Charge controllers

A charge controller regulates the flow of electricity from solar panels to batteries. It controls the rate at which an electric current is added to or drawn from the batteries to avoid overcharging. This extends the battery life and ensures the overall efficiency and safety of the off-the-grid solar system. Charge controllers are also necessary for batteries in order to control the voltage and current which enter the system. The actual life cycle of a battery is determined by the number of discharge-charge cycles that the battery would experience before it fails [29], [31], [31].

2.3.5 Cabling

DC and AC cables are the primary components of a solar energy system, providing a connection from a PV module cell to the grid. AC and DC cables are single and double insulated, respectively. Copper wire in DC is a tinned copper wire that protects the wire from rusting and from environmental hazards [26]. Cables and wires guarantee that every component of the system is connected, creating pathways for power to move throughout the PV system. Together, these parts are intended to function and to accomplish the goal of producing electrical energy [31].

2.4 Different types of PV systems

There are three primary PV systems: grid-connected/grid-tied (with or without batteries), standalone or off-grid and hybrid [33],[34], [35], [36].

2.4.1 Grid-connected system

In a grid-connected system, also known as grid-tied solar PV system, there are solar panels, inverter, meter and power or grid utility. However, the main components may differ in detail. A typical grid-connected system is illustrated in Figure 4.

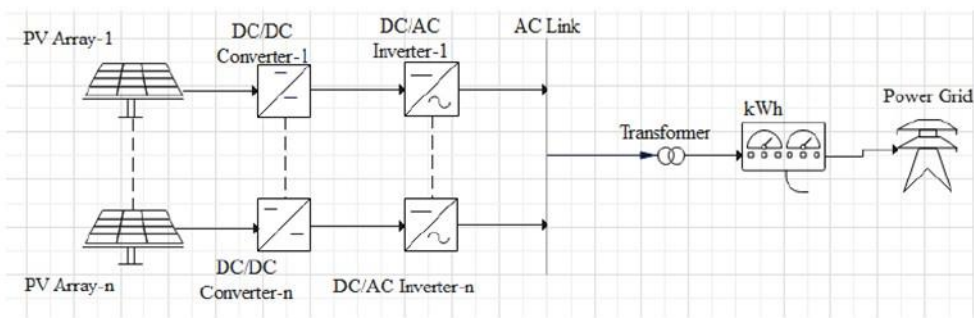


Figure 4: A grid-connected PV system [19].

The solar irradiation generates PV energy, which is DC in nature, and a DC-DC converter is used. It is an essential part of a grid-connected solar PV system because it can control the variation in the PV system and regulate the DC voltage. Inverters are used to convert a DC into an AC. This system is dependent on climatic conditions to generate electricity [33]. Most grid connected systems do not use battery because all the power generated can easily be absorbed by the grid. Moreover, there

is a metering system that is integrated into the setup which calculates the amount of electricity generated [37].

One of the setbacks of this system is that solar it is intermittent. Therefore, at night when there is no sun or when weather conditions are not conducive (because there is no support of solar energy) or there is a problem with the electricity grid, as is the case with planned or unplanned outages, in which electricity cannot be stored for immediate usage.

2.4.2. Off-grid system

The off-grid system, also known as standalone, consists of a solar cell, an inverter and a battery instead of being connected to the electricity grid. The battery is used as back up and this is shown in Figure 5. A generator may also be used as a back-up for power. If excess electricity is generated, it is stored in batteries, which will be used where there is no generation or at night. This system is more advantageous in remote areas or locations where there is limited or no accessibility to the utility grid [33], [34].

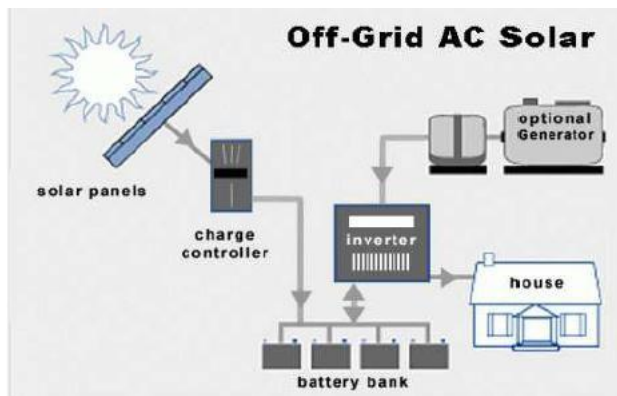


Figure 5: Off-grid PV system [33].

The off-grid system is more advantageous for rural communities or for remote areas where there is no access to grid electricity. In order to overcome this setback, a hybrid solar system may be integrated.

2.4.3 Hybrid system

A hybrid solar system combines the features of the grid-tied and off-grid solar systems as depicted in Figure 6. According to Badwawi et al., PV hybrid systems integrate a solar generator with

additional power sources, usually a diesel generator. However, they also occasionally use another renewable energy source such as a wind turbine. Typically, the PV system generator is sized to satisfy the base load need. This kind of connection is particularly common in countries with inadequate grid electricity[38]. Hybrid PV systems outperform standalone PV systems by 1.72–2.74% under weather conditions [39]. Integration with wind and battery storage in microgrids improves reliability and reduces battery stress, thus enhancing storage efficiency by 1.8 Wh [39]. Mobile PV systems, adaptable for off-grid or temporary use, are gaining traction for their flexibility and for carbon reduction potential.

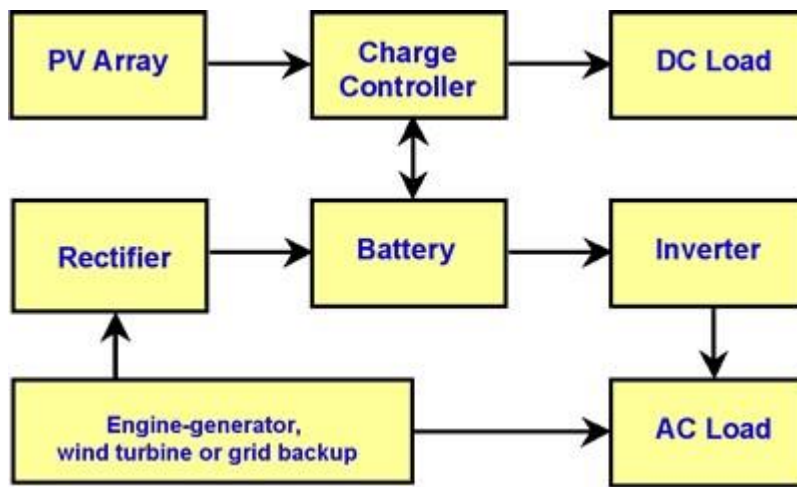


Figure 6: Hybrid PV system [23].

2.5 Factors affecting PV system performance

The technical performance of PV systems is influenced by a wide range of factors such as temperature, wind speed, solar irradiation, air pollution, etc., along with operational and maintenance factors[40], [41],[42], [43] which are related to environmental conditions.

2.5.1 Humidity

Humidity is defined as the amount of water vapour measured in the air. It may affect performance in a) deposition of water droplets on the surface of the solar cell module as it reflects or diffracts the sunlight away from the solar cells, and b) as a result of the metal used in the solar panel module for construction [40], [44]. Relative humidity is responsible for the accumulation of tiny water droplets and water vapour on solar panels from the atmosphere. The high humidity levels can lead

to corrosion of electrical contacts and degradation of encapsulation materials, particularly in tropical climates. Segbefia et al. investigated the role of moisture ingress in PV module degradation. Their study found that improved encapsulation materials and edge sealing techniques can extend module lifespans by up to 10 years [16]. Furthermore, PV modules may be corroded by prolonged exposure to a humid environment. In addition, Shaik et al. and Hassan et. al. stated that high relative humidity causes dust layers to accumulate on PV surfaces [44], [45]. This accumulation may lead to soiling, which in turn may negatively impact power output.

2.5.2 Dust and soiling

Dust accumulation is one of the most significant weather-dependent factors affecting PV system performance [34]. Studies show that efficiency can decline by up to 24% under typical dusty conditions [32] while in arid regions, the combination of dust and humidity may create mud-like layers that cause power losses as high as 60–70% [33]. Even small amounts of deposition can be harmful. For example, a dust density of only 1 g/m² has been linked to considerable annual energy losses [36]; efficiency reductions of up to 26% have been reported as dust density increased from 0 to 22 g/m² [37]. The magnitude of these losses depends on several variables, including dust type, climate, wind speed, the tilt angle of the PV modules and surface properties of the panels. For example, strong winds may remove accumulated dust, while slow wind speeds encourage build-up. Likewise, panels with lower tilt angles tend to collect more dust compared to steeper installations. These findings demonstrate that site-specific environmental conditions must be carefully considered in plant design and maintenance strategies to minimise dust-related performance losses. According to studies, the type of dust varies depending on the location and is affected by the surrounding conditions [46]. According to a previous study on the impact of a PV system performance, dust particles from industrial settings have been found to reduce the PV system's electric output by 80% [46]. Another study examined how airborne dust affected the operation of PV systems and found that efficiency may drop by as much as 65.8% [47]. According to other research, there is a greater likelihood of dust accumulation on panels in regions with high humidity [48]. When Zaihidee et al. examined the relationship between wind velocity and dust accumulation, they found that slow wind patterns increase dust collection on PV modules whereas fast wind would remove the dust that had accumulated on the panels. In a similar manner, a horizontal PV system installation is more prone to gather dust than one that is angled. Furthermore,

dust accumulation is more likely to occur on a sticky panel than on a less adhesive surface [48]. To lessen the impact of dust on performance, routine simple maintenance tasks such as cleaning the panels are necessary [14]. Dust accumulation, known as soiling, on PV modules, can block sunlight and reduce energy output. The impact of soiling in arid regions leads to reported daily energy losses of up to 0.3% without cleaning. It has been highlighted that the effectiveness of anti-soiling coatings and automated cleaning systems is reducing these losses [49].

2.5.3 Temperature

The temperature increases degrade efficiency by $0.05\%/^{\circ}\text{C}$, with a 20.22% drop observed when panels heat from 25°C to 45°C [50]. Wind, though cooling panels, exacerbates dust deposition [51]. Panel efficiency decreases by approximately 0.4–0.5% for every 1°C increase above the standard test condition (STC) temperature of 25°C . Advanced cooling techniques or heatresistant panels may be necessary to optimize performance. Kok et al. note that high temperatures exacerbate the effects of dust accumulation, further reducing energy yield [52]. Temperature has a dual effect, which is a) increased irradiance with heat and b) reduced voltage and efficiency [53] on PV performance. Higher temperatures increase electron mobility and they also reduce the open-circuit voltage, leading to lower overall efficiency. Studies indicate that in hot climates, every 1°C increase in module temperature above 25°C reduces efficiency by approximately 0.4–0.5% [19]. They recommend integrating the cooling systems or using temperature-tolerant materials to mitigate thermal losses.

2.5.4 Solar Irradiance

Solar irradiance is the power per unit area received from the Sun in the form of electromagnetic radiation, and it is a critical parameter for assessing the performance and efficiency of PV systems [54]. Solar irradiance is defined as the power per unit area received from the Sun in the form of electromagnetic radiation. It is a crucial parameter in various scientific and engineering applications [55]. Irradiance is measured in watts per square meter (W/m^2), it represents the energy potential of solar radiation at a given location and time. The understanding and accurate measurement of solar irradiance are essential in fields such as renewable energy generation, climate modeling and agricultural planning. A study by Qin et al. (2022) highlights the importance of high-resolution solar irradiance data for improving the accuracy of PV system performance models. They

emphasize the role of satellite-based measurements in complementing ground-based observations to capture spatial and temporal variations effectively [56].

Climate change is expected to alter solar irradiance patterns, posing challenges for long-term PV system planning [57]. The impacts of climate change on solar irradiance in the Middle East has been projected that there will be a 5–10% decrease in direct irradiance by 2050 due to increased cloud cover and aerosols [58]. Solar irradiance is the primary driver of PV system performance. Variations in direct and diffuse irradiance significantly impact energy generation [59]. Kreuwel et.al. demonstrated that high-frequency fluctuations in solar irradiance caused by cloud transients can reduce the efficiency of PV systems by up to 15%. They emphasise the importance of advanced forecasting models to mitigate these effects [60].

2.5.5 Shading Effects

One of the biggest contributors to PV systems' subpar performance is shading. This is because trees, nearby solar PV structures, utility poles, clouds or other obstructions momentarily block the sun rays; then the shadowing of PV panels results in uneven solar radiation [14], [62]. Research has demonstrated that when a portion of the PV array is shaded, its temperature drops relative to the unshaded portion of the array. The performance of the PV system declines as a result of the array heat distribution being uneven [15]. In addition, hot patches on modules are caused by shading conditions, which, in short-term, harm the cells [14]. According to a study by Dhimish et.al., power transmission changes and irregular panel voltage are caused by array shading. These have a significant impact on the converter's performance and, in turn, on the PV system's overall output [61]. Lou et al. (2023) studied the impact of shading on bifacial PV systems and proposed the use of bypass diodes and Module-Level Power Electronics (MLPE) to minimize the losses. Their results showed a 12% improvement in energy yield under partial shading conditions [62].

2.5.6 Design and Installation Optimization

Optimal design parameters, such as tilt angle adjustments (up to five times annually), can increase energy yield by 3.63% [63]. Solar tracking systems and electrical configuration optimizations (such as MPPT algorithms) further enhance energy capture [64]. Case studies in Malaysia demonstrate

that monocrystalline modules, paired with optimisers, elevate annual energy production from 88,986 MWh to 89,782 MWh [26].

2.5.7 Module Orientation and Tilt Angle

The orientation and tilt angle of PV modules determine the amount of solar radiation intercepted, directly influencing energy yield. Alhamer used optimization algorithms to determine the optimal tilt angle for fixed-tilt systems in various latitudes. They found that deviations of $\pm 10^\circ$ from the optimal angle could result in energy losses of up to 8% [65].

2.5.8 Technological Innovations in Cooling and Materials

Advanced cooling techniques are pivotal for mitigating temperature-induced losses. Active cooling, such as liquid-based systems) and passive cooling (such as radiative cooling) can lower panel temperatures by 1.8–50°C, improving efficiency by 1–50% [63]. Hybrid cooling systems, combining active and passive methods, balance cost and performance [59]. Material innovations like perovskites and tandem cells enhance light absorption and thermal stability, pushing commercial efficiencies toward 26–29% [64]. Bifacial modules, which capture sunlight on both sides, are increasingly deployed in large-scale plants for higher irradiance absorption [63].

2.5.9 Maintenance

Automated cleaning systems to address dust and soiling and manual cleaning schedules based on seasonal soiling rates, are emphasized as the importance of regular cleaning to maintain high energy yields [66]. Regular cleaning of PV modules is necessary to remove dust, dirt and other contaminants that reduce efficiency [67]. Pillai et al. analyzed the economic benefits of robotic cleaning systems in large-scale PV plants. They found that automated cleaning reduced labour costs by 30% while improving energy yield by 5% [68].

2.6 Performance indicators

Several indicators are commonly applied to evaluate the technical performance of utility-scale PV plants. These include final yield, reference yield, performance ratio capacity factor or capacity utilization factor (CUF), energy yield and degradation rate [22], [53], [56]. Studies such as Jahn et al. (2015), Fraunhofer ISE, and IRENA (2020) confirm that these metrics provide a reliable basis

for assessing operational efficiency and benchmarking performance across different plants and regions [69].

2.6.1 Energy Yield

The energy yield measures the total electricity generated by a PV plant per unit of installed capacity (kWh/kWp) and is the key indicator of system efficiency. It reflects how effectively a plant converts installed capacity into usable electrical output, considering site-specific solar resources, system design, and operational conditions. Winkler et al. [57] report that solar plants in South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) consistently meet or surpass their projected energy yields, highlighting both the robustness of the programme project design and the reliability of this metric for benchmarking performance across different installations.

2.6.2 Reference Yield

The reference yield (Y_R) is defined as the ratio of the total in-plane solar radiation received on the PV array surface (H_t , expressed in kWh/m²) to the reference irradiance under standard test conditions ($H_r = 1$ kW/m²). It represents the number of peak sun hours available to the PV system at a given location, independent of the plant actual performance. In practice, Y_R is used as a benchmark for estimating the maximum possible energy output based solely on solar resource availability. This parameter represents the number of hours of sunshine equivalent to solar irradiance at standard conditions and is dependent on the location, the orientation and the tilt angle of the PV plant [21], [29], [31]. It is described through the following Equation [32]:

$$Y_R = \frac{H_t(\text{Wh}/\text{m}^2)}{G_0(\text{W}/\text{m}^2)} \quad (1)$$

H_t = total horizontal irradiance on array plane (Wh/m²)

G_0 = global irradiance at STC (W/m²)

2.6.3 Final Yield

The final yield (Y_F) is defined as the ratio of the net AC energy output of a PV system (measured daily, monthly, or annually) to the peak power of the installed capacity under Standard Test

Conditions (STC: 1000 W/m² solar irradiance and 25°C cell temperature). It is expressed in units of kWh/kWp per day. Mathematically,

$$Y_F = \frac{E_{AC}(kWh)}{P_{PV,rated,STC}(kW)} \quad (2)$$

Where E_{AC} is the actual net AC energy output and $P_{PV,rated,STC}$ is the installed PV capacity under STC. Final yield provides a normalized measure of energy production that allows comparison across PV plants of different sizes and capacities. For example, two plants with different installed capacities can be directly compared using Y_F to determine which one performs more efficiently under its operating environment. Y_F is one of the critical indicators for assessing operational performance and identifying potential losses due to environmental factors, system inefficiencies or maintenance issues [32].

2.6.4 Performance ratio

The PR is one of the key metrics used to evaluate the efficiency of a solar PV plant. It is defined as the ratio of the actual energy output of the system to its theoretical maximum output under STC: 1000 W/m² irradiance and 25°C cell temperature. Equivalently, PR can be expressed as the ratio of the final yield to the reference yield, making it independent of both the size and the geographic location of the plant [27], [58],[60].

Fezzani et al. emphasize that PR is one of the most important indicators for characterizing the overall technical performance of PV power plants [27]. Historically, PR values have improved significantly, rising from about 50% in the 1980s to over 90% in the 2020s, largely due to advancements in PV components, better designs and reduced shading losses [22], [59]. While PR can approach high values, a perfect score of 100% is unrealistic because of unavoidable system losses, including thermal losses from module heating, inverter conversion inefficiencies, and wiring resistances [61]. PR can be expressed as follows:

$$PR = \frac{Y_F}{Y_R} \times 100 \quad (3)$$

2.6.5 Capacity factor

The CF is the measure or ratio of actual total annual energy output (E_{AC}) of the PV system injected into the grid to the energy that would be generated if the plant is operated at full capacity, P_{PV} , daily for 24 hours throughout the year [35], [41], [71]. The solar PV plant CF also depends on the global solar irradiance, cell conversion efficiency of the PV panels and operating time of the solar plant [41]. CF can therefore be expressed as follows:

$$CF = \frac{E_{AC}}{P_{PV, rated} \times T} \times 100 \quad (4)$$

E_{AC} = actual energy output (kWh)

P_{PV} = plant capacity (kW)

T = time in hours

In high-irradiance regions, utility-scale solar PV plants typically achieve CUF values in the range of 20–30%. Studies, including those by Ghosh et al. [63] confirm that large-scale PV plants in such regions consistently operate within this range, with many achieving values close to 25–30% under optimal conditions [62].

2.7 Performance metrics Methodologies/evaluation

Evaluating the technical performance of solar PV plants involves a mix of methodologies such as IEC 61724-1 Standard Monitoring, real-time Supervisory Control and Data Acquisition (SCADA) systems, modeling and simulation software such as pvsyst (simulation tools) [23].

3.0 METHODOLOGY

3.1 Plant description

The Ramarothole Solar PV Plant Phase I is a 30MWp facility without a Battery Energy Storage System (BESS). It is located in the Mafeteng district of Lesotho (29°47'50.88" S, 27°20'18.27" E) and was developed by the Chinese company TBEA Xinjiang New Energy. It is operated by the Lesotho Energy Generation Company (LEGCO) in the Ministry of Energy. The project reflects Lesotho's effort to reduce reliance on imported electricity and improves the national energy security. The absence of a BESS in this initial phase can be attributed to cost considerations and the priority placed on immediate power generation rather than storage, although future phases are expected to incorporate storage to improve grid stability.

The project was fully supported and financed by the Lesotho government because of its strategic importance in meeting the country’s growing electricity demand and closing the supply–demand gap. The ground-mounted solar panels occupy approximately 65 hectares of land, as shown in Figure 7.

Although the plant began generating electricity in June 2023, performance data are available only from November 2023 to March 2025. This is largely due to the commissioning process, which typically requires several months of testing, calibration and grid integration before stable and reliable data can be recorded. The available dataset therefore represents the period after the plant reached consistent operation, making it suitable for performance analysis. The solar PV plant performance has been evaluated for a year, January to December 2024.



Figure 7: Ramarothole ground mounted solar panels.

The Ramarothole Solar PV Plant is a utility-scale installation comprising 73,248 photovoltaic panels, each rated at 410 Wp, giving a total installed capacity of approximately 30 MWp. The panels are configured in strings of 28 modules, which are connected through 14 combiner boxes per inverter. The plant operates with eight inverter transformer stations, each equipped with inverters rated at 3,125 kW and producing an output voltage of 630 V, which is then stepped up to 33 kV by the inverter transformers. The main transformer further increases the voltage to 132 kV through a 31.5 MVA, 33/132 kV transformer, enabling efficient integration of generated power into the national grid.

The summary of the plant technical specifications is provided in Table 2. These details highlight not only the scale of the project but also its design for grid-level electricity injection, demonstrating that the plant is engineered to meet utility requirements for stability, reliability, and efficiency.

Table 2: Ramarothole solar PV plant details

| Item | Specification |
|---|----------------------|
| Number of panels | 73248 @410Wp/panel |
| Number of panels per string | 28 |
| Number of inverter transformer stations | 8 |
| Combiner boxes | 14 per inverter |
| Combiner box output voltage | 0-1500Vdc |
| Inverter rated power | 3125kW |
| Inverter output voltage | 630V |
| Inverter transformer output voltage | 33kV |
| Main transformer | 31.5MVA, 33kV/132kV |

3.2 Data collection

The dataset used for this study covers the period from January to December 2024, with measurements recorded at 30-minute intervals as provided in Table 3 for January. The data have been provided in both Excel and PDF formats by the plant personnel at LEGCO, and it includes the key operational parameters such as global in-plane solar irradiance, ambient temperature,

module temperature and net AC electricity output at the point of interconnection. These variables were selected because they form the basis for evaluating solar PV plant performance.

Site visits and meetings with plant personnel were conducted to verify the accuracy of the data and to clarify any operational issues that may influence performance results.

Table 3: Hourly production data profile at 30 minutes intervals

| # | Date | Time | Produced Power[MW] | Produced Energy [MWh] | Cumulative Produced Energy [MWh] |
|----|-------------------------|----------|--------------------|-----------------------|----------------------------------|
| 0 | Monday, 01 January 2024 | 12:30 am | 0,00 | 0 | |
| 1 | Monday, 01 January 2024 | 1:00 am | 0,00 | 0 | |
| 2 | Monday, 01 January 2024 | 1:30 am | 0,00 | 0 | |
| 3 | Monday, 01 January 2024 | 2:00 am | 0,00 | 0 | |
| 4 | Monday, 01 January 2024 | 2:30 am | 0,00 | 0 | |
| 5 | Monday, 01 January 2024 | 3:00 am | 0,00 | 0 | |
| 6 | Monday, 01 January 2024 | 3:30 am | 0,00 | 0 | |
| 7 | Monday, 01 January 2024 | 4:00 am | 0,00 | 0 | |
| 8 | Monday, 01 January 2024 | 4:30 am | 0,00 | 0 | 0,2 |
| 9 | Monday, 01 January 2024 | 5:00 am | 0,00 | 0 | 0,65 |
| 10 | Monday, 01 January 2024 | 5:30 am | 0,00 | 0 | 1,85 |
| 11 | Monday, 01 January 2024 | 6:00 am | 0,40 | 0,2 | 4,65 |
| 12 | Monday, 01 January 2024 | 6:30 am | 0,90 | 0,45 | 9,35 |
| 13 | Monday, 01 January 2024 | 7:00 am | 2,40 | 1,2 | 15,8 |
| 14 | Monday, 01 January 2024 | 7:30 am | 5,60 | 2,8 | 23,8 |
| 15 | Monday, 01 January 2024 | 8:00 am | 9,40 | 4,7 | 33,1 |
| 16 | Monday, 01 January 2024 | 8:30 am | 12,90 | 6,45 | 43,55 |
| 17 | Monday, 01 January 2024 | 9:00 am | 16,00 | 8 | 55,05 |
| 18 | Monday, 01 January 2024 | 9:30 am | 18,60 | 9,3 | 67,1 |
| 19 | Monday, 01 January 2024 | 10:00 am | 20,90 | 10,45 | 79,2 |
| 20 | Monday, 01 January 2024 | 10:30 am | 23,00 | 11,5 | 89,9 |
| 21 | Monday, 01 January 2024 | 11:00 am | 24,10 | 12,05 | 100,65 |
| 22 | Monday, 01 January 2024 | 11:30 am | 24,20 | 12,1 | 112,85 |
| 23 | Monday, 01 January 2024 | 12:00 pm | 21,40 | 10,7 | 125,35 |
| 24 | Monday, 01 January 2024 | 12:30 pm | 21,50 | 10,75 | 137,4 |
| 25 | Monday, 01 January 2024 | 1:00 pm | 24,40 | 12,2 | 149,15 |
| 26 | Monday, 01 January 2024 | 1:30 pm | 25,00 | 12,5 | 160,05 |
| 27 | Monday, 01 January 2024 | 2:00 pm | 24,10 | 12,05 | 170,2 |
| 28 | Monday, 01 January 2024 | 2:30 pm | 23,50 | 11,75 | 179,1 |
| | | | | | 183,25 |
| | | | | | 184,95 |
| | | | | | 186,2 |
| | | | | | 187,15 |
| | | | | | 187,8 |

| | | | | |
|----|--------------------------|----------|--------|-------|
| 37 | Monday, 01 January 2024 | 7:00 pm | 0,30 | 0,15 |
| 38 | Monday, 01 January 2024 | 7:30 pm | 0,00 | 0 |
| 39 | Monday, 01 January 2024 | 8:00 pm | 0,00 | 0 |
| 40 | Monday, 01 January 2024 | 8:30 pm | 0,00 | 0 |
| 41 | Monday, 01 January 2024 | 9:00 pm | 0,00 | 0 |
| 42 | Monday, 01 January 2024 | 9:30 pm | 0,00 | 0 |
| 43 | Monday, 01 January 2024 | 10:00 pm | 0,00 | 0 |
| 44 | Monday, 01 January 2024 | 10:30 pm | 0,00 | 0 |
| 45 | Monday, 01 January 2024 | 11:00 pm | 0,00 | 0 |
| 46 | Monday, 01 January 2024 | 11:30 pm | 0,00 | 0 |
| 47 | Tuesday, 02 January 2024 | 12:00 am | 0,00 | 0 |
| 29 | Monday, 01 January 2024 | 3:00 pm | 21,80 | 10,9 |
| 30 | Monday, 01 January 2024 | 3:30 pm | 20,30 | 10,15 |
| 31 | Monday, 01 January 2024 | 4:00 pm | 17,80 | 8,9 |
| 32 | Monday, 01 January 2024 | 4:30 pm | 8,30 | 4,15 |
| 33 | Monday, 01 January 2024 | 5:00 pm | 3,40 | 1,7 |
| 34 | Monday, 01 January 2024 | 5:30 pm | 2,50 | 1,25 |
| 35 | Monday, 01 January 2024 | 6:00 pm | 501,90 | 0,95 |
| 36 | Monday, 01 January 2024 | 6:30 pm | 1,30 | 0,65 |

187,95

3.3 Performance metrics

For the performance assessment, the collected data is applied to calculate internationally recognized indicators developed by the International Energy Agency (IEA). Specifically, irradiance data is used to determine the Y_R . AC output data is used to compute the Y_F and together these enable the calculation of the PR. Similarly, the total AC output relative to installed capacity is used to derive the CF, while the energy yield serves as a measure of electricity generated per unit of installed capacity.

Reference yield

By comparing Y_R with the actual energy yield of the plant, operators can assess how effectively the system converts available solar energy into electricity, thereby identifying performance gaps or inefficiencies.

Final Yield

A higher Y_F value indicates that the system is converting available solar resources more effectively into usable electricity.

Performance Ratio

Performance Ratio provides a practical benchmark for comparing system performance across different technologies and time periods.

Capacity Factor

The CF or CUF is a performance metric that measures the ratio of the actual energy generated by a solar PV plant over a specific period to the energy that could have been produced if the plant had operated continuously at its rated capacity. It is expressed as a percentage and provides a long-term indicator of system productivity by accounting for site-specific conditions such as solar irradiance, system design and operational efficiency.

Energy yield

High energy yield values suggest efficient utilisation of available solar radiation, while lower values may point to issues such as shading, soiling or equipment underperformance.

These indicators collectively provide a comprehensive evaluation of the technical performance of the plant.

Methodology evaluation

IEC 61724-1 Standard Monitoring is an international standard for PV system performance monitoring that ensures consistent tracking of key metrics such as PR, energy yield and system availability. This methodology ensures global consistency in performance evaluation, enabling fair comparisons across technologies and geographies, moreover, it aids benchmark performance across its array configuration and supports transparent reporting to stakeholders. The simulation tools use detailed site-specific inputs such as irradiance, temperature, tilt, losses so that they may simulate expected performance and it is widely used software. This method usually supports preconstruction feasibility studies and post-installation performance benchmarking. The Real-Time SCADA Monitoring systems collect live data on voltage, current, temperature and inverter status. Thus, it enables fault detection, predictive maintenance and operational optimization. For this study, real-time SCADA monitoring system and IEC 61724-1 Standard Monitoring approaches were applied to ensure accuracy, reliability and alignment with both global best practices and local grid conditions.

4.0 RESULTS ANALYSIS AND DISCUSSION

4.1 Energy production and yield

The annual energy generated for 2024 (January to December) is 59,326.40MWh. A summary of monthly production measured at 30 30-minute interval is presented in Table 4.

Table 4: Ramarothole solar PV monthly generated energy for 2024

| Month | Energy generated (MWh) |
|----------|------------------------|
| January | 5,201.67 |
| February | 5,330.14 |
| March | 5,302.76 |
| April | 3,978.88 |
| May | 5,000.77 |
| June | 4,086.89 |
| July | 5,167.39 |

| | |
|--------------|------------------|
| August | 5,556.89 |
| September | 4,800.09 |
| October | 5,716.50 |
| November | 4,679.97 |
| December | 4,504.46 |
| Total | 59,326.40 |

Analysis of the 2024 generation data shows that the plant recorded its lowest monthly energy outputs in April (3,978.88 MWh) and June (4,086.89 MWh), while May, although part of the same period, produced a relatively higher output of 5,000.77 MWh. By contrast, the highest generation occurred during the summer months from October to March, with October recording the peak output of 5,716.50 MWh. The variation in energy generation is strongly influenced by seasonal changes in solar irradiance. Winter months (April to June) are characterized by shorter days and reduced sunshine hours, which limit energy production. Conversely, the summer months benefit from longer daylight hours and higher solar irradiance, resulting in higher yields. The energy yield varies significantly between 3,978.88MWh and 5,716.50 MWh. This exhibits substantial fluctuations, with peak production occurring in the early months (January-March 2024) and towards the end of the year (November-December 2024), while significant drops are observed in mid-year (September-December 2024), with the exception of October, which has the highest yield, as indicated in Table 4. These variations suggest seasonal influences on solar irradiance, as well as possible equipment maintenance or system.

4.2 The Performance Metrics Calculation

To quantitatively assess the technical performance of the Ramarothole Solar PV Plant, this study applies a set of internationally recognized KPIs recommended by the IEA and aligned with IEC 61724-1 monitoring standards. These metrics, namely Y_F , PR, and CF provide a standardized framework for evaluating energy conversion efficiency, system reliability, and operational effectiveness, independent of plant size or geographic location. The calculations are based on high-resolution, 30-minute interval operational data provided by LEGCO for the full calendar year of 2024, including net AC energy output, in-plane solar irradiance, and ambient/module temperatures. The following subsections detail the methodology and results for each performance indicator,

offering a comprehensive evaluation of the plant's real-world performance under Lesotho's climatic conditions.

4.2.1 Final yield

The final yield reflects real-world performance after accounting for system losses and environmental factors. It is the actual energy delivered to the grid per unit of installed capacity. It is calculated as follows;

$$Y_F = \frac{56,529,050.00(kWh)}{30,000kW \cdot 1kW/m^2}$$

$$Y_F = 1884.3hrs$$

4.2.2 Reference yield

The reference could not be evaluated. This is because the annual average irradiation of 4345kWh/m² provided by the plant does not tally with the expected annual average of the location of the solar plant which is 2111.1kWh/m² as per the feasibility study of project phase 1 of 30MWp [71].

$$Y_R = \frac{H_i(Wh/m^2)}{G_o(W/m^2)}$$

4.2.3 Performance Ratio

The PR calculation is usually based on equation 3. However, the annual average irradiation of 4345kWh/m² is provided by the plant Figure 8. The data provided in figure 8 covers the period April 2024 to March 2025. Data from January to March 2024 was provided through an email. These numbers do not tally with the expected annual irradiance average of the location (Ramarothole, Mafeteng) of the solar plant which is 2111.1kWh/m² as per the feasibility study of project phase 1 of 30MWp [71].



**LESOTHO ELECTRICITY GENERATION
COMPANY (LEGCO)**

JUNE 2025

Table 1. Generated Energy and Total Radiation for 2024/25

| Month | Generated Energy (MWh) | Total Radiation (W/m ²) |
|--------------|------------------------|-------------------------------------|
| April | 3647.95 | 402.34 |
| May | 4789.2 | 466.01 |
| June | 3927.9 | 383.05 |
| July | 4903.4 | 468.78 |
| August | 5270.05 | 506.92 |
| September | 4576.95 | 467.567 |
| October | 5463 | 559.49 |
| November | 4324.05 | 522.77 |
| December | 4384.3 | 548.56 |
| January | 4799.25 | 540.51 |
| February | 3920.8 | 454.48 |
| March | 3810.65 | 416.71 |
| Total | 53817.6 | 478.10 |

Figure 8: irradiance data provided by LEGCO.

Therefore, as a result the reference yield could not be evaluated. This has led to the alternative calculation to be used; which is the actual energy output (AC)/energy production (DC) as indicated below. The average PR has been found to be 94.8%.

$$PR = \frac{56,259.09}{59,326.40} \times 100$$

PR=94.8%

=95%

The PR for Ramarothole solar PV plant fluctuates between 92% and 97%, with the annual average of 94.8%, indicating a relatively high operational efficiency. A notable peak is observed from October to March. It peaks in May, July and August. The notable peak of 97% is in December.

There is a notable drop in February, April and November to 92% and this suggests potential efficiency losses due to dust accumulation, inverter inefficiencies or ageing components. Regular maintenance, improved cooling mechanisms, and real-time performance monitoring are essential to sustaining a high-performance ratio, as shown in Table 5 and in Figure 9.

In comparison with the PR performance of PV plants in other countries, Ramarothole is still performing well. The 1.3MW Phakalane plant in Gaborone, Botswana, had an average of 79%, Algeria 82% and Moshoeshoe 1 International airport, Lesotho, was 70% [35], [41], [71]. From a recent study by the National University of Lesotho, simulations using PVsyst software showed the following for Ramarothole solar PV 30MWp: average PR calculated was 79.9% over the year, peak summer PR dips slightly due to the elevated module temperatures, winter PR improves as a result of cooler ambient conditions and lower thermal losses [72]. Figure 9 illustrates impact of temperature in relation to PR.

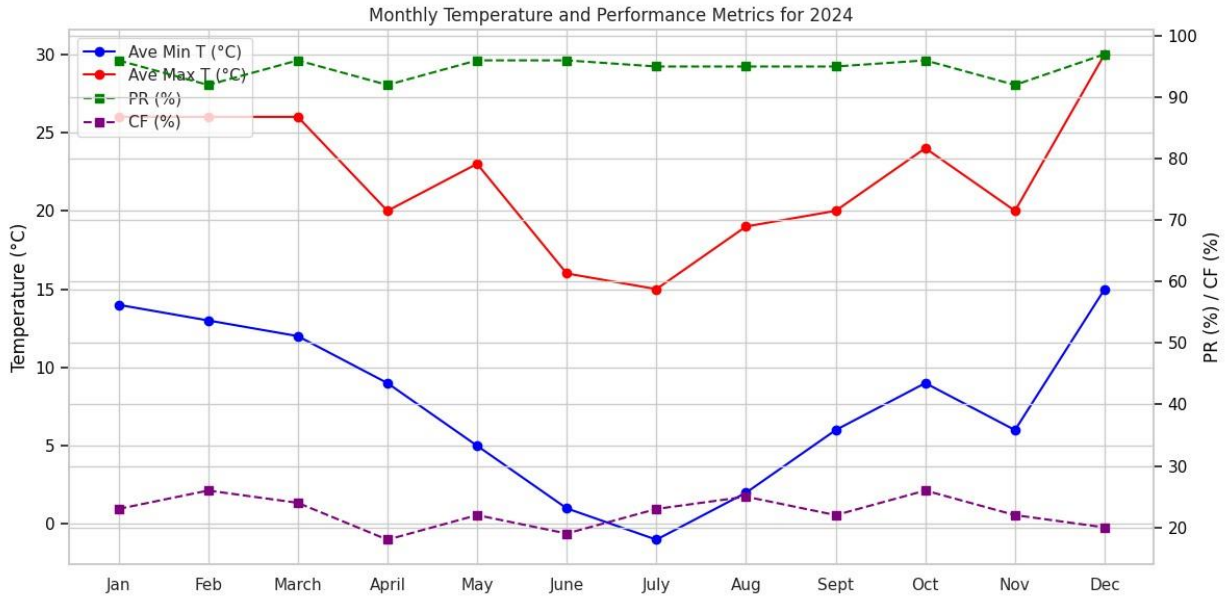


Figure 9: PR, CF in relation to temperature

4.2.4 Capacity Factor (CF)

The average CF has been calculated with monthly CFs (January to December 2024).

$$CF = \frac{E_{AC}}{P_{PV, rated} \times T} \times 100$$

$$CF = \frac{56,259.05}{30.03 MW \times 8760 hrs}$$

$$CF = \frac{56,259.05}{263,062.80}$$

$$CF = 21\%$$

The Capacity Factor (%) ranges between 17% and 24% with the annual average value of 21%, as stated in Table 5. This indicates improvements in plant efficiency, reduced down time or increased solar exposure. However, fluctuations throughout the year suggest that external environmental factors and operational inefficiencies continue to affect performance. Enhancing system reliability and minimizing technical losses would help improve the overall capacity factor.

The CF ranges for solar PV plants in Europe and Southern Africa are 10–15% and 18–25% respectively [73]. This range reflects the relatively lower solar irradiance across much of Europe,

especially in northern and central regions. Southern Africa benefits from high solar insolation/insulation, making the CFs significantly higher.

The SolarNPlus article explains that areas with high solar irradiation such as Lesotho, Namibia and South Africa enable higher CUFs due to better weather conditions and system design.

Temperature

The Ramarothole Site Conditions are as follows:

- Summer daytime temperatures: 25–32°C
- Winter daytime temperatures: 10–20°C
- Altitude: ~1,600 meters above sea level, which helps with cooling due to thinner air and wind exposure

Temperatures peak in December-January and dip in June-July

The high summer temperatures did not significantly reduce the PR, as indicated in Figures 9 and 10. This could be due to good thermal management.

According to Figure 10 there is a very weak positive relationship between the maximum average temperature and the PR with +0.24 correlation (r). This is because the hotter months tend to have slightly higher PR; thus the effect of temperature is minimal. The average minimum temperatures essentially have no relationship with a +0.02 correlation. This indicates that a lower temperature does not influence PR.

The average maximum temperature also has a weak positive relationship with CF as indicated by a correlation of +0.23. The CF rises a little in the hotter months. Average minimum temperatures also have a minimal effect on CF, with a correlation of +0.11.

There is no strong negative correlation with high temperatures, even at 30 °C in December. PR is highest at 97 %, which indicates good thermal management and minimal heat-related efficiency loss. On the other hand, CF is more influenced by solar resources such as irradiance and length of the day than by the temperature itself. Winter months have a good PR but lower CF due to shorter days.

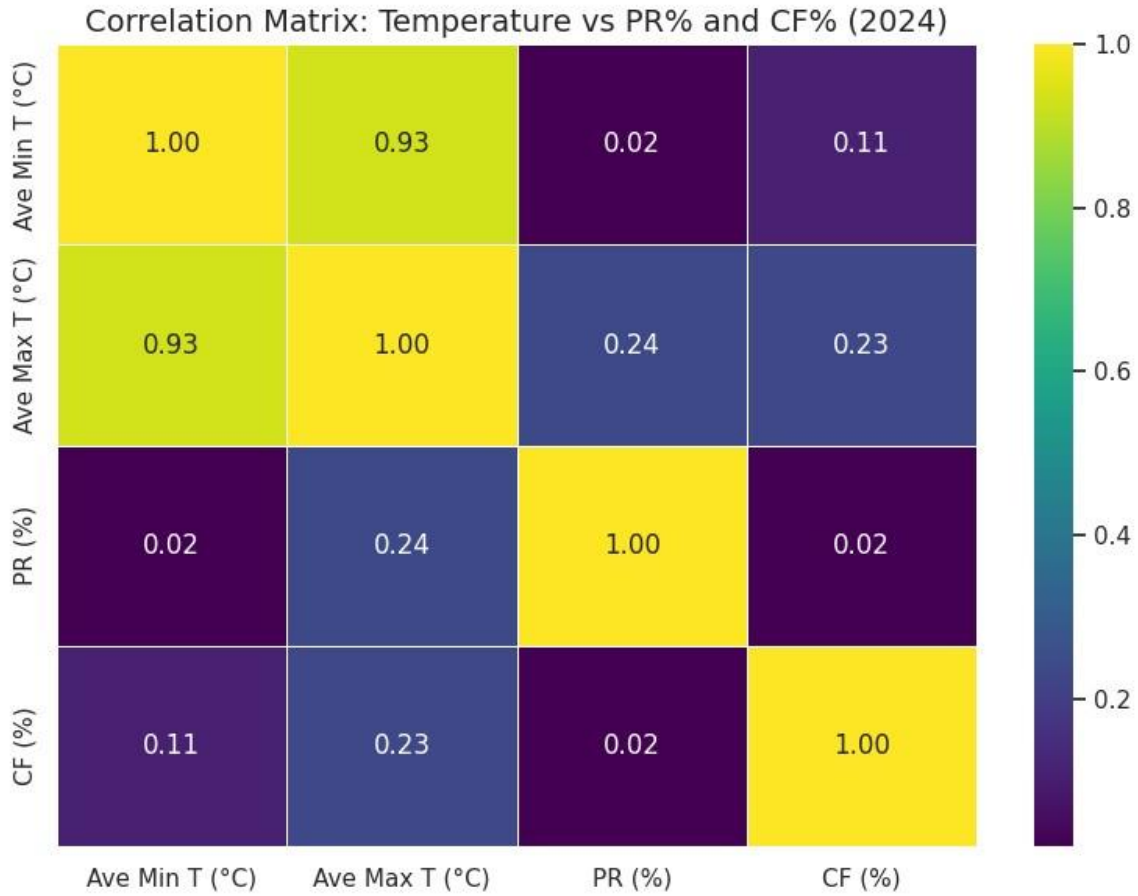


Figure 10: Heat map showing the correlation between temperature vs PR and CF

Table 5: Ramarothole solar PV plant 2024 energy production, PR, CF and T^o)

| Parameter | | Months | | | | | | | | | | | Annual | |
|--------------------------------|------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|------------------|
| | | Jan | Feb | March | April | May | June | July | Aug | Sept | Oct | Nov | | Dec |
| Energy yield (MW) | | 4978 | 4915.05 | 5079.2 | 3647.95 | 4789.2 | 3927.9 | 4903.40 | 5270.05 | 4576.95 | 5463 | 4324.05 | 4384.30 | 56,259.05 |
| Energy production (MWh) | | 5,201.67 | 5,330.14 | 5,302.76 | 3,978.88 | 5,000.77 | 4,086.89 | 5,167.39 | 5,556.89 | 4,800.09 | 5,716.50 | 4,679.97 | 4,504.46 | 59,326.40 |
| Performance Ratio (PR) | | 95.70% | 92% | 96% | 92% | 96% | 96% | 95% | 95% | 95% | 96% | 92% | 97% | 94.83% |
| Capacity Factor (CF) | | 22.28% | 24% | 23% | 17 | 21% | 18% | 22% | 24% | 21% | 24% | 20% | 20% | 21.39% |
| Temperature (°C) | Min | 11-16 | 11-16 | 7-16 | 1-12 | -2-9 | -3-9 | -5-5 | -4-8 | -2-12 | -1-16 | -2-11 | 9-18 | |
| | Max | 22-30 | 22-30 | 21-32 | 14-24 | 18-26 | 6-10 | 8-21 | 13-25 | 9-25 | 11-35 | 12-26 | 24-36 | |

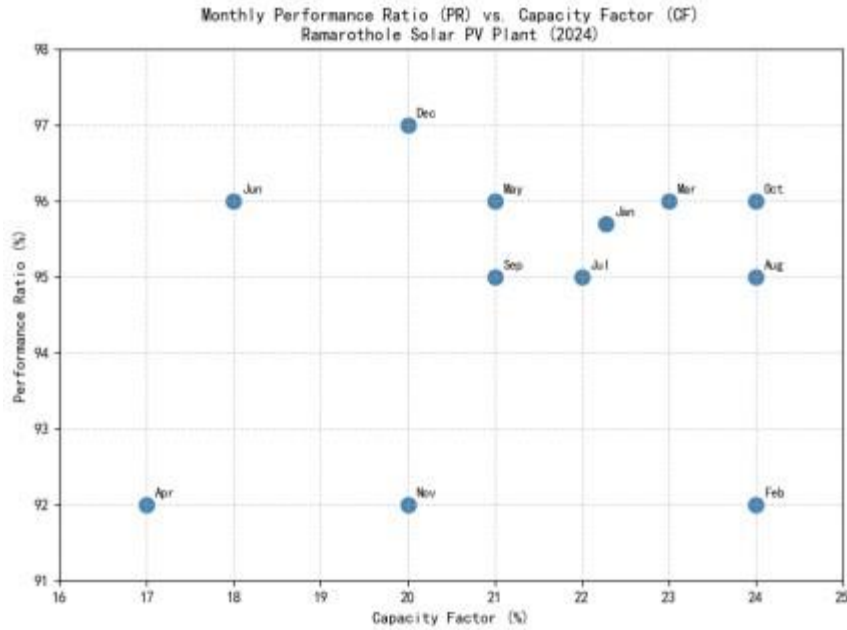


Figure 11: Monthly PR vs CF for Ramarothole Solar PV plant (2024)

Figure 11 presents a scatter plot of the monthly PR versus the monthly CF for the year 2024. The plot reveals a weak but positive correlation between the two metrics, which aligns with the theoretical expectation that a more efficient plant (higher PR) should, all else being equal, convert a greater proportion of available solar energy into grid electricity (higher CF). However, the scatter and the presence of distinct outliers provide critical insights into the operational dynamics of the plant.

The Main Cluster: The majority of the data points (e.g., January, March, May, July, August, October) form a central cluster with PR values between 95% and 96% and CF values between 21% and 24%. This cluster represents periods of stable, high-performance operation where high efficiency directly translates to high energy productivity.

The Low-PR Outliers (February, April and November): These months are characterized by a PR of 92% but maintained CFs of 20-24%. This pattern suggests that while the amount of solar resource (irradiance) was sufficient for decent energy production, the system experienced significant efficiency losses. This is a strong indicator of issues such as dust and soiling, which block sunlight and reduce efficiency without necessarily reducing the number of sunlight hours, or transient inverter inefficiencies. The fact that these months are not the ones with the lowest CF confirms that the primary constraint was not a lack of sun, but a loss in conversion efficiency.

The High-PR Outlier (December): December recorded the highest PR of the year 97% but a relatively lower CF of 20%. This scenario indicates that during December, the plant operated at peak efficiency, but the total energy productivity was limited. The most plausible explanation for this is the higher frequency of cloud cover or rain typical of Lesotho's summer thunderstorms. The system was highly effective at converting the available sunlight into power, but the total available solar energy was less than in months like October. This is further supported by December's high average temperatures; the maintained high PR underscores the effectiveness of the plant's thermal management at high altitudes, even when energy yield is seasonally constrained. This scatter plot analysis powerfully demonstrates that PR and CF, while related, diagnose different aspects of plant performance. PR is the ultimate measure of system health and operational efficiency, while CF is a measure of energy productivity relative to the installed capacity, heavily influenced by the solar resource. Investigating their relationship allows for a more nuanced understanding than either metric can provide alone, directly pinpointing months that warrant further investigation into specific operational or environmental issues.

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter synthesizes the analytical journey undertaken in this dissertation, which set out to address a critical knowledge gap in Lesotho's renewable energy landscape. The absence of empirical, validated technical performance data for utility-scale solar PV installations. The Ramarothole Solar PV Plant which is Lesotho's first grid-connected, 30 MWp facility, serves as both the focal point and the proving ground for this investigation. By applying internationally recognized performance indicators recommended by the IEA, this study not only evaluates the plant's operational efficiency but also establishes a foundational benchmark for future solar projects in the country and the broader sub-Saharan region.

5.2 Summary of the Dissertation's Journey

5.2.1 Introduction and Problem Foundation

The dissertation began by contextualizing Lesotho's persistent energy deficit where nearly 50% of national demand is met through imports and highlighting the urgent need to harness indigenous renewable resources. Despite the commissioning of the Ramarothole Solar PV Plant, there existed no systematic, data-driven assessment of its technical performance. This gap formed the core problem statement. The chapter articulated the study's aim: to evaluate the plant's efficiency, reliability, and sustainability using KPIs such as PR, CF, and Y_F . Four research questions were formulated to guide the investigation, emphasizing energy output, environmental influences, data reliability, and actionable recommendations.

5.2.2 Literature Review and Gap Identification

A comprehensive review of global and regional literature established the theoretical and empirical foundations for PV performance evaluation. It covered PV system fundamentals, component functionalities, and the multifaceted factors affecting performance, including temperature, dust, irradiance, and maintenance practices. Critically, the review revealed a scarcity of validated, long-term performance studies from sub-Saharan Africa, and none from Lesotho. This gap justified the originality and necessity of the present work, positioning it not only as a national case study but also as a regional contribution to sustainable energy knowledge.

5.2.3 Methodology

This chapter detailed the methodological framework, grounded in IEA and IEC 61724-1 standards. It described the Ramarothole plant's technical configuration (30 MWp, 73,248 monocrystalline panels, 8 inverter stations) and the data acquisition process. High-resolution (30minute interval) operational data for the full calendar year of 2024, including AC output, ambient and module temperatures, and irradiance were obtained from LEGCO. The chapter outlined the calculation protocols for all KPIs and emphasized the use of real-time SCADA monitoring aligned with global best practices.

5.2.4 Results Analysis and Discussion

Chapter Four presented the empirical findings: total annual generation of 59,326.40 MWh, an annual average PR of 94.8%, CF of 21%, and Final Yield of 1,884.3 hours. These metrics were contextualized against regional benchmarks for PR (e.g., Botswana at 79% and Algeria at 82%), revealing Ramarothole's superior performance. Seasonal trends were analyzed, linking energy fluctuations to irradiance and day length rather than temperature, thanks to Lesotho's highaltitude cooling effect. Minor PR dips (to 92%) in February, April, and November were noted as potential indicators of transient operational issues. The plant generated 59,326.40 MWh of electricity in 2024.

Overall, the Ramarothole plant stands as a successful model of utility-scale solar deployment in Lesotho, demonstrating that large PV installations can operate reliably and efficiently in the local environment, thereby contributing meaningfully to national energy security.

5.3 Synthesis of Key Findings and Fulfillment of Objectives

This dissertation makes three explicit contributions to knowledge and practice:

First Validated Dataset: It provides the first publicly documented, validated annual technical performance dataset for a utility-scale solar PV plant in Lesotho, a milestone for national energy planning and academic research.

Benchmark Establishment: By calculating PR, CF, and Y_F using real operational data, the study establishes performance benchmarks that surpass regional averages, proving that highefficiency solar deployment is achievable under Lesotho's climatic conditions.

Evidence-Based Policy Input: The findings directly inform national strategies for renewable energy expansion, grid integration, and plant maintenance, fulfilling the study’s objective to bridge technical analysis with policy relevance.

All original research objectives were met:

Objective 1 (KPI assessment) was fulfilled through rigorous calculation and contextualization of PR, CF, and Y_F .

Objective 2 (factor identification) was addressed by correlating performance with temperature, seasonality, and operational anomalies.

Objective 3 (lessons for future projects) is embedded in the robust recommendations that follow.

5.4 Recommendations

In order to sustain and enhance the performance of the Ramarothole plant and to inform future solar projects in Lesotho the following recommendations are proposed:

Enhance Irradiance Monitoring Infrastructure: Install calibrated, on-site pyranometers to provide accurate, real-time solar irradiance data. This will enable precise calculation of Y_R and PR per IEC 61724-1 standards and support performance benchmarking.

Implement a Structured Preventive Maintenance Program: Given the potential impact of dust and soiling especially during dry, low-wind periods, establish a seasonal cleaning schedule informed by soiling rate measurements. Consider piloting automated or robotic cleaning systems to reduce labor costs and improve consistency.

Adopt Advanced Monitoring and Diagnostics: Integrate Module-Level Power Electronics (MLPE) or string-level monitoring to quickly detect underperforming modules, shading issues, or inverter faults. This will reduce downtime and improve overall system availability.

Align Plant Operations with National Energy Planning: Coordinate generation profiles with Lesotho's demand patterns and grid stability requirements. Future phases should consider integrating BESS to enable dispatchable solar power and support grid resilience during evening peak demand.

Conduct Long-Term Degradation Studies: Initiate a multi-year performance tracking program to assess annual degradation rates of PV modules under local conditions. This data will be invaluable for financial modeling and warranty validation in future projects.

Develop Local Technical Capacity: Invest in training for LEGCO engineers and technicians on PV system diagnostics, data validation, and performance analysis to reduce reliance on external consultants and ensure sustainable plant management.

Publish and Share Performance Data Nationally: Make anonymized operational data available to researchers, policymakers, and developers to build a national knowledge base on solar PV performance, supporting evidence-based renewable energy policy and investment.

By implementing these measures, Lesotho can not only optimize the Ramarothole plant's output but also establish a replicable framework for high-performance, utility-scale solar deployment across the country, accelerating progress toward energy independence and climate resilience.

REFERENCES

- [1] J. A. Luceño-Sánchez, A. M. Díez-Pascual, and R. Peña Capilla, “Materials for Photovoltaics: State of Art and Recent Developments,” *International Journal of Molecular Sciences*, vol. 20, no. 4, Art. no. 4, Jan. 2019, doi: 10.3390/ijms20040976.
- [2] OECD/IEA, “Renewables 2017: Analysis and Forecasts to 2022.” International Energy Agency Paris, France, 2017.
- [3] P. Borah, L. Micheli, and N. Sarmah, “Analysis of Soiling Loss in Photovoltaic Modules: A Review of the Impact of Atmospheric Parameters, Soil Properties, and Mitigation Approaches,” *Sustainability*, vol. 15, no. 24, p. 16669, Dec. 2023, doi: 10.3390/su152416669.
- [4] G. Masson, E. Bosch, A. Van Rechem, and M. de l’Epine, “Snapshot of Global PV Markets -2023,” 2024.
- [5] B M Tael, L Mokhutšoane, and Himanshu Narayan, “Solar energy resources potential and sustainable production of biomass energy in Lesotho,” 2010, *Unpublished*. doi: 10.13140/RG.2.1.2962.0882.
- [6] H. Liu *et al.*, “Effect of Solar Farms on Soil Erosion in Hilly Environments: A Modeling Study From the Perspective of Hydrological Connectivity,” *Water Resources Research*, vol. 59, no. 12, p. e2023WR035067, Dec. 2023, doi: 10.1029/2023WR035067.
- [7] “GET.transform-Lesotho-ESTO-Aug-2024.pdf.” Accessed: Aug. 29, 2025. [Online]. Available: <https://www.get-transform.eu/wp-content/uploads/2024/08/GET.transformLesotho-ESTO-Aug-2024.pdf>
- [8] “LEWA-Annual-Report-2023-24.pdf.”
- [9] J. A. Luceño-Sánchez, A. M. Díez-Pascual, and R. P. Capilla, “Materials for Photovoltaics: State of Art and Recent Developments,” www.mdpi.com. Accessed: Sept. 03, 2025. [Online]. Available: <https://www.mdpi.com/1422-0067/20/4/976>
- [10] A. Hammach, “Study of the type inversion of the semiconductor in irradiated solar cells,” doctoral, Université Mohamed Khider - Biskra, 2018. Accessed: June 03, 2025. [Online]. Available: <http://thesis.univ-biskra.dz/3855/>
- [11] A. M. Oni, A. S. M. Mohsin, Md. M. Rahman, and M. B. Hossain Bhuiyan, “A comprehensive evaluation of solar cell technologies, associated loss mechanisms, and efficiency enhancement strategies for photovoltaic cells,” *Energy Reports*, vol. 11, pp. 3345–3366, June 2024, doi: 10.1016/j.egyr.2024.03.007.
- [12] R. K. Saini *et al.*, “Effects of dust on the performance of solar panels – a review update from 2015–2020. Energy and Environment.,” <https://journals.sagepub.com/>, vol. 34, no. 6, 2023, Accessed: Sept. 03, 2025. [Online]. Available: <https://journals.sagepub.com/doi/abs/10.1177/0958305X221105267>
- [13] Yogender *et al.*, “Effects of Dust Accumulation on Energy Efficiency Losses in PV Systems,” in *Advances in Mechanics of Materials*, M. N. Alam, A. H. Khan, and M. Talha, Eds., Singapore: Springer Nature, 2025, pp. 1–11. doi: 10.1007/978-981-96-6732-1_1.
- [14] J. Ma, X. Pan, K. L. Man, X. Li, H. Wen, and T. On Ting, “Detection and Assessment of Partial Shading Scenarios on Photovoltaic Strings,” *IEEE Transactions on Industry Applications*, vol. 54, no. 6, pp. 6279–6289, Nov. 2018, doi: 10.1109/TIA.2018.2848643.

- [15] A. Mudlapur, V. V. Ramana, R. V. Damodaran, V. Balasubramanian, and S. Mishra, "Effect of Partial Shading on PV Fed Induction Motor Water Pumping Systems," *IEEE Transactions on Energy Conversion*, vol. 34, no. 1, pp. 530–539, Mar. 2019, doi: 10.1109/TEC.2018.2876132.
- [16] O. K. Segbefia, A. G. Imenes, and T. O. Sætre, "Moisture ingress in photovoltaic modules: A review," *Solar Energy*, vol. 224, pp. 889–906, Aug. 2021, doi: 10.1016/j.solener.2021.06.055.
- [17] Mohammad Abusara, Tapas Mallick, and Rashid Al Badwaw, "A Review of Hybrid Solar PV and Wind Energy System: Smart Science:," vol. 3, no. 3, pp. 127–138, 2015.
- [18] M. Sunitha, "Performance Evaluation of 10MWp solar power plant at Shiva Samudram power station".
- [19] M. Dida, S. Boughali, D. Bechki, and H. Bouguettaia, "Experimental investigation of a passive cooling system for photovoltaic modules efficiency improvement in hot and arid regions," *Energy Conversion and Management*, vol. 243, p. 114328, Sept. 2021, doi: 10.1016/j.enconman.2021.114328.
- [20] V. R. Pannase and H. B. Nanavala, "A review of PV technology power generation, PV material, performance and its applications," in *2017 International Conference on Inventive Systems and Control (ICISC)*, Jan. 2017, pp. 1–5. doi: 10.1109/ICISC.2017.8068655.
- [21] "Basic-Solar-PV-System-Types.pdf." Accessed: July 21, 2025. [Online]. Available: <https://www.apec.org/docs/default-source/Publications/2016/2/Training-Curriculum-forSolar-PV-Installers-and-System-Designers/TOC/Basic-Solar-PV-System-Types.pdf>
- [22] M. V. Dambhare, B. Butey, and S. V. Moharil, "Solar photovoltaic technology: A review of different types of solar cells and its future trends," *J. Phys.: Conf. Ser.*, vol. 1913, no. 1, p. 012053, May 2021, doi: 10.1088/1742-6596/1913/1/012053.
- [23] B. Laumert, R. E. G. Mata, and S. Trevisan, "Utility-Scale Solar Power Plants with Storage: Cost Comparison and Growth Forecast Analysis".
- [24] A. C. Lazaroiu, M. Gmal Osman, C.-V. Strejoiu, and G. Lazaroiu, "A Comprehensive Overview of Photovoltaic Technologies and Their Efficiency for Climate Neutrality," *Sustainability*, vol. 15, no. 23, p. 16297, Jan. 2023, doi: 10.3390/su152316297.
- [25] J. M. Xavier, "Performance Analysis of a PV Grid-connected System at the Universidade Nacional Timor Lorosa'e".
- [26] L. Sundaram, and Y. I. Go, "Correlations of System Degradation, Losses and Significant Parameters for 49 MW Large Scale Solar Plant with Real Site Data Validations - Clean Energy and Sustainability - Full-Text HTML - SCIEPublish." Accessed: June 03, 2025. [Online]. Available: <https://www.sciepublish.com/article/pii/353>
- [27] L. Sundaram and Y. I. Go, "Correlations of System Degradation, Losses and Significant Parameters for 49 MW Large Scale Solar Plant with Real Site Data Validations," *Clean Energy and Sustainability*, vol. 3, no. 1, p. 10022, Nov. 2024, doi: 10.70322/ces.2024.10022.
- [28] K. S. Hayibo, A. Petsiuk, P. Mayville, L. Brown, and J. M. Pearce, "Monofacial vs bifacial solar photovoltaic systems in snowy environments - ScienceDirect." Accessed: June 05, 2025. [Online]. Available: <https://www.sciencedirect.com/science/article/abs/pii/S0960148122006917>

- [29] Bitrus, I, Abba, H, and Onwuasoanya, N.C, “Design Analysis of a Typical Off-Grid Solar Power System and The Need for Adequate Maintenance: A Case Study of a Two Bedroom Flat Apartment,” vol. 4, no. 4, 2020.
- [30] Y.-X. Huang, Z.-Y. Shu, Z.-Q. Liu, Y. Cai, W.-W. Wang, and F.-Y. Zhao, “Transient cooling performance and parametric characteristic of active–passive coupling cooling system integrated air-conditioner, PV-PCM envelope, and ice storage,” *Energy and Buildings*, vol. 329, p. 115296, Feb. 2025, doi: 10.1016/j.enbuild.2025.115296.
- [31] A. K. Tripathi *et al.*, “Integration of Solar PV Panels in Electric Vehicle Charging Infrastructure: Benefits, Challenges, and Environmental Implications,” *Energy Science & Engineering*, vol. 13, no. 4, pp. 2135–2152, 2025, doi: 10.1002/ese3.70014.
- [32] S. Dorel, M. Gmal Osman, C.-V. Strejoiu, and G. Lazaroiu, “Exploring Optimal Charging Strategies for Off-Grid Solar Photovoltaic Systems: A Comparative Study on Battery Storage Techniques,” *Batteries*, vol. 9, no. 9, Art. no. 9, Sept. 2023, doi: 10.3390/batteries9090470.
- [33] T. Maddileti and L. Cherukuri, “REVIEW ON TYPES OF SOLAR POWER SYSTEMS,” vol. 10, no. 10, 2019.
- [34] W. Ali, H. Farooq, A. U. Rehman, Q. Awais, M. Jamil, and A. Noman, “Design Considerations of Stand-Alone Solar Photovoltaic Systems,” in *2018 International Conference on Computing, Electronic and Electrical Engineering (ICE Cube)*, Nov. 2018, pp. 1–6. doi: 10.1109/ICECUBE.2018.8610970.
- [35] L. Gobodi, D. Setlhaolo, and J. D. Sakala, “Performance Metrics of a Grid Connected Photovoltaic Plant: A Practical Case of the 1.3MW Phakalane Plant in Gaborone, Botswana,” vol. 98, no. 1.
- [36] “Classification of photovoltaic system | Download Scientific Diagram,” ResearchGate. Accessed: July 21, 2025. [Online]. Available: https://www.researchgate.net/figure/Classification-of-photovoltaic-system_fig1_342147674
- [37] S. N. Tackie, “A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES OF NEAR EAST UNIVERSITY”.
- [38] R. A. Badwawi, Abusara ,Mohammad, and T. and Mallick, “A Review of Hybrid Solar PV and Wind Energy System,” *Smart Science*, vol. 3, no. 3, pp. 127–138, Jan. 2015, doi: 10.1080/23080477.2015.11665647.
- [39] E. Jacob and H. Farzaneh, “Modeling and performance evaluation of hybrid photovoltaic thermal, wind, and battery microgrids using optimization and dynamic simulation | Scientific Reports.” Accessed: June 04, 2025. [Online]. Available: <https://www.nature.com/articles/s41598-025-95149-w>
- [40] Professor in the Department of Civil Engineering, Institute of Technical Education and Research, Siksha ‘O’ Anusandhan (Deemed to be University), Bhubaneswar (Odisha), India and Dr. M. Ranjan Das*, “Effect of Different Environmental Factors on Performance of Solar Panel,” *IJITEE*, vol. 8, no. 11, pp. 15–18, Sept. 2019, doi: 10.35940/ijitee.J9889.0981119.
- [41] A. Fezzani *et al.*, “Performances Analysis of Three Grid-Tied Large-Scale Solar PV Plants in Varied Climatic Conditions: A Case Study in Algeria,” *Sustainability*, vol. 15, no. 19, p. 14282, Sept. 2023, doi: 10.3390/su151914282.

- [42] H. A. Kazem and M. T. Chaichan, “Experimental analysis of the effect of dust’s physical properties on photovoltaic modules in Northern Oman,” *Solar Energy*, vol. 139, pp. 68–80, Dec. 2016, doi: 10.1016/j.solener.2016.09.019.
- [43] E. Skoplaki and J. A. Palyvos, “On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations,” *Solar Energy*, vol. 83, no. 5, pp. 614–624, May 2009, doi: 10.1016/j.solener.2008.10.008.
- [44] K. Hasan, S. B. Yousuf, M. S. H. K. Tushar, B. K. Das, P. Das, and Md. S. Islam, “Effects of different environmental and operational factors on the PV performance: A comprehensive review,” *Energy Science & Engineering*, vol. 10, no. 2, pp. 656–675, Feb. 2022, doi: 10.1002/ese3.1043.
- [45] F. Shaik, S. S. Lingala, and P. Veeraboina, “Effect of various parameters on the performance of solar PV power plant: a review and the experimental study,” *Sustainable Energy res.*, vol. 10, no. 1, p. 6, Apr. 2023, doi: 10.1186/s40807-023-00076-x.
- [46] M. S. El-Shobokshy and F. M. Hussein, “Effect of dust with different physical properties on the performance of photovoltaic cells,” *Solar Energy*, vol. 51, no. 6, pp. 505–511, Dec. 1993, doi: 10.1016/0038-092X(93)90135-B.
- [47] O. L. Vieira *et al.*, “Comparison of Photovoltaic Plant Performance Estimation Models: A Case Study for Fortaleza, Brazil,” *IEEE Latin America Transactions*, vol. 16, no. 7, pp. 1898–1906, July 2018, doi: 10.1109/TLA.2018.8447355.
- [48] F. M. Zaihidee, S. Mekhilef, M. Seyedmahmoudian, and B. Horan, “Dust as an unalterable deteriorative factor affecting PV panel’s efficiency: Why and how,” *Renewable and Sustainable Energy Reviews*, vol. 65, pp. 1267–1278, Nov. 2016, doi: 10.1016/j.rser.2016.06.068.
- [49] Abdelrahman Mohamed, Al Marri, Malek Masmoudi, Ahmed Hachicha, Atidel B, and Hadj-Alouane., “Optimizing the Cleaning Plan of a Solar Pv System Plant by , :: SSRN.” doi: 2025.
- [50] V. Gupta, M. Sharma, R. K. Pachauri, and K. N. Dinesh Babu, “Comprehensive review on effect of dust on solar photovoltaic system and mitigation techniques,” *Solar Energy*, vol. 191, pp. 596–622, Oct. 2019, doi: 10.1016/j.solener.2019.08.079.
- [51] S. Z. Said, S. Z. Islam, N. H. Radzi, C. W. Wekesa, M. Altimania, and J. Uddin, “Dust impact on solar PV performance: A critical review of optimal cleaning techniques for yield enhancement across varied environmental conditions,” *Energy Reports*, vol. 12, pp. 1121–1141, Dec. 2024, doi: 10.1016/j.egy.2024.06.024.
- [52] J. F. Kok *et al.*, “Mineral dust aerosol impacts on global climate and climate change,” *Nat Rev Earth Environ*, vol. 4, no. 2, pp. 71–86, Feb. 2023, doi: 10.1038/s43017-022-00379-5.
- [53] C. Sun, Y. Zou, C. Qin, B. Zhang, and X. Wu, “Temperature effect of photovoltaic cells: a review | Advanced Composites and Hybrid Materials.” Accessed: June 04, 2025. [Online]. Available: <https://link.springer.com/article/10.1007/s42114-022-00533-z>
- [54] Zainab Usman, Joseph Tah, Henry Abanda, and Charles Nche., “A Critical Appraisal of PV-Systems’ Performance,” <https://www.mdpi.com>. Accessed: Sept. 04, 2025. [Online]. Available: <https://www.mdpi.com/2075-5309/10/11/192>
- [55] D. Y. Goswami, *Principles of Solar Engineering*, 4th ed. Boca Raton: CRC Press, 2022. doi: 10.1201/9781003244387.

- [56] J. Qin, H. Jiang, N. Lu, L. Yao, and C. Zhou, “Enhancing solar PV output forecast by integrating ground and satellite observations with deep learning,” *Renewable and Sustainable Energy Reviews*, vol. 167, p. 112680, 2022, doi: <https://doi.org/10.1016/j.rser.2022.112680>.
- [57] Y. Wang, H. Dai, Z. Chen, S. He, W. Wang, and M. Gao, “Simulation study on a novel solid–gas coupling hydrogen storage method for photovoltaic hydrogen production systems,” *Energy Conversion and Management*, vol. 299, p. 117866, Jan. 2024, doi: [10.1016/j.enconman.2023.117866](https://doi.org/10.1016/j.enconman.2023.117866).
- [58] M. Alotaibi, N. S. Alhajeri, F. M. Al-Fadhli, S. Al Jabri, and M. Gabr, “Impact of Climate Change on Crop Irrigation Requirements in Arid Regions,” *Water Resour Manage*, vol. 37, no. 5, pp. 1965–1984, Mar. 2023, doi: [10.1007/s11269-023-03465-5](https://doi.org/10.1007/s11269-023-03465-5).
- [59] X. Huang *et al.*, “Hybrid deep neural model for hourly solar irradiance forecasting,” *Renewable Energy*, vol. 171, pp. 1041–1060, June 2021, doi: [10.1016/j.renene.2021.02.161](https://doi.org/10.1016/j.renene.2021.02.161).
- [60] F. P. M. Kreuwel, W. H. Knap, L. R. Visser, W. G. J. H. M. van Sark, J. Vilà-Guerau de Arellano, and C. C. van Heerwaarden, “Analysis of high frequency photovoltaic solar energy fluctuations,” *Solar Energy*, vol. 206, pp. 381–389, Aug. 2020, doi: [10.1016/j.solener.2020.05.093](https://doi.org/10.1016/j.solener.2020.05.093).
- [61] M. Dhimish, V. Holmes, P. Mather, and M. Sibley, “Preliminary assessment of the solar resource in the United Kingdom | Clean Energy | Oxford Academic.” Accessed: June 04, 2025. [Online]. Available: <https://academic.oup.com/ce/article/2/2/112/5092454>
- [62] C. Luo *et al.*, “Influence and characteristic of shading on photovoltaic performance of bifacial modules and method for estimating bifacial gain,” *Build. Simul.*, vol. 16, no. 10, pp. 1821–1833, Oct. 2023, doi: [10.1007/s12273-022-0966-0](https://doi.org/10.1007/s12273-022-0966-0).
- [63] S. Y. Khan, S. Rauf, S. Liu, W. Chen, Y. Shen, and M. Kumar, “Revolutionizing the solar photovoltaic efficiency: a comprehensive review on the cutting-edge thermal management methods for advanced and conventional solar photovoltaics,” *Energy Environ. Sci.*, vol. 18, no. 3, pp. 1130–1175, Feb. 2025, doi: [10.1039/D4EE03525A](https://doi.org/10.1039/D4EE03525A).
- [64] L. A. Iturralde Carrera, M. G. Garcia-Barajas, C. D. Constantino-Robles, J. M. ÁlvarezAlvarado, Y. Castillo-Alvarez, and J. Rodríguez-Reséndiz, “Efficiency and Sustainability in Solar Photovoltaic Systems: A Review of Key Factors and Innovative Technologies.” Accessed: June 04, 2025. [Online]. Available: <https://www.mdpi.com/2673-4117/6/3/50>
- [65] E. E. Alhamer, “Solar Photovoltaic Tilt Angle Optimization in the United States.” Accessed: June 04, 2025. [Online]. Available: https://etd.ohiolink.edu/acprod/odb_etd/etd/r/1501/10?clear=10&p10_accession_num=dayton1639409796352829
- [66] O. Bazaluk *et al.*, “Improving Energy Efficiency of Grain Cleaning Technology,” *Applied Sciences*, vol. 12, no. 10, Art. no. 10, Jan. 2022, doi: [10.3390/app12105190](https://doi.org/10.3390/app12105190).
- [67] S. A. Memon, Q. Javed, W. G. Kim, Z. Kim, U. Khan, and M. Shahzad, “A Machine Learning-Based Robust Classification Method for PV Panel Faults.” Accessed: June 05, 2025. [Online]. Available: <https://www.mdpi.com/1424-8220/22/21/8515>
- [68] D. S. Pillai, J. L. Garcia, B. Figgis, S. Jain, and V. B. Benito, “Impact of Robotic Cleaning on the LCOE of Utility Scale PV Power Plants: A Global Assessment Based on KoppenGeiger Climatic Zones | IEEE Conference Publication | IEEE Xplore.” Accessed: June 05, 2025. [Online]. Available: <https://ieeexplore.ieee.org/abstract/document/10749017>

- [69] E. Lohmüller, S. Lohmüller, P. Saint-Cast, J. Greulich, S. Glunz, and R. Preu, “Review and Highlights of More Than 30 Years Research on Ever Improving Technology for PERC Solar Cells at Fraunhofer Ise,” in *European Photovoltaic Solar Energy Conference and Exhibition 2024*, 2024. Accessed: June 06, 2025. [Online]. Available: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/conferencepaper/41th-eu-pvsec-2024/Lohmueller_Paper.pdf
- [70] M. Mpholo, T. Nchaba, and M. Monese, “Yield and performance analysis of the first gridconnected solar farm at Moshoeshe I International Airport, Lesotho,” *Renewable Energy*, vol. 81, pp. 845–852, Sept. 2015, doi: 10.1016/j.renene.2015.04.001.
- [71] “Feasibility Study of Project Phase I -30MWp--70MWp Solar Power Plant Project In Ramarothahole, Mafeteng Region, Kingdom of Lesotho (1).pdf.”
- [72] K. Motopela, “Sizing of a Battery Energy Storage System for Peak Shaving in Lesotho”. [73] solarnplus, “How to Calculate Solar Power Plant Capacity Factor,” Solar N Plus. Accessed: Sept. 02, 2025. [Online]. Available: <https://www.solarnplus.com/how-to-calculate-solarpower-plant-capacity-factor/>