Performance Challenges of On-grid Solar PV Power Plants in Emerging Markets: The Case of Botswana

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Abstract

The rapid global transition to renewable energy has led to large-scale installations of various clean technologies, with solar PV dominating deployment capacity. However, emerging markets continue to encounter challenges despite having good resources. Performance analysis of existing systems is imperative for evidence-based decision making and effective integration of renewable energies. The study evaluated the performance of the Phakalane 1.3MW solar PV power plant in Gaborone, Botswana using the IEC 61724 standard. The main parameters assessed were the performance ratio (PR), capacity factor (CF), final yield, and the system efficiency which were found to be 50.5%, 13.11%, 1503.6MWh, and 6.76% respectively. Comparing these findings to the System Advisor Model (SAM) simulation (a final yield of 2296.7MWh, PR of 72%, CF of 19.9%) results indicated a 35% shortfall. This discrepancy was attributed to high ambient temperatures, inadequate local technical capacity, inadequate maintenance, grid unavailability, and weak monitoring systems. These findings highlight that performance challenges in emerging markets are technical as well as institutional. Recommendations for performance improvement include adopting module cooling and cleaning practices, integrating battery storage and inverter redundancy to increase plant availability, implementation of local capacity building initiatives, robust operation and maintenance practices, development of adequate monitoring infrastructure.

Keywords: renewable energy, solar PV, grid-connected PV power plants, performance analysis, IEC 61724, SAM

1. Introduction

Renewable energies offer resources-constrained developing countries an opportunity to be energy secure. According to IRENA, COP30 and GRA, (2025), 581.91 GW of renewable energy capacity was added in 2024, and solar PV accounted for about 78% of this added capacity. The added capacity, though high, represented 15.1% growth, just 1.5% short of the stipulated 16.1% annual growth required to meet the UAE COP28 consensus target of tripling renewable energies to 11.2 TW by 2030. To attain this growth, all countries, including developing countries, must come on board. Botswana, a developing country, is endowed with the solar resource, receiving at least 2100 kWh/m^2 per year which translates to 5.5 kWh/m^2/day (Government of Botswana, 2019). The country's commitment to renewable energy sources is evident in the national energy documents (National Energy Policy, Vision 2036, the Integrated Energy Resource Plan (IERP)). Despite these efforts and the abundant solar resource, Botswana has a coal-dominated energy mix. Most of the country's electricity is from the state-owned Morupule 600 MW coal power station and assisted by two diesel plants (Matshelagabedi (70 MW) and Orapa (90 MW)) during peak times (IRENA, 2021). Furthermore, the country also imports electricity from the South African Power Pool (SAPP) to cover shortages and electrify villages far from the national grid (Tlhalerwa and Mulalu, 2019).

According to IRENA, (2025) there is only 10 MW of installed PV capacity currently, which is just a 4 MW increase resulting from the commissioning of the Shakawe 1 MW and the Bobonong 3 MW utility-scale grid-connected solar PV power plants. These are part of the 35 W project to install utility-scale grid-connected solar PV power stations in villages around Botswana (Dailynews, 2023). Before these, there had been only one utility-scale solar PV plant, the Botswana Power Corporation's Phakalane 1.3 MW plant, commissioned in

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2012 with technical assistance from the Government of Japan.

The slow integration of solar PV technology may be due to the high initial capital investment required, an inadequate policy framework to support the installations of these plants, and inadequate human capital. These challenges may be exacerbated by limited research on the performance of solar PV locally, which could avail data to aid decision-making processes, thereby increasing reliability and investor confidence. Such data would also enable education and information dissemination, optimal operation and maintenance of current and envisaged plants, and strengthening policy frameworks. Currently, local research in the area includes a study by Moilwa et al. (2023), who found that grid losses and fault levels could be reduced by integrating solar PV plants into the Greater Gaborone distribution network. Similarly, Gobodi et al. (2024) analyzed the performance of the Phakalane PV plant, focusing only on the effects of prolonged downtime and grid unavailability, and reported that the plant had a technical availability of 57.4%, with a Mean Time Before Failure of 129 hours and a Mean Time to Repair of 96 hours.

The performance of grid-connected PV plants often falls short of projected values in spite of widespread deployment, especially in developing markets. The performance of grid-connected PV plants is impacted by various factors. High PRs were observed in cooler months by Mensah et al. (2019) in Ghana, while in India, Sharma and Goel (2017) and Malvoni et al. (2020) reported lower PRs in hotter months resulting from reduced efficiencies. Findings from these studies reveal an indirect relationship between temperature (ambient and module) and module efficiency. This then implies that cooler environments are ideal for enhanced PV performance. This is aligned with a performance evaluation of a 4.5 MW plant in the temperate climate of France by Jed et al. (2021) where low ambient temperature reduced the capture losses, resulting in the plant PR values greater than 85%.

Irradiance and sunshine hours are also vital in the performance of PV plants. In Morocco, Attari et al. (2016) reported that winter months were characterized by low yields, which was attributed to reduced solar hours. Similarly, Dobaria et al. (2016) observed a performance decline during the cloudy, rainy monsoon months in Gujarat, India. These studies show that limited solar irradiance and shortened sunshine hours reduce the amount of energy available for conversion. Another major factor affecting PV output is dust accumulation, especially in semi-arid and arid regions. Hachicha et al. (2019) observed an almost linear relation between dust density and module power loss, with accumulated dust over a 5-month period resulting in 13% energy reduction. In addition, accumulated dust not only shades the module's surface; it also contributes to its increased operating temperature. Dusty modules were found to be 2-6°C hotter than cleaner modules, compounding performance losses (Rashid et al., 2023). These findings highlight the importance of module cleaning and optimum tilt design in dusty environments, which is a characteristic of emerging solar markets.

In addition to environmental factors, grid-connected solar PV plant performance is also affected by operation and grid-related challenges, especially in developing markets where underdeveloped grids are prevalent. Frequent grid interruptions and missing data points were identified to be principal contributors to lower PRs in an Algerian PV system analyzed by Fezzani et al. (2023). Likewise, Padmavathi and Daniel, (2013) and Tiwari et al. (2017) found long load shedding hours, inverter failure, and inadequate maintenance to reduce the amount of energy deposited into the grid. Padmavathi and Daniel, (2013) further shows that corrective maintenance improved PR from below 60% to about 70%, emphasizing the importance of optimal operation and maintenance. These studies show that often times in emerging markets, performance losses are from operation inefficiencies than resource limitations.

The sources of operational inefficiencies of solar PV systems are not only technological but also include policy and institutional barriers. IRENA, (2021) and Maswabi et al., (2021) reported that in Botswana operational inefficiencies are due to weak governance, limited local technical expertise, unavailability of spare parts locally, and inadequate monitoring infrastructure. These challenges are likely to be encountered in emerging markets like Botswana, where robust policies and synergy are limited. Such could contribute to low renewable energy penetration and low investor confidence.

Other factors that influence system performance of grid-connected solar PV plants include PV cell technology (Hussin et al. 2018; Ebhota and Tabakov, 2023), solar irradiance, temperature (Vaillon et al. 2018; Stanislawski et al. 2022), soiling (Cordero et al. 2018; Cui et al. 2021), humidity (Das, 2019;Shaik et al., 2023), shading (Giyantara et al. 2021). Performance analysis helps understand the extent of the effect of different factors on

PV systems and enables identification of effective mitigation strategies. PV plant performance analysis is guided by the International Electrotechnical Commission (IEC) 61724 standard which covers parameters such as the final yield, Performance Ratio (PR), Capacity Factor (CF), system efficiency, and reference yield) as key performance indicators for grid-connected PV plants. The standard allows results from different PV systems and regions to be compared objectively Martín-Martínez et al. (2019). The use of this standard ensures accuracy, transparency, and comparability in performance reporting. However, currently, no published studies that have applied the IEC 61724 approach in Botswana were found. This study, therefore, used the IEC 61724 standard to analyze the performance of the 1.3 MW Phakalane grid-connected solar PV power plant with specific objectives to determine performance level of the Phakalane 1.3 MW solar PV power plant, identify factors influencing the overall performance of the plant, and propose performance enhancement practices.

In summary, grid-connected PV power plants performance is influenced by environmental (irradiance, temperature, sunshine hours and dust), operation (maintenance and grid reliability) and both policy and institutional barriers. Mitigating these challenges is important to enhance the reliability of PV in emerging markets.

2. Methodology

2.1. Case study

A performance analysis of a solar PV power plant was executed. The case study is the Phakalane 1.3MW plant owned and operated by Botswana Power Corporation. The plant is situated 15km North of Gaborone at 24°34'25.6"S 25°58'08"E. The plant consists of 5920 Sharp Solar module (ND-220E1J) polycrystalline silicone ground mounted panels rated 220W DC. These panels are connected in parallel strings comprising 16 panels each to give a peak voltage of 470 V DC. The strings converge to junction boxes which then connect to 13 Hitachi HSP900-1000LFH 100kW inverters that transfer the energy to the national grid. Figure 1 illustrates the layout of the plant.

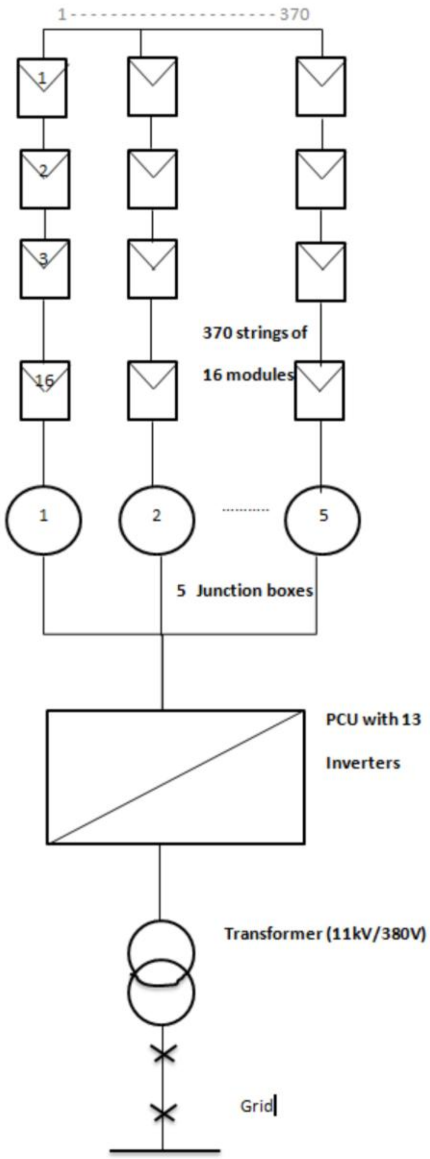

Figure 1: Phakalane 1.3 MW solar PV plant block circuit diagram.

2.2. Data Collection

Raw data used in this study was obtained from Botswana Power Corporation (BPC) in the form of Excel sheets containing time-series data recorded in 30-minute intervals. One year (May 2021-April 2022) of continuous data was used.

2.3. Data cleaning

Data Quality Routines (DQRs) described by (Livera et al. 2021) were used to do away with anomalies in data sets ensuring their quality before analysis. Anomalies include outliers and non-value data entries. They were executed using the Python Pandas library. The clean data was input in the IEC 61724 standard performance analysis.

2.4. Performance Analysis

The performance analysis was guided by the IEC 61724 (2017) standard. Parameters evaluated in this study include the reference yield (Y_R), final yield (Y_F), Performance Ratio (PR), Capacity Factor (CF), and system efficiency. Parameters are executed as follows (Yalawar and Nayak, 2018; Martín-Martínez et al. 2019):

- Reference yield: the total amount of theoretical energy a plant would produce if it operated at its rated efficiency (Cavalcante et al., 2019).

$$Y_R = \frac{H_{POA}}{G_{STC}} \qquad \text{(eq. 1)}$$

Where H_{POA} is the in-plane solar irradiance in kWh/m^2 and G_{STC} is the standard PV reference irradiance in kW/m^2.

- Final yield: the total amount of energy injected into the grid (in this case daily).

$$Y_{F,D} = \frac{E_{AC}}{P_{NOM}} \qquad \text{(eq. 2)}$$

Where E_{AC} is the alternating current fed into the grid and P_{NOM} is the installed capacity.

- Performance Ratio (PR): a dimensionless parameter that indicates the effect of system losses resulting from factors on PV performance. A PR value greater than 75% indicates good plant performance (Fezzani et al. 2023)

$$PR = \frac{Y_F}{Y_R} \qquad \text{(eq. 3)}$$

- Capacity Factor (CF): the ratio of energy that is fed into the grid to the energy that a plant would produce if it worked at nominal efficiency for 24 hours in a given period (here, a year). The CF values range from 0.1 to 0.25 because in reality the sun does not shine for 24 hours (Odeh, 2018).

$$CF = \frac{E_{AC}}{365(24)P_{NOM}} \qquad \text{(eq. 4)}$$

- System efficiency: evaluated as the ratio of alternating current (AC) output energy to the product of incident in-plane solar irradiance (H_{POA}) and array area (A_{array}) (total input energy).

$$\eta_{sys} = \frac{E_{AC}}{H_{POA} \times A_{Array}} \qquad \text{(eq. 5)}$$

The parameters quantify the Phakalane 1.3 MW solar PV power plant performance.

2.5. Simulation

The simulation was done using System Advisor Model (SAM) 2023.21.17, SSC 288. Apart from being free, SAM enables economic and technical evaluation of renewable energy systems, including solar PV, geothermal, Concentrated Solar Plant (CSP), biomass and wind. The software also allows users to input specifications and create new elements if they are not available in the database. The software also allows for detailed sensitivity analysis of systems. (Ezeanya et al., 2018; González-Sala et al., 2021; Kavuma et al., 2022). The software requires input of plant layout, inverter and module specifications, and location coordinates of the plant and the Typical Meteorological Year (TMY).

3. Results and Discussion

Performance analysis indicated that the Phakalane plant had a final yield of 1503.6MWh, PR of 50.5%, CF of 13.22%, and a system efficiency of 6.36%. The simulated final yield was 2296.7MWh, PR= 72%, and a CF = 19.9% (see Table 1). This showed that the plant uder-performed with a 35% energy shortfall; The shortfall suggests the presence of factors inhibiting optimal plant performance.

The same effect of temperature reported by Malvoni et al. (2020); Mensah et al. (2019) was also observed in the plant. High Gaborone ambient temperatures resulted in a drop in module efficiency and low PRs in summer, whilst the winter season was characterized by high energy output. Thermodynamically, the increase of module temperature results in high resistance, which impedes voltage, causing low power production. Dust accumulation was also observed on module surfaces during site visits. The dust could have contributed to the low performances recorded. Paudyal and Shakya, (2016); Hachicha et al. (2019) report dust to cause power losses ranging from 10% to 20%. Dust was also found to increase the module operating temperature (Rashid et al., 2023). These findings necessitate cleaning and cooling solutions to mitigate these losses. Routine cleaning of modules as part of maintenance practices could reduce dust-induced losses. A 9.22% power gain was reported by Abbood Al-Khazzar, (2015) after panel cleaning. Cooling the backside of modules, increasing panel height off the ground, and increasing array spacing have also been found to improve module temperature. The simulation of array spacing approach for cooling using SAM shows that the current plant studied is optimally spaced at 5.2m because increasing array spacing has no significant improvement in module temperature. These results agree with Prilliman et al. (2022) who stated that this method only works in places with low average ambient temperature unlike Gaborone.

Table 1: The effect of row (array) spacing on performance parameters

Row spacing (m)	Direct Current (DC)(MW)	PR (%)	CF (%)	Temperature losses (%)
3.5	2162.9	65	17.7	20.95
4	2305.0	70	18.9	16.52
4.5	2420.4	73	19.7	13,19
5	2432.8	73	19.9	12.7
5.2	2439.8	74	20	12.6
6	2448.0	74	20	12.5
6.5	2451.0	74	20	12.5

Performance of PV grid-connected plants is also affected by operation factors; hence, low plant performance was also due to inadequate monitoring and fault detection as grid interruption would go unnoticed for days. During this time no energy was injected into the grid resulting in low final yield, PR, and CF values. Grid interruptions were found to contribute to low performance by Tiwari et al. (2017) and Fezzani et al. (2023). Furthermore, Gobodi et al. (2024) reported that the current plant's Mean Time to Repair was 96 hours, indicating insufficient maintenance practices. Some of the inverters at the Phakalane plant were not working at the time of study, and this may also have contributed to the low performance of the plant because not all produced energy was transferred to the grid. Padmavathi yielded about a 10% increase in power performance following inverter maintenance, and their study underpins the importance of operation and maintenance. The performance of the plant in the current study was therefore affected by environmental and operating factors.

Beyond environmental and technical factors, grid-connected solar PV plant performance may be affected by governance factors. Poor governance might have caused the actual performance to be just about 65% of the simulated potential. Maswabi et al., (2021) stated that Botswana's weak renewable energy governance with unclear stakeholder roles and overlapping regulatory framework contributed to poor plant performance and reduced reliability of plants. Inadequate governance leads to perpetuation of inadequate data-monitoring infrastructure and practices, lack of local technical capacity to execute operation and maintenance of plants, underdeveloped grid and inconsistent regulatory oversight. This goes to show that a good solar resource does not guarantee a good generation. Botswana has one of the world's best solar resources but is not harnessing the resource effectively. Good governance plays a crucial role because it removes policy and institutional barriers which are currently Botswana's reality.

Mitigation measures include developing local technical capacity as this may improve self-reliance. South Africa has a national renewable energy training centre to facilitate training and certification in renewable energies focusing mainly on their operation and management as well as technical quality assurance. Since its inception in 2012, thousands of South Africans have been trained and there is now a standardized national qualification on PV installation (Eskom, 2022). Moreover, South Africa through the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), requires all Independent Power Producer (IPPs) include skill transfer sections in their proposal. This ensures all renewable energy developers actively partake in local capacity in addition to business. Botswana could benchmark on these initiatives and develop conducive initiatives for local capacity building. Strengthening local capacity could improve local research, which in turn could boost manufacturing of locally relevant products and hence efficiency.

Botswana Energy Regulation Authority (BERA) and the ministry could institutionalize periodic performance reporting and introduce penalties for underperforming plants and benefits for optimal performance. Germany has the Renewable Energy Sources act whose target is to increase renewable energy share to 80% of gross electricity consumption by 2030 (IEA,2025). To achieve this, renewable plant operators are monitored annually by an independent auditor to ensure targets are met. The act sets the expected performance level of PRs and CFs, plant operators who fail to meet those risk penalties such as their feed-in-tariff being reduced until performance improves. These kinds of penalties can help foster good operation and maintenance practices, as well as adequate monitoring, thereby improving plant performance.

Development of battery integration policy that will encourage development of hybridization and redundancy guidelines to increase plant availability. Sarita et al. (2023) incorporated inverter redundancy in PV plants and realized an average increase in plant availability of 10%. The battery technology continues to go down the experience curve, this implies that it will become affordable soon, thus its incorporation in systems is becoming tangible (Tejero-Gómez and Bayod-Rújula, 2023). A technoeconomic evaluation of a hybrid battery-PV system in Mauritius by Edoo and King, (2021). Findings illustrated that battery system increases plant availability, and the levelized cost of the hybrid system was comparable to that of fossil fuel-fired plants. This shows that redundancy and integration of energy batteries would help and would be valuable in the quest to improve plant performance.

All suggested mitigation measures if implemented, would help the country improve solar PV efficiencies, in line with the UAE Consensus and ultimately help the country achieve its national renewable energy goals including the recently launched Energy Compact Botswana which seeks to increase the share of renewables in the energy mix (Government of Botswana, 2025).

In conclusion, a performance evaluation of the Phakalane 1.3 MW grid-connected solar PV was undertaken. The plant was found to be underperforming with a 35% deficit compared to its simulated performance. The performance parameters were found to be final yield=1503.6MWh, PR= 50.5%, system efficiency= 6.76%, and CF =13.22% whilst simulated parameters were final yield 22096.7MWh, PR=72%, and Cf=19.9%. The deficit was probably due to high ambient and module temperatures, dust accumulation, inadequate operation and maintenance, as well as monitoring infrastructure. In addition, policy and intuitional barriers may have also contributed to the poor performance, further indication that performance is not only affected by environmental factors in emerging markets. These barriers include inadequate local technical expertise to operate and maintain PV power plants, unclear roles and fragmented regulations, and grid unavailability resulting from inadequate monitoring.

The study proposed mitigation measures to improve plant efficiency and reliability. The study recommends local capacity buidling, regular maintenance, performance monitoring, and accountability strategies where plant operators are required to perform at certain levels to access full incentives. These will most probably improve energy security and ensure compliance with set standards in the country and similar emerging markets.

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