

# Performance Evaluation of a 2 MW On-grid Solar Photovoltaic Plant with Single-Axis Tracker in the Hyper-Arid Climate of Traghn, South Libya

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## Abstract

Southern Libya possesses some of the highest solar irradiance levels globally, presenting a significant opportunity for utility-scale solar photovoltaic (PV) deployment to address the nation's energy deficit. However, the harsh desert environment creates unique challenges for system performance and durability. This study presents a comprehensive, one-year performance evaluation of a 2 MWAC grid-connected PV plant utilizing horizontal single-axis trackers (HSAT) located in Traghn, South Libya. Meteorological and operational data were acquired via a SCADA system, and performance metrics were calculated according to the IEC 61724 standard. The analysis confirms the site's exceptional solar resource, with the single-axis tracking system delivering an annual in-plane irradiation of 2,680 kWh/m<sup>2</sup>, a 19% gain over the global horizontal irradiation. Despite this high resource, extreme ambient temperatures significantly curtailed system efficiency. The plant achieved an annual average Performance Ratio (PR) of 79.4% and a Capacity Factor (CF) of 24.1%. Thermal capture losses were identified as the dominant performance constraint, causing monthly PR to drop to approximately 74% during summer when module temperatures frequently exceeded 65°C. Soiling losses, quantified at an estimated 4.5% annually, were also significant, necessitating frequent cleaning cycles. The results validate the technical viability of single-axis tracker technology in Southern Libya but underscore the critical necessity of selecting modules with low-temperature coefficients and implementing robust, climate-adapted operation and maintenance protocols to mitigate thermal and soiling losses.

**Keywords:** Solar Photovoltaic (PV); Performance Ratio; Single-Axis Tracker; Desert Climate; IEC 61724; Soiling Losses; Thermal Losses; Libya.

## 1. Introduction

Libya faces a significant paradox in its energy sector: while endowed with abundant fossil fuel resources, it contends with severe electricity supply deficits due to aging infrastructure, political instability, and rising demand [1]. Concurrently, the country is situated within the globe's "Sun Belt," boasting one of the world's highest theoretical solar energy potentials, particularly in its vast southern desert regions [1]. A strategic transition toward utility-scale solar photovoltaic (PV) deployment is increasingly recognized as essential for enhancing Libya's energy security, reducing reliance on hydrocarbons, and fostering economic diversification.

Southern Libya, characterized by a hot desert climate (Köppen classification BWh), offers exceptional direct normal irradiance (DNI) and global horizontal irradiance (GHI). However, these high irradiance levels are coupled with extreme ambient temperatures and frequent dust storms, environmental factors known to substantially degrade PV performance compared to Standard Test Conditions (STC) [2]. To maximize energy yield in such high-irradiance regions, single-axis tracking systems (SAT) are often favored over fixed-tilt installations. Horizontal single-axis trackers (HSAT), in particular, increase incident irradiation on the module plane by tracking the sun's azimuth, which can improve annual energy yield by 20–30% compared to optimally tilted fixed arrays at similar latitudes [3].

Despite the compelling theoretical potential, there is a stark paucity of published empirical performance data for utility-scale PV plants operating in the hyper-arid conditions of the Sahara Desert, specifically within Southern Libya. Most existing studies rely on simulation models or data from smaller test installations. Bridging the gap between simulated projections and actual operational performance is crucial for de-risking future large-scale investments in the region. The primary objective of this paper is to address this knowledge gap by presenting a detailed, one-year performance evaluation based on monitored data from an operational 2 MWAC grid-connected PV plant equipped with horizontal single-axis trackers in Traghn, South Libya. Adhering to the international standard IEC 61724 [4], this study quantifies energy yields, analyzes the impact of high temperatures and dust on system efficiency, and provides actionable insights for the design and operation of PV plants in similar extreme desert environments.

## 2. Methodology

### 2.1 Site Description and Meteorological Context

The 2 MWAC PV plant is located near the town of Traghn in the Murzuq District of southwestern Libya (approximate coordinates: 25.9° N, 14.4° E). The site features flat terrain and is characterized by a hyper-arid desert climate (BWh). The region experiences extreme summer temperatures, with ambient air temperatures frequently exceeding 40°C, and considerable diurnal temperature variations during winter months. Atmospheric clarity is generally high, resulting in abundant solar resources. However, the site is periodically affected by seasonal Harmattan winds, which transport fine dust and can lead to significant soiling on module surfaces.

### 2.2 Plant Technical Specifications

The plant has a total installed DC (peak) capacity ( $P_{DC,STC}$ ) of 2.3 MWp and is connected to the grid at an AC capacity of 2.0 MW. The array comprises high-efficiency monocrystalline silicon PV modules, selected for their superior temperature coefficients compared to polycrystalline alternatives. The modules are mounted on horizontal single-axis trackers (HSAT) with a North-South axis orientation. The tracking system follows the sun's path from East to West daily, with a maximum rotation angle of  $\pm 55^\circ$ . A backtracking algorithm is employed during early morning and late afternoon hours to prevent inter-row shading. DC power is consolidated and converted to AC via central inverters before being stepped up to the medium-voltage grid connection point.

### 2.3 Data Acquisition and Processing

A comprehensive Supervisory Control and Data Acquisition (SCADA) system was used to collect synchronized meteorological and electrical parameters at a 15-minute interval over a continuous 12-month period.

**Meteorological Data:** Global Horizontal Irradiance (GHI) and Global Tilted Irradiance (GTI) in the plane of the tracking array were measured using ISO 9060 secondary standard pyranometers. Ambient temperature ( $T_{amb}$ ), module temperature ( $T_{mod}$ , measured via resistive temperature detectors on module rear surfaces), and wind speed/direction were recorded by an on-site weather station.

**Electrical Data:** DC current and voltage were monitored at string combiner boxes. AC output power, energy, voltage, frequency, and power factor were measured at the inverter outputs and the grid interconnection point using calibrated energy meters. Data post-processing involved quality checks to filter out periods of plant downtime due to grid outages or scheduled maintenance, ensuring the analysis reflected performance under normal operational conditions.

#### 2.4 Performance Parameters (IEC 61724)

System performance was evaluated according to the IEC 61724-1:2017 standard [4]. The key metrics, calculated on monthly and annual bases, are defined as follows:

**Reference Yield ( $Y_r$ ):** The system's theoretical operational hours at STC for the received in-plane irradiation.

$$Y_r = H_i / G_{STC} \quad [\text{kWh/kWp}]$$

where  $H_i$  is the total in-plane irradiation ( $\text{kWh/m}^2$ ) and  $G_{STC}$  is the reference irradiance ( $1 \text{ kW/m}^2$ ).

**Final Yield ( $Y_f$ ):** The actual AC energy output normalized by the installed DC capacity.

$$Y_f = E_{AC} / P_{DC,STC} \quad [\text{kWh/kWp}]$$

where  $E_{AC}$  is the total net AC energy fed into the grid (kWh).

**Performance Ratio (PR):** The ratio of final yield to reference yield, representing the overall system efficiency after accounting for all losses (thermal, electrical, optical, and soiling).

$$*PR = (Y_f / Y_r) \times 100 \quad [\%]*$$

**Capacity Factor (CF):** The ratio of actual energy output to the maximum possible output if the plant operated at its rated AC power continuously.

$$*CF = [E_{AC} / (P_{AC,rated} \times 8760)] \times 100 \quad [\%]*$$

**Loss Analysis:** Total system losses ( $L_{total}$ ) are defined as  $Y_r - Y_f$ . These are decomposed into:

**Array Capture Losses ( $L_c$ ):**  $L_c = Y_r - Y_a$ , where  $Y_a$  is the array yield (DC energy normalized by  $P_{DC,STC}$ ). This primarily includes losses due to temperature, soiling, and module mismatching.

**System Losses ( $L_s$ ):**  $L_s = Y_a - Y_f$ , encompassing inverter conversion losses and other AC-side losses.

### 3. Results and Discussion

#### 3.1 Solar Resource and Thermal Conditions

The monitored data confirms the exceptional solar potential of the Tragn site. The annual Global Horizontal Irradiance (GHI) was  $2,250 \text{ kWh/m}^2$ . Crucially, the single-axis tracking system enhanced the energy harvested, with the annual Global Tilted Irradiance (GTI) on the plane of the array reaching  $2,680 \text{ kWh/m}^2$ . This represents a significant 19% gain in incident irradiation attributable to the tracker, aligning with expectations for this technology at  $\sim 26^\circ\text{N}$  latitude. As illustrated in Figure 1, high irradiation levels during summer months (May-August) coincide with extreme thermal conditions. Average daily maximum ambient temperatures in this period consistently exceeded  $38^\circ\text{C}$ . Analysis of module temperatures (Figure 2) revealed that during peak summer irradiance,  $T_{mod}$  frequently operated in the range of  $65\text{--}70^\circ\text{C}$ . Given the typical power temperature coefficient for monocrystalline

silicon modules ( $\gamma \approx -0.38\%/^{\circ}\text{C}$ ), these elevated operating temperatures result in an instantaneous DC power reduction of 15–18% relative to STC ( $25^{\circ}\text{C}$ ).

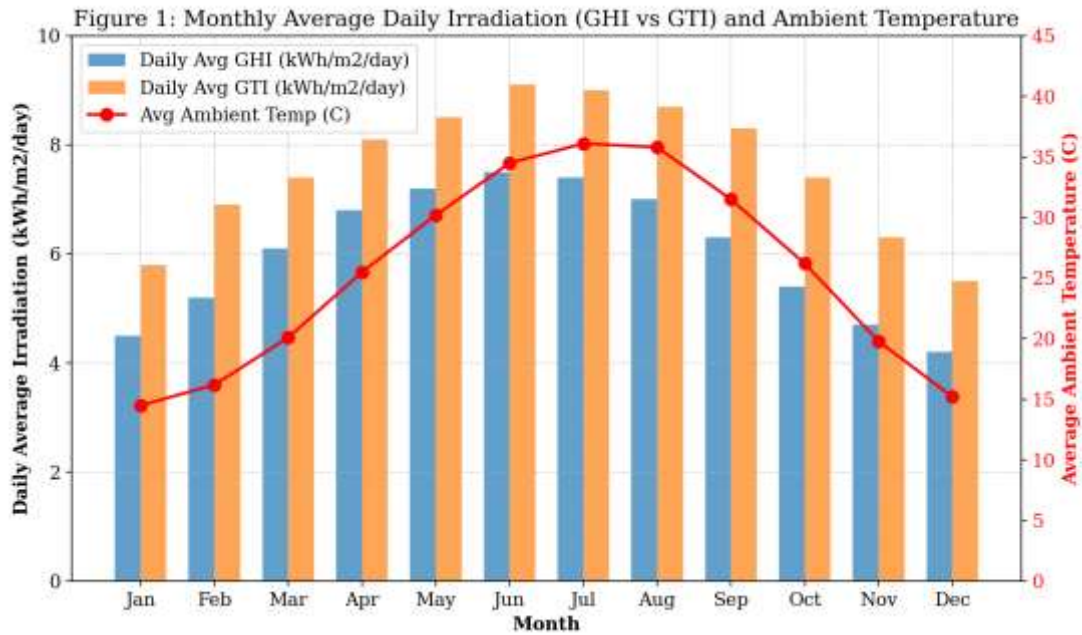


Figure 1: Monthly average daily GHI, GTI, and Ambient Temperature.

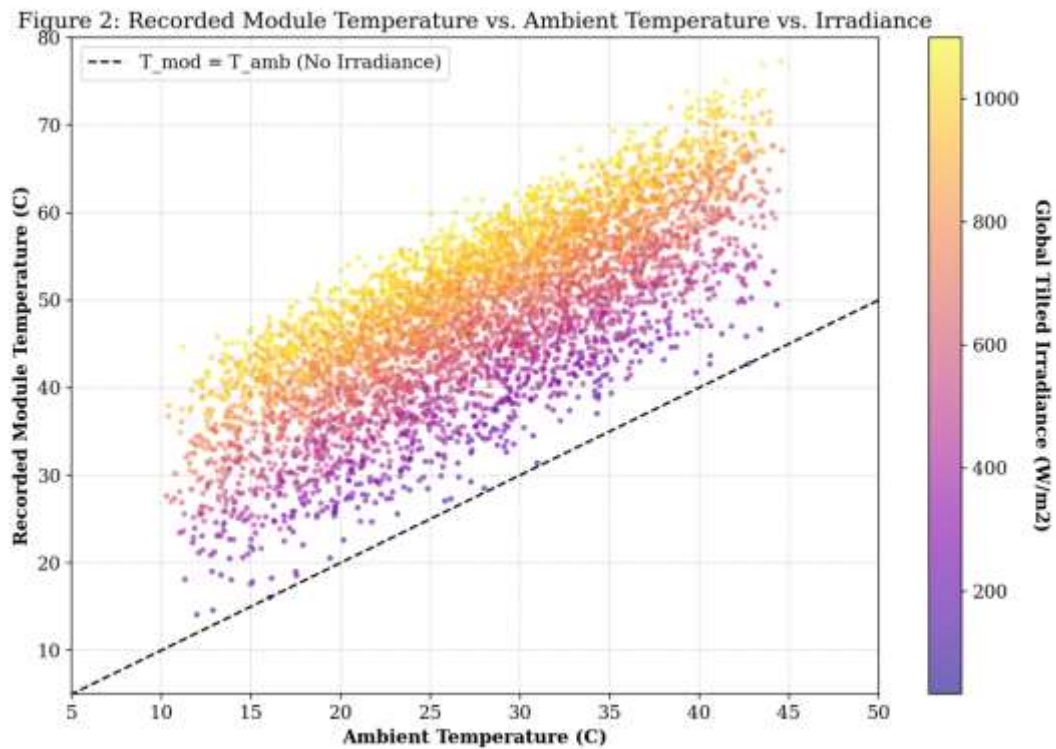


Figure 2: Recorded Module Temperature vs. Ambient Temperature vs. Irradiance.

### 3.2 Energy Production and Yield Analysis

Over the 12-month evaluation period, the plant delivered a total of 4,220 MWh of AC energy to the grid. Table 1 presents the monthly and annual performance parameters. The annual Final Yield ( $Y_f$ )

was 1,835 kWh/kWp. Notably, the highest monthly final yields were not observed in the peak-irradiation summer but in the spring (March-April) and autumn (October). This phenomenon, evident in Table 1, highlights the "temperature cliff" effect: while summer offers the longest days and highest irradiance, the concomitant extreme heat severely depresses module conversion efficiency, curtailing potential gains.

**Table 1: Monthly and annual performance summary of the 2 MW Traghn PV Plant.**

Month	GTI (kWh/m <sup>2</sup> )	Final Yield, Y <sub>f</sub> (kWh/kWp)	Reference Yield, Y <sub>r</sub> (h)	Performance Ratio, PR (%)
Jan	180	151	180	83.9
Feb	195	162	195	83.1
Mar	230	186	230	80.9
Apr	245	194	245	79.2
May	265	204	265	77.0
Jun	275	206	275	74.9
Jul	280	207	280	73.9
Aug	270	203	270	75.2
Sep	250	198	250	79.2
Oct	230	191	230	83.0
Nov	190	163	190	85.8
Dec	170	149	170	87.6
<b>Year</b>	<b>2680</b>	<b>1835</b>	<b>2680</b>	<b>79.4 (avg)</b>

### 3.3 Performance Ratio and Capacity Factor

The annual average Performance Ratio was **79.4%**. This value is considered robust for a desert environment but is notably lower than the >85% PR typically achievable in temperate climates [5]. As shown in **Figure 3**, PR exhibited strong seasonal variation, inversely correlated with temperature. It peaked at **87.6%** in the cool month of December and reached its minimum of **73.9%** in July. This trend irrefutably identifies **thermal losses as the primary efficiency constraint** for PV systems in this region.

The plant achieved an annual **Capacity Factor of 24.1%**, demonstrating the high energy production potential enabled by the combination of abundant solar resource and single-axis tracking, despite the efficiency penalties.

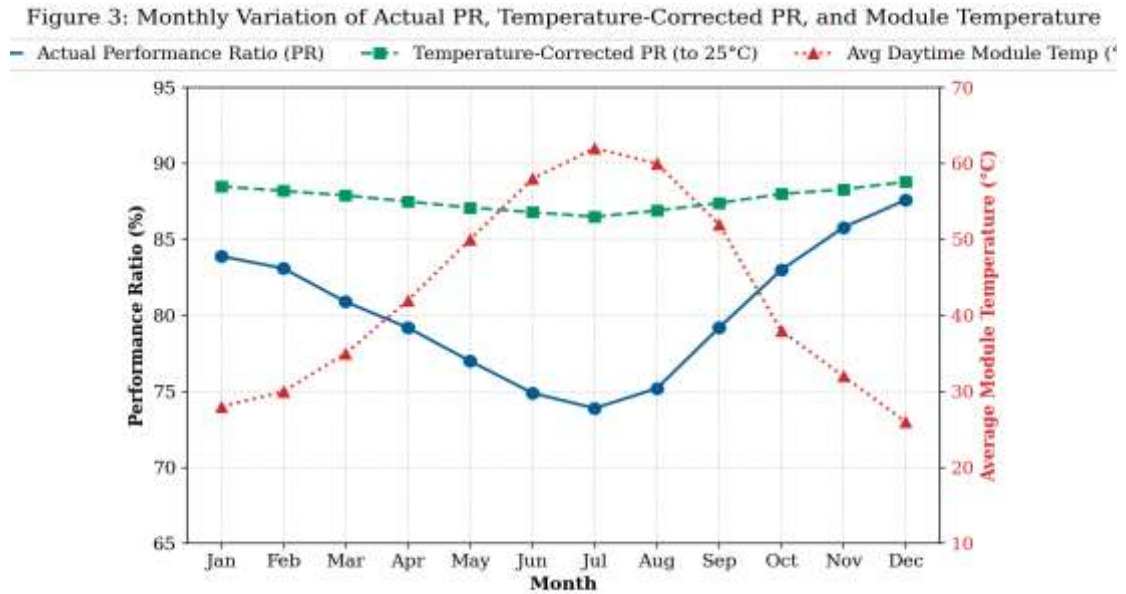


Figure 3: Monthly variation of Performance Ratio and Temperature-Corrected PR.

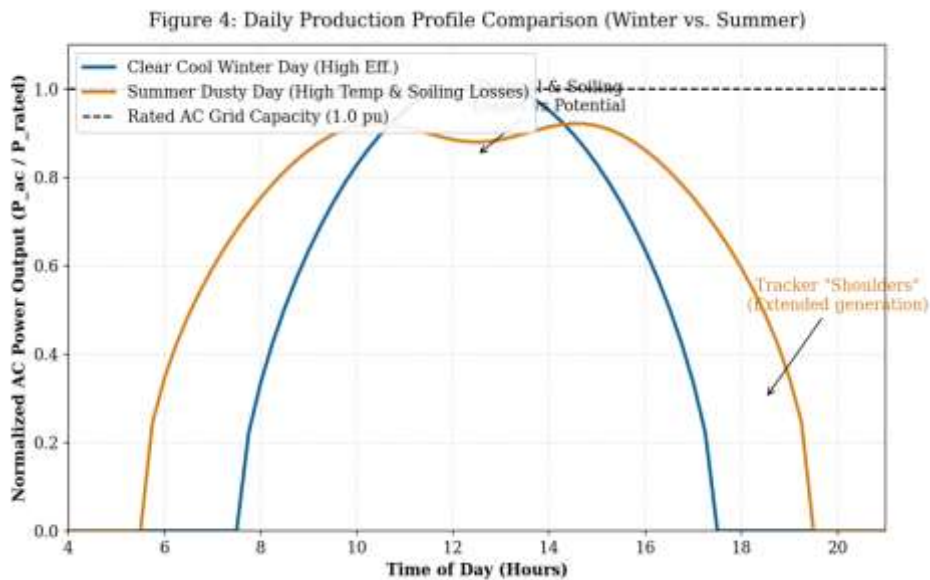


Figure 4: Daily production profile comparing clear winter day vs. summer dusty day.

### 3.4 Loss Analysis: Thermal and Soiling Effects

Capture losses ( $L_c$ ) constituted the dominant share of total losses. Inverter efficiency remained consistently high ( $>98\%$ ), indicating that system losses ( $L_s$ ) were minimal. Therefore, the performance gap is primarily attributed to array-level losses.

**Thermal Losses:** As discussed, module temperature derating was the most significant factor. The difference between summer and winter PR values (~14 percentage points) is largely attributable to this effect.

**Soiling Losses:** Analysis of daily PR trends revealed gradual declines during prolonged dry periods, with sharp recoveries following rain events or manual cleaning (**Figure 4**). During seasonal sandstorms, daily energy production dropped by over 30% until cleaning was performed. Using regression analysis of PR degradation between cleanings, the average annual energy loss due to soiling is estimated at 4.5%. This underscores the critical importance of an optimized cleaning regimen, balanced against water scarcity and O&M costs.

#### 4. Conclusion and Recommendations

This study presented a detailed, one-year performance evaluation of a 2 MW grid-connected PV plant with horizontal single-axis trackers in the hyper-arid desert of Tragh, South Libya. The analysis confirms the site's world-class solar resource, with tracking providing a 19% boost in-plane irradiation to 2,680 kWh/m<sup>2</sup>/year.

The plant delivered a substantial annual yield of 1,835 kWh/kWp and a capacity factor of 24.1%, validating the technical and economic rationale for employing single-axis tracker technology in Southern Libya. However, the harsh environment imposes significant efficiency penalties, reflected in an annual average PR of 79.4%. Thermal losses were the predominant performance limiter, causing a pronounced summer "temperature cliff," followed by appreciable soiling losses estimated at 4.5% annually.

For future utility-scale PV deployments in similar Saharan environments, this study recommends:

1. **Module Technology Selection:** Prioritize PV modules with the lowest possible temperature coefficients (e.g., heterojunction or advanced N-type cells) to directly mitigate the largest loss factor.
2. **Climate-Adapted O&M Strategy:** Implement a proactive, frequent cleaning schedule. Given water scarcity, investment in water-efficient or waterless (e.g., electrostatic, robotic brush) cleaning technologies should be evaluated.
3. **Justification for Tracking:** Despite added mechanical complexity and O&M in a dusty setting, the significant irradiance gain ( $\geq 19\%$ ) from single-axis tracking remains essential for maximizing project economics in this high-resource region.
4. **Further Research:** Future work should focus on the long-term reliability of tracking mechanisms under abrasive dust conditions and the lifecycle cost-benefit analysis of advanced cooling techniques (e.g., passive rear-side ventilation) for modules in such extreme climates.

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