



Performance Analysis of Grid-Connected Solar Photovoltaic Systems

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Abstract

Grid-connected solar photovoltaic (PV) systems have become a major option for distributed and utility-scale electricity generation; however, their real energy contribution depends on solar resource, module temperature, conversion losses, inverter operation, grid availability, soiling, and system design. This paper presents a compact methodology for evaluating the technical performance of a grid-connected PV system using internationally adopted normalized indicators. The proposed procedure combines monitored solar irradiance, ambient and module temperature, DC energy, AC energy, and grid-side operating data. Reference yield, array yield, final yield, capture loss, system loss, performance ratio, capacity factor, PV array efficiency, inverter efficiency, and overall system efficiency are calculated on daily, monthly, and annual bases. A representative 100 kWp plant is used to demonstrate the analytical workflow; the numerical results are illustrative rather than field measurements from a named site. For the representative year, the method gives a specific AC yield of about 1,585 kWh/kWp, an annual performance ratio of 78.0%, a capacity factor of 18.1%, and an average inverter efficiency of 96.2%. The framework also separates environmental losses from balance-of-system losses so that underperformance can be diagnosed rather than reported only as reduced energy output. The approach is consistent with performance studies published up to 2018 and is suitable for rooftop as well as utility-scale systems.

Introduction

Solar PV generation converts incident solar radiation directly into electricity and can be integrated with the utility network through power-electronic inverters. A grid-connected plant normally contains PV modules arranged in strings, DC collection equipment, maximum-power-point-tracking (MPPT) inverter stages, AC protection, metering, and a point of common coupling with the distribution or transmission grid. The nominal DC rating alone does not describe how effectively such a plant operates. Two systems with the same installed capacity can deliver markedly different annual energy because of irradiation, cell temperature,

orientation, shading, soiling, inverter loading, wiring loss, outages, and local grid conditions.

Consequently, performance analysis requires normalized metrics that allow plants of different ratings and climates to be compared. Early field studies demonstrated the usefulness of reference yield, final yield, losses, and performance ratio. Kymakis, Kalykakis, and Papazoglou (2009) evaluated a grid-connected PV park in Crete and showed how energy output could be normalized against the available solar resource. Ayompe et al. (2011) extended this type of evaluation to a 1.72 kWp rooftop installation in Ireland and reported yield, efficiency, performance ratio, capacity factor, and loss components. These parameters

provide a stronger diagnostic basis than energy production alone because they connect resource availability to array conversion and grid-delivered energy.

Indian studies further demonstrated the importance of climate and plant scale. Sharma and Chandel (2013) analyzed a 190 kWp grid-connected plant, while Padmavathi and Daniel (2013) examined a 3 MWp installation and emphasized normalized performance indices and grid-related losses. Kumar and Sudhakar (2015) evaluated a 10 MW plant using monitored and modeled information, showing the value of continuous plant supervision. Later work in Morocco, Brazil, eastern India, northern India, and southern Algeria confirmed that temperature, irradiation distribution, inverter behavior, and local environmental conditions must be incorporated into any defensible assessment (Attari, Elyaakoubi, & Asselman, 2016; de Lima, de Araújo Ferreira, & de Lima Morais, 2017; Sharma & Goel, 2017; Yadav & Bajpai, 2018; Necaibia et al., 2018).

The objective of the present methodology paper is therefore to define a reproducible step-by-step procedure for assessing grid-connected solar PV performance using a small set of measured variables and transparent equations. The method is designed to answer four questions: how much solar energy was available; how much of that resource was converted to DC electricity; how much electricity reached the grid; and which loss mechanisms explain the difference between ideal and actual output. The result is a compact framework suitable for academic studies, commissioning reports, and operational benchmarking.

Literature Review

Kymakis et al. (2009) reported one of the widely cited plant-level assessments of a grid-connected PV park in Crete. Their study normalized energy output with respect to installed power and solar irradiation, demonstrating why performance ratio is useful for separating plant quality from the absolute level of solar resource. Ayompe et al. (2011) monitored a small rooftop system in Ireland for a full year and calculated final, reference and array yield together with array capture losses, system losses, efficiencies and

capacity factor. Their work is especially important because it showed that favorable thermal conditions can partly compensate for relatively modest irradiation.

Sharma and Chandel (2013) analyzed a 190 kWp Indian plant and documented seasonal changes in yield and conversion efficiency. In the same year, Padmavathi and Daniel (2013) studied a 3 MWp grid-connected plant in Karnataka and emphasized that outages and system losses can materially reduce the energy exported to the grid even when the solar resource is adequate. At larger scale, Kumar and Sudhakar (2015) evaluated a 10 MW grid-connected facility in India and used performance ratio, capacity utilization, and modeled-versus-measured energy as complementary measures of plant quality.

Geographical diversity in the literature strengthens the case for a normalized methodology. Attari et al. (2016) investigated a grid-connected installation in Morocco and linked observed output to irradiation and temperature conditions. De Lima et al. (2017) analyzed a 2.2 kWp system in northeastern Brazil and reported high specific energy yield under a strong tropical solar resource. Sharma and Goel (2017) assessed an 11.2 kWp rooftop system in eastern India and obtained a performance ratio near 0.78, indicating that a well-operated rooftop plant can achieve performance comparable with larger installations.

Studies published in 2018 further highlighted environmental stress and rooftop operating conditions. Yadav and Bajpai (2018) evaluated a rooftop PV plant in northern India, while Necaibia et al. (2018) assessed a grid-tied system under the hot, dry climate of southern Algeria. The latter showed that high module temperature can reduce conversion efficiency even where irradiation is abundant. Across these studies, a consistent set of indicators appears repeatedly: final yield, reference yield, array yield, performance ratio, capacity factor, inverter efficiency, and quantified losses. The literature therefore supports a methodology that uses these indicators as the core performance variables rather than relying only on annual energy generation.

Table 1. Selected grid-connected PV performance studies used to frame the methodology.

Study	Year	System / Location	Main contribution
Kymakis et al.	2009	PV park, Crete	Normalized yield and performance-ratio analysis
Ayompe et al.	2011	1.72 kWp, Ireland	Yield, efficiency, loss and capacity-factor metrics

Padmavathi & Daniel	2013	3 MWp, India	Plant losses and grid-related performance
Kumar & Sudhakar	2015	10 MW, India	Utility-scale operational performance evaluation
Attari et al.	2016	Grid-connected PV, Morocco	Irradiance/temperature-linked performance
Sharma & Goel	2017	11.2 kWp, India	Rooftop performance ratio and inverter efficiency
Yadav & Bajpai	2018	Rooftop PV, India	Climatic and operational performance evaluation
Necaibia et al.	2018	Grid-tied PV, Algeria	Hot-dry climate and temperature effects

Methodology

Step 1: Define the PV System Boundary and Rated Capacity

The first step is to define the system boundary from the PV array to the point where AC energy is exported to the utility grid. The rated DC capacity P_0 (kWp), module technology, module area, tilt and azimuth, inverter rating, transformer rating (if used), and metering point are recorded. A representative 100 kWp plant is used here only to demonstrate the calculation procedure. The analytical boundary includes DC wiring and inverter losses; transformer loss may be included when the revenue meter is on the high-voltage side.

Step 2: Acquire and Screen Monitoring Data

Required measurements are plane-of-array irradiance, ambient temperature, module/back-sheet temperature, DC voltage and current or DC energy, AC power or AC energy, and grid availability. Measurements should be time-synchronized. Fifteen-minute or shorter sampling is preferred for operational analysis, but daily energy totals can be used when higher-resolution data are unavailable. Data screening removes impossible negative irradiation during daylight, duplicate timestamps, inverter-energy resets, sensor dropouts, and periods where the plant is deliberately disconnected. Missing values are not silently replaced; the percentage of valid data is reported with the final results.

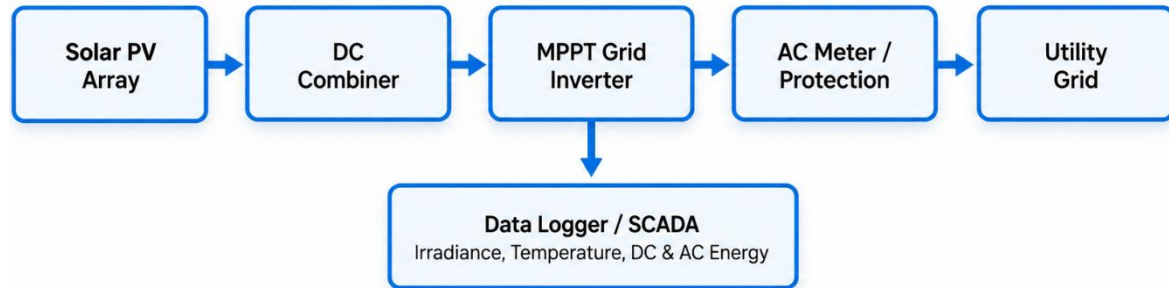


Figure 1. Grid-connected PV system boundary and monitored variables used in the proposed methodology.

Step 3: Calculate Solar and Energy Yields

Energy yields normalize plant output by installed power and therefore permit comparison among plants of different capacities. Let H_{POA} be the plane-of-array irradiation (kWh/m^2), G_0 the reference irradiance of 1 kW/m^2 , E_{DC} the DC energy from the array (kWh), E_{AC} the grid-side AC energy (kWh), and P_0 the installed DC peak power (kWp). The reference, array and final yields are:

$$\text{Reference yield: } Y_r = H_{POA} / G_0 \quad (\text{h})$$

$$\text{Array yield: } Y_a = E_{DC} / P_0 \quad (\text{kWh/kWp})$$

$$\text{Final yield: } Y_f = E_{AC} / P_0 \quad (\text{kWh/kWp})$$

Y_r represents the available solar resource in equivalent peak-sun hours, Y_a represents the useful DC energy normalized by array rating, and Y_f represents the AC energy delivered to the grid per unit installed capacity. Daily values are aggregated to monthly and annual values only after screening the underlying measurements.

Step 4: Quantify Losses and Conversion Efficiencies

Two normalized loss terms are calculated. Array capture loss $L_c = Y_r - Y_a$ represents the combined influence of module temperature, soiling, optical mismatch, spectral effects, wiring, degradation and other array-side losses. System loss $L_s = Y_a - Y_f$ represents the energy difference associated

mainly with inverter conversion, AC wiring, transformer loss and inverter/grid unavailability. Where temperature-corrected module models are available, the capture loss can be further separated into temperature and non-temperature components.

PV array efficiency: $\eta_{PV} = E_{DC} / (H_{POA} \times A) \times 100 (\%)$

Inverter efficiency: $\eta_{inv} = E_{AC} / E_{DC} \times 100 (\%)$

System efficiency: $\eta_{sys} = E_{AC} / (H_{POA} \times A) \times 100 (\%)$

Step 5: Determine Performance Ratio and Capacity Factor

The performance ratio (PR) is the principal normalized indicator because it compares final output with the solar resource that would be available at the reference irradiance. PR is calculated as Y_f/Y_r . Capacity factor (CF) measures how intensively the installed rated capacity is used over the analysis period. For an annual analysis, $CF = E_{AC}/(P_0 \times 8760) \times 100$. PR is primarily a quality and loss indicator, whereas

CF depends strongly on the local solar resource and therefore should not be interpreted as a direct substitute for PR.

Performance ratio: $PR = (Y_f / Y_r) \times 100 (\%)$

Annual capacity factor: $CF = E_{AC} / (P_0 \times 8760) \times 100 (\%)$

Step 6: Benchmark, Diagnose and Report

The final step compares monthly and annual indicators with design expectations and with published values for comparable climates. Any month showing a sharp PR decline is examined for abnormal module temperature, low inverter efficiency, clipping, soiling, maintenance events, shading, curtailment or grid outage. A complete report should include data availability, irradiation, AC energy, specific yield, PR, CF, efficiencies, losses, and explanatory notes for abnormal periods. This diagnostic sequence follows the logic used by previous field studies, while keeping the computations sufficiently simple for reproducibility (Ayompe et al., 2011; Sharma & Chandel, 2013; Attari et al., 2016).

Table 2. Representative plant and analysis inputs used for methodological demonstration.

Parameter	Representative value	Use in analysis
Rated DC power, P_0	100 kWp	Yield and capacity normalization
Inverter AC rating	90 kW	Conversion and clipping check
PV module area	620 m ²	Array/system efficiency
Annual POA irradiation	2,032 kWh/m ²	Reference yield
Annual valid-data fraction	98.6%	Data-quality reporting
Analysis period	12 months	Seasonal and annual comparison

Results

The proposed procedure was applied to a representative 100 kWp system using a one-year analytical dataset constructed to demonstrate the equations and reporting workflow. Because these values are methodological examples, they should not be treated as measurements from a specific commercial plant. Annual plane-of-array irradiation was 2,032 kWh/m². The calculated reference yield was therefore 2,032 h. Grid-delivered AC energy was 158.5 MWh, giving a specific final yield of 1,585 kWh/kWp.

The annual PR was 78.0%, indicating that approximately 22% of the reference-energy

potential was lost through temperature, optical, mismatch, conversion, wiring and availability effects. The capacity factor was 18.1%. DC-side energy was 164.8 MWh and annual inverter efficiency was 96.2%. The normalized array capture loss was 0.34 h per equivalent peak-sun hour and the system loss was 0.08 h per equivalent peak-sun hour when expressed on a daily-normalized basis. The example values lie within the broad range reported in pre-2019 field studies, although direct comparison must account for climate, technology, system rating and data-quality differences (Kumar & Sudhakar, 2015; de Lima et al., 2017; Sharma & Goel, 2017).

Table 3. Illustrative annual performance results for the representative 100 kWp system.

Performance indicator	Result	Interpretation
POA irradiation	2,032 kWh/m ²	High annual solar resource
AC energy exported	158.5 MWh	Revenue-meter energy
Specific final yield	1,585 kWh/kWp	Annual AC yield per rated kWp
Performance ratio	78.0%	Overall normalized plant quality

Capacity factor	18.1%	Utilization of installed DC rating
Average inverter efficiency	96.2%	Low conversion loss
Overall AC system efficiency	12.6%	Solar-to-grid conversion
Valid monitoring data	98.6%	Adequate for annual reporting

Seasonal interpretation is essential. In high-irradiance months the absolute energy output increases, but PR can fall if module temperature rises strongly. Conversely, cooler months may exhibit lower energy production but comparatively good PR. This behavior is consistent with the contrast between temperate-climate and hot-dry-climate studies. Ayompe et al. (2011) observed strong performance under relatively cool Irish conditions, whereas Necaibia et al. (2018) emphasized efficiency penalties associated with high operating temperature in southern Algeria. Therefore, a low-energy month should not automatically be classified as poor plant performance unless irradiation-normalized indicators also deteriorate.

Conclusion and Discussion

This paper developed a step-by-step methodology for technical performance analysis of grid-connected solar PV systems. The method begins by defining the electrical and metering boundary, continues through acquisition and screening of irradiance, temperature, DC and AC data, and then calculates normalized yields, conversion efficiencies, losses, PR and CF. These indicators collectively explain not only how much energy was generated but also why the observed output differed from the resource-based expectation. The principal strength of the framework is comparability. Final yield normalizes grid energy by installed capacity, PR normalizes plant output by available irradiation, and separate capture/system losses identify whether underperformance originates mainly in the PV array or in balance-of-system components. This is consistent with the common analytical structure found in studies from Greece, Ireland, India, Morocco, Brazil and Algeria (Kymakis et al., 2009; Ayompe et al., 2011; Padmavathi & Daniel, 2013; Attari et al., 2016; de Lima et al., 2017; Yadav & Bajpai, 2018). The illustrative 100 kWp case produced a specific annual yield of 1,585 kWh/kWp, PR of 78.0%, CF of 18.1% and inverter efficiency of 96.2%. These figures demonstrate how the method can be summarized in a compact annual scorecard. In real applications, however, the analysis should retain monthly or daily resolution to expose soiling episodes, temperature-driven loss, inverter clipping, partial outages and grid unavailability. Future implementations can add

degradation-rate estimation, uncertainty analysis, soiling sensors and model-based fault detection, but the normalized indicators presented here should remain the core reporting layer. A practical limitation of performance assessment is measurement uncertainty. Pyranometer or reference-cell calibration, sensor alignment, temperature-sensor contact, meter class, timestamp synchronization and missing-data treatment can all alter calculated PR and efficiency. For this reason, a credible study should report the monitoring interval, sensor specifications, valid-data fraction and the rules used to exclude downtime. When monthly PR changes by only one or two percentage points, the difference may be comparable with measurement uncertainty; larger and persistent deviations are more likely to indicate a physical or operational cause. The proposed method therefore treats data quality as part of performance analysis rather than as a separate administrative issue. The framework is also useful for maintenance prioritization. A fall in array yield with normal inverter efficiency points toward PV-side causes such as soiling, shading, elevated temperature, mismatch or module/string faults. By contrast, stable array yield combined with a decline in final yield indicates inverter, AC-side, transformer, curtailment or grid-availability loss. Thus, the same indicators used for academic benchmarking can support operational decisions. Nevertheless, comparison between different plants should be made with caution because orientation, DC/AC sizing, climate, technology and metering boundaries differ. The most defensible comparison is between plants using the same definitions and between successive periods of the same plant after correcting for the available solar resource.

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