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Normalized Performance Assessment and Loss Evaluation of Grid-Connected Photovoltaic Systems

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Abstract

The technical performance of grid-connected photovoltaic systems depends not only on available solar irradiation but also on module temperature, inverter operation, system losses, grid availability, maintenance, and long-term component degradation. This study presents a reproducible methodology for normalized performance assessment and loss evaluation of grid-connected photovoltaic systems using routinely monitored plant and meteorological data. The framework begins with data acquisition and quality screening and then calculates reference yield, final yield, performance ratio, capacity factor, conversion efficiency, and normalized array and system losses. Monthly and annual aggregation is used to identify seasonal variation, while environmental and operational analysis is applied to distinguish irradiation-related effects from temperature, soiling, mismatch, inverter downtime, wiring loss, and grid-interruption impacts. Performance ratio is treated as a central normalized indicator because it allows plant conversion quality to be evaluated with reduced dependence on absolute solar-resource magnitude. The methodology is validated using published benchmark studies covering rooftop, commercial, and utility-scale grid-connected PV installations operating under different climatic conditions and module technologies. The reviewed evidence shows substantial variation in annual performance ratio and specific energy yield across sites, confirming that system performance should be interpreted relative to local climate, technology, plant age, maintenance history, and data quality rather than against a single universal threshold. The proposed framework supports technical diagnosis, operation and maintenance assessment, technology comparison, commissioning review, and long-term degradation monitoring of grid-connected photovoltaic assets.

Introduction

Solar photovoltaic power plants directly convert incident solar radiation into electrical energy and can be connected to the utility network through power-conditioning units and grid-synchronized inverters. Unlike conventional generators, the available PV power changes continuously with the solar resource and module temperature.

Therefore, installed capacity alone cannot describe whether a plant is operating effectively. Performance evaluation requires normalized indicators that relate the measured energy output to the available irradiation, rated array capacity, conversion losses, and plant operating time. This is particularly important for grid-connected systems because inverter behavior,

grid interruptions, clipping, wiring losses, soiling, mismatch, and temperature effects can reduce the energy finally exported to the network.

Early field studies demonstrated the usefulness of standardized indicators for comparing PV plants installed under very different climatic conditions. Kymakis et al. (2009) used reference yield, final yield, performance ratio, and detailed loss accounting for a 171.36 kWp plant in Crete. Ayompe et al. (2011) extended this type of analysis to a rooftop grid-connected system in Ireland and reported monthly and annual values for yield, efficiencies, losses, performance ratio, and capacity factor. In India, Sharma and Chandel (2013) evaluated a long-operating 190 kWp plant and compared measured energy production with PVsyst predictions, while Padmavathi and Daniel (2013) analyzed a 3 MWp plant using monitored data and normalized IEC-style metrics. Together these studies show that performance analysis must combine resource-normalized measures with component-level and operational loss information.

The objective of the present methodology is to provide a step-by-step framework for assessing the technical performance of a grid-connected PV power generation system using routinely available measurements. The methodology is designed to answer four practical questions: (i) how much energy the plant produces per unit installed capacity, (ii) how effectively the plant converts the available solar resource into grid energy, (iii) where major losses occur, and (iv) whether performance changes with season or time. The framework is intentionally general so that it can be adapted to rooftop, commercial, and utility-scale installations.

Literature Review

Published research up to 2019 provides a broad evidence base for evaluating grid-connected PV systems. Kymakis et al. (2009) reported an annual performance ratio of 67.36% for a 171.36 kWp park in Crete and quantified temperature, soiling, internal, power electronics, grid-availability, and interconnection losses. Ayompe et al. (2011) reported an annual performance ratio of 81.5% for a 1.72 kWp rooftop system in Dublin, demonstrating that high normalized performance can be achieved even under

relatively low insolation when operating temperatures are moderate. These studies established that climatic conditions affect energy yield but do not alone determine normalized plant performance.

Indian studies are especially useful for hot-climate applications. Sharma and Chandel (2013) reported an annual average performance ratio of 74% for a 190 kWp grid-interactive plant at Khatkar-Kalan and found the simulated annual energy yield to be close to the measured value. Padmavathi and Daniel (2013) reported approximately 1372 kWh/kWp annual energy generation and an average performance ratio of about 0.70 for a 3 MWp plant in Karnataka. These results emphasize the need to evaluate thermal, inverter, grid-failure, mismatch, and wiring losses in addition to solar resource. Milosavljević et al. (2015) reported a high annual mean performance ratio for a 2-kW rooftop system in Niš and showed that energy efficiency decreased with increasing ambient temperature, illustrating the importance of local climate and module temperature.

Later research focused on comparability, technology choice, and long-term assessment. Khalid et al. (2016) reviewed performance ratio definitions and argued that PR is a crucial indicator for diagnosing underperformance and comparing plants. Li (2018) compared seven PV technologies under the same climate and showed that output, efficiency, yield, and performance ratio depend on module technology as well as weather. Purohit and Purohit (2018), using data from 39 Indian projects, showed that the choice of solar radiation database can materially affect predicted capacity factor and economic assessment. Ramanan et al. (2019) compared co-located polycrystalline-silicon and CIS systems and reported annual average PR values of 78.48% and 86.73%, respectively. Roumpakias and Stamatelos (2019) demonstrated the value of multi-year monitoring by identifying a small but measurable performance deterioration after six years of operation. The literature therefore supports a methodology that integrates normalized performance indicators, data quality checks, environmental variables, and time-trend analysis.

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

Study	System / Location	Main indicator(s)	Key methodological contribution
Kymakis et al. (2009)	171.36 kWp, Crete	PR, yields, losses	Explicit loss breakdown and grid-availability effects
Ayompe et al. (2011)	1.72 kWp, Ireland	YF, YR, PR, CF, efficiencies	Monthly/annual monitoring under cool maritime climate

Sharma & Chandel (2013)	190 kWp, India	PR, CF, system efficiency	Measured vs. PVsyst energy-yield comparison
Padmavathi & Daniel (2013)	3 MWp, India	PR, yield, capture/system losses	IEC-style plant evaluation with grid/inverter failures
Li (2018)	Seven 8 kWp technologies, China	Energy, efficiency, PR, yields	Technology comparison under identical climate
Ramanan et al. (2019)	p-Si and CIS, India	PR, yield, PV efficiency	Measured vs. simulated technology comparison

Methodology

The proposed method uses one complete year of synchronized plant and meteorological data where available; shorter periods may be used for preliminary assessment, while multi-year records are preferred for degradation studies. Measurements should include plane-of-array

irradiance (GPOA), ambient and/or module temperature, AC energy exported to the grid, rated DC capacity, inverter status, and grid availability. DC array energy is desirable because it allows separation of array and inverter/system losses. The calculation sequence is shown in Figure 1.

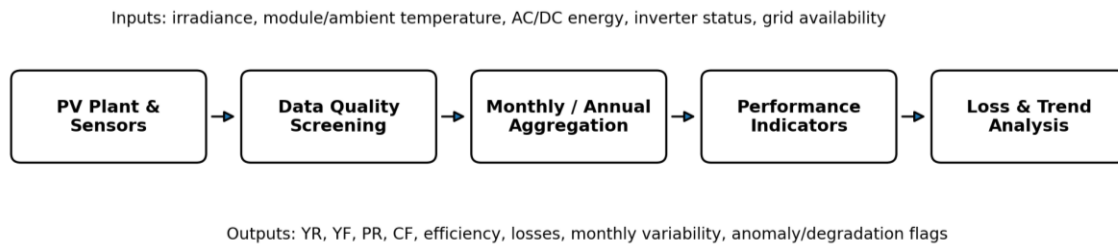


Figure 1. Step-by-step workflow for performance analysis of a grid-connected solar PV system.

Step 1 - System definition and data acquisition

Record the installed DC capacity P_0 (kWp), module technology, number of modules, array area, tilt and azimuth, inverter rating, transformer/grid connection, monitoring interval, and sensor specifications. Acquire time-synchronized irradiance, temperature, energy, inverter, and grid-status data. A 5- or 15-minute interval is preferred for operational analysis, but hourly data are sufficient for monthly energy metrics.

Step 2 - Data-quality screening

Remove duplicate timestamps, impossible sensor values, night-time irradiance artifacts, and periods in which sensors are known to have failed. Flag rather than silently delete inverter or grid outages because they represent real availability losses. For performance-ratio calculations, exclude records with missing irradiance or exported energy. Calculate data completeness for each month; months with substantial missing data should be reported separately and not directly compared with complete months.

Step 3 - Performance indicator calculations

The analysis is based on normalized energy indicators widely used in grid-connected PV studies. Let HPOA be the integrated plane-of-array irradiation (kWh/m^2), GSTC = $1 \text{ kW}/\text{m}^2$ the reference irradiance, EAC the AC energy delivered to the grid (kWh), and P_0 the rated DC

array power (kWp). The main indicators are calculated as follows:

Reference yield: $YR = \text{HPOA} / \text{GSTC}$ (h or kWh/kWp -equivalent)

Final yield: $YF = \text{EAC} / P_0$ (kWh/kWp)

Performance ratio: $PR = (YF / YR) \times 100$ (%)

Capacity factor: $CF = \text{EAC} / (P_0 \times T) \times 100$ (%)

For annual calculations, T is normally 8760 h. If array area A is known, the overall system conversion efficiency can be estimated as $\eta_{\text{sys}} = \text{EAC} / (\text{HPOA} \times A) \times 100$. Where DC energy is measured, array yield $YA = \text{EDC} / P_0$, array capture loss $LC = YR - YA$, and system loss $LS = YA - YF$. These normalized losses allow the analyst to distinguish resource-to-array losses from inverter and downstream electrical losses.

Step 4 - Environmental and operational loss analysis

Group the data by irradiance and module-temperature ranges to examine thermal sensitivity. Compare high-irradiance periods with lower-energy output to identify temperature or clipping effects. Compare inverter-availability logs and grid-outage periods with lost production. If cleaning records are available, evaluate yield before and after cleaning to estimate soiling influence. Mismatch, cable, transformer, and inverter losses should be reported using measured DC/AC data or manufacturer-based estimates when direct measurements are unavailable.

Step 5 - Monthly, annual, and long-term comparison

Calculate monthly EAC, YR, YF, PR, CF, and efficiency before computing annual values from annual energy and irradiation totals. Do not average monthly PR values without weighting when monthly irradiation differs markedly. Compare the resulting indicators with published plants operating under similar climates and technologies. For multi-year data, regress normalized annual yield or temperature-corrected efficiency against operating year to identify degradation trends, following the long-term logic used by Roumpakias and Stamatelos (2019).

Results

Because this paper presents a methodology rather than a new monitored plant, the results are expressed as literature-benchmark validation ranges. The selected studies confirm that the proposed indicators are sufficiently sensitive to climate, technology, maintenance, and plant condition to support diagnostic evaluation. Table 2 summarizes representative reported outcomes from the reference set. The values should not be treated as universal acceptance limits; they are comparison points for interpreting a new plant after differences in climate, technology, age, and data availability are considered.

Table 2. Literature benchmarks for interpreting calculated performance indicators

Reference	Capacity / site	Annual PR	Specific energy / other result	Interpretation
Kymakis et al. (2009)	171.36 kWp, Crete	67.36%	229 MWh exported in 2007	Loss accounting identifies temperature, soiling and availability effects.
Ayompe et al. (2011)	1.72 kWp, Ireland	81.5%	885.1 kWh/kWp; CF 10.1%	Cool conditions can support high normalized performance despite lower insolation.
Sharma & Chandel (2013)	190 kWp, India	74%	812.76 kWh/kWp; CF 9.27%	Measured/simulated agreement helps validate energy models.
Padmavathi & Daniel (2013)	3 MWp, India	~70%	1372 kWh/kWp	Grid and inverter failures should be separated from solar-resource effects.
Ramanan et al. (2019)	p-Si vs. CIS, India	78.48% / 86.73%	CIS AC energy 7.61% higher	Co-located technology comparison isolates technology effects.
Roumpakias & Stamatelos (2019)	99.84 kWp, Greece	Multi-year	1-4% deterioration indicated	Long-term normalized analysis can reveal ageing/degradation.

Three practical observations follow from these benchmarks. First, performance ratio is more informative than energy yield alone when plants experience different solar resources, consistent with the review by Khalid et al. (2016). Second, a high annual irradiation does not guarantee a high PR because temperature, inverter conversion, clipping, soiling, downtime, and mismatch can increase losses. Third, technology comparisons should ideally use co-located systems; Li (2018) and Ramanan et al. (2019) showed that module technology can produce measurable differences even under the same environment. In large portfolios, predicted performance also depends on the quality of irradiation data, as demonstrated by Purohit and Purohit (2018). For application to a new plant, a useful diagnostic sequence is therefore to verify data

completeness, calculate monthly YF and PR, identify months with abnormal deviation, correlate those months with temperature and availability, and finally compare the annual indicators with similar plants. A sustained decrease in temperature-corrected PR across years warrants inspection for soiling patterns, module degradation, interconnection resistance, inverter ageing, or persistent grid curtailment rather than being attributed to seasonal irradiation alone.

Conclusion and Discussion

This methodology provides a concise and reproducible approach for technical performance assessment of grid-connected solar PV power generation systems. The method begins with plant and sensor definition, applies explicit data-

quality checks, calculates normalized energy indicators, separates array and system losses where DC measurements are available, and evaluates environmental and operational causes of underperformance. The central indicators are final yield, reference yield, performance ratio, capacity factor, conversion efficiency, and normalized losses. Among them, PR is particularly useful because it enables comparison across time and, with appropriate caution, across different sites. The reviewed literature shows that annual PR and specific yield vary widely with climate, technology, age, system design, and maintenance. Consequently, a single threshold should not be used as a universal definition of satisfactory performance. Instead, a plant should be assessed against its own historical baseline, design simulation, local solar resource, and peer plants using similar technology. The approach also highlights the importance of distinguishing solar-resource variability from controllable losses such as inverter downtime, soiling, mismatch, cable losses, and grid outages. The method is appropriate for academic case studies, commissioning reviews, operation-and-maintenance audits, and long-term performance tracking. Its main limitation is dependence on reliable irradiance and energy measurements; inaccurate irradiance sensors can bias PR and loss calculations. Future applications should incorporate sensor uncertainty, automated anomaly detection, temperature-corrected degradation analysis, and comparison with high-resolution simulation. When these controls are applied, the framework provides a strong basis for identifying performance gaps and improving the energy delivered by grid-connected PV assets.

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