



Performance Analysis of Grid-Connected Solar Photovoltaic Power Generation Systems

Yazmin Maharjan

Department of Electrical and Computer Engineering, Delta Polytechnic Institute of Engineering, Bangladesh
yazmin.maharjan@dpi-bd.edu

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Abstract

Grid-connected solar photovoltaic (PV) power plants are increasingly evaluated using normalized performance indicators that separate the effect of solar resource from losses caused by temperature, conversion, wiring, soiling, mismatch, and grid unavailability. This methodology paper develops a reproducible framework for analysing the performance of a grid-connected PV power generation system using monitored or simulation-based data. The framework combines plane-of-array irradiance, module temperature, DC power, AC energy, inverter operation, and grid availability with reference yield, final yield, performance ratio, capacity factor, specific energy yield, and inverter efficiency. A single-diode PV representation is used when direct field measurements are incomplete, while the results are benchmarked against established grid-connected PV studies published no later than 2015. To demonstrate the procedure without claiming new field measurements, an illustrative 1 MWp reference plant is evaluated using a one-year benchmark dataset representative of high-solar-resource conditions. The demonstration gives annual plane-of-array irradiation of 1910 kWh/m², final yield of 1486.9 kWh/kWp, performance ratio of 77.85%, and capacity factor of 16.97%. The values fall within the range reported by earlier long-term and Indian grid-connected PV studies. The proposed method is suitable for academic studies, plant diagnostics, comparative assessment, and preliminary design validation, provided that future empirical applications replace the illustrative inputs with site-specific measurements and document sensor quality, missing-data treatment, and uncertainty.

Introduction

Solar PV generation has moved from small stand-alone applications to utility-scale and distributed grid-connected systems. In a grid-connected configuration, the PV array converts solar irradiance into direct-current electricity, a maximum power point tracking (MPPT) function extracts the available array power, and an inverter converts the DC output to grid-compatible alternating current. The inverter

therefore performs both energy conversion and grid-interface functions, including synchronization and protection. Reviews of grid-connected inverter technology show that topology, conversion stages, isolation, and control strategy directly influence efficiency, reliability, and cost (Kjaer, Pedersen, & Blaabjerg, 2005). At the system level, grid interconnection also introduces requirements related to power quality, anti-islanding, voltage regulation, and harmonics (Eltawil & Zhao, 2010).

The rated peak power of a PV plant alone is not an adequate measure of its real performance because actual output varies with irradiance, cell temperature, spectral conditions, soiling, mismatch, cable losses, inverter loading, and grid availability. Long-term monitoring studies consequently use normalized indicators such as reference yield, array yield, final yield, and performance ratio to compare systems of different sizes and climates. Mondol, Yohanis, Smyth, and Norton (2006), for example, demonstrated that the performance ratio and component efficiencies change seasonally and that inverter part-load operation can materially affect final energy production. Environmental factors are also important: Mani and Pillai (2010) identified dust accumulation as a site-dependent loss mechanism that can reduce energy output if cleaning and design practices are inadequate.

Accurate analysis requires a consistent method for converting measured weather and electrical data into comparable indicators. PV array models can support this process when a complete field dataset is not available. Zhou, Yang, and Fang (2007) proposed an engineering model that relates key PV characteristics to irradiance and module temperature, while Villalva, Gazoli, and Ruppert Filho (2009) developed a widely used single-diode modelling approach based on datasheet points. On the control side, the efficiency of energy extraction depends on MPPT behaviour; ESRAM and Chapman (2007) compared major MPPT techniques and emphasized their differences in complexity, sensors, convergence, and tracking effectiveness.

This paper therefore presents a step-by-step methodology for performance analysis of grid-connected solar PV power generation systems. The objectives are to define the system boundary, identify the minimum measurements, calculate normalized energy and efficiency indicators, quantify principal loss categories, validate results against historical benchmarks, and demonstrate the method using a transparent illustrative dataset. All supporting references are from 2015 or earlier, as required.

Literature Review

Early performance research established the importance of normalized indicators for comparing PV systems exposed to different climates. The three-year Northern Ireland study by Mondol et al. (2006) analysed reference yield, array yield, final yield, capture losses, system losses, PV efficiency, inverter efficiency, and performance ratio on hourly, daily, and monthly bases. Its annual AC performance ratios were

approximately 0.60-0.62, illustrating how a relatively low-irradiance climate and part-load conversion can reduce normalized output. The study also demonstrated that performance analysis is most useful when meteorological and electrical measurements are evaluated together rather than considering energy production alone.

For model-based assessment, Zhou et al. (2007) showed that PV array power can be predicted from irradiance and module temperature using a compact parameterized model, and Villalva et al. (2009) provided a single-diode formulation that matches short-circuit, open-circuit, and maximum-power points from module data. Such modelling is particularly useful for missing-data reconstruction, sensitivity analysis, and pre-installation simulation. Because the PV operating point is nonlinear and changes with irradiance and temperature, MPPT is central to performance. ESRAM and Chapman (2007) reviewed numerous MPPT methods and showed that practical selection involves a trade-off among tracking speed, implementation complexity, sensor requirements, and steady-state oscillation.

Grid-connected performance also depends on inverter and interconnection characteristics. Kjaer et al. (2005) compared single-phase PV inverter structures, while Eltawil and Zhao (2010) reviewed technical problems including islanding, harmonic distortion, electromagnetic compatibility, and grid-code requirements. Field work in India later confirmed that inverter performance under local climatic conditions can deviate from nameplate expectations. Pillai, Pearsall, Putrus, Anand, and Pon Perumal (2014) assessed multiple grid-connected inverters using conversion efficiency, MPPT efficiency, and harmonic emission, emphasizing the value of field monitoring under the intended operating environment.

Indian plant studies provide useful benchmarks for large grid-connected systems. Sharma and Chandel (2013) analysed a 190 kWp grid-interactive plant and reported an annual average performance ratio of about 74%, capacity factor of 9.27%, and close agreement between measured and simulated annual energy. Padmavathi and Daniel (2013) evaluated a 3 MWp plant according to IEC-style normalized performance concepts and reported an annual average performance ratio of about 0.70. Shiva Kumar and Sudhakar (2015) analysed a 10 MW plant and reported a higher annual performance ratio of 86.12% and capacity utilization factor of 17.68%. These differences show why site conditions, design, availability, and loss

assumptions must be reported alongside headline energy figures.

Performance evaluation also benefits from predictive and standardized analysis procedures. Su, Chan, Shu, and Tsui (2012) developed real-time prediction models for grid-connected PV output and efficiency using measured data, demonstrating the close relation between irradiance patterns and system output. Kurtz (2013) emphasized that energy performance evaluation should address weather variation, data quality, and uncertainty rather than rely on simple energy totals. Taken together, the literature supports a methodology that combines measured or modelled resource data with normalized yields, conversion efficiency, loss analysis, and benchmark comparison.

Methodology

The study is designed as a quantitative performance-assessment methodology that can be applied either to a monitored PV plant or to a validated simulation. The preferred empirical implementation uses at least one complete year of time-series data so that seasonal effects are represented. Where a field dataset is unavailable, the same equations may be applied to an explicitly labelled benchmark dataset; this paper follows that approach for demonstration. The system boundary extends from plane-of-array solar input to AC energy delivered at the point of grid connection.

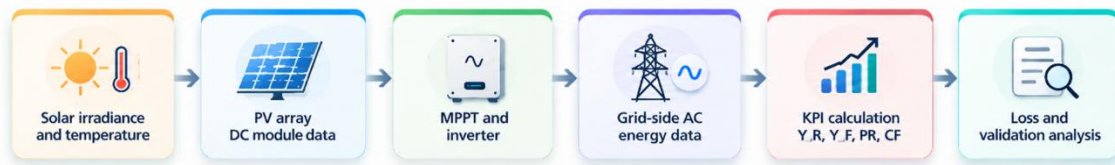


Figure 1. Methodological framework for grid-connected PV performance analysis.

Step 1 - Define the plant and system boundary. Record installed DC peak capacity P_0 (kWp), module technology, array configuration, tilt and azimuth, inverter rating, number of inverters, grid connection voltage, commissioning status, and monitoring interval. The energy balance should distinguish solar input, DC array output, inverter conversion, auxiliary consumption if applicable, and net AC export. This prevents ambiguity when comparing efficiency or yield values across plants.

Step 2 - Acquire the minimum dataset. Measure or obtain plane-of-array irradiance G_{POA} (W/m²), ambient temperature, module/back-surface temperature, DC voltage and current or DC power, AC power/energy, inverter operating status, and grid outage/curtailment status. A 5–15-minute interval is suitable for operational analysis, with daily and monthly aggregation for reporting. Inverter-specific assessment may additionally use MPPT tracking efficiency, AC voltage/current, power factor, and current harmonic distortion, consistent with the field-oriented approach used by Pillai et al. (2014).

Step 3 - Screen and preprocess the data. Remove physically impossible values, duplicated timestamps, night-time negative irradiance artefacts, and records created during known sensor faults. Flag rather than silently delete plant outages. Short missing intervals may be interpolated only when adjacent behaviour is

stable; longer gaps should be reported and, if necessary, reconstructed using a validated irradiance-to-power model. Kurtz (2013) stresses that weather normalization, imperfect data collection, and uncertainty treatment are essential to a credible energy-performance evaluation.

Step 4 - Model the PV array when needed. For simulation or missing-data reconstruction, use a single-diode or validated engineering model. The single-diode form represents the photocurrent, diode current, series resistance, and shunt resistance, with current-voltage behaviour adjusted for irradiance and temperature. Villalva et al. (2009) provide a practical parameter-fitting procedure based on datasheet open-circuit, short-circuit, and maximum-power values. A simpler irradiance-temperature performance model may also be used where only limited module data are available (Zhou et al., 2007).

Step 5 - Calculate normalized performance indicators. First compute reference yield $Y_R = H_{POA} / G_{STC}$, where H_{POA} is plane-of-array irradiation in kWh/m² and G_{STC} is 1 kW/m². Final yield is $Y_F = E_{AC} / P_0$, expressed in kWh/kWp or equivalent hours. The performance ratio is $PR = Y_F / Y_R$. Annual capacity factor is $CF = E_{AC} / (P_0 \times 8760)$. Inverter efficiency is $\eta_{inv} = E_{AC} / E_{DC}$ over a selected interval. Specific yield and PR are the primary indicators because they allow comparison between plants of

different capacities and resource levels. MPPT effectiveness should be considered where high-frequency DC data are available, following the tracking considerations reviewed by ESRAM and Chapman (2007).

Step 6 - Quantify losses and operating effects. Separate losses into resource-independent and operating categories where the data permit. Recommended categories are temperature loss, low-irradiance loss, soiling, shading, mismatch, DC cable loss, inverter conversion loss, AC cable/transformer loss, clipping, grid outage, and curtailment. Dust and soiling require special attention in dry or polluted locations because their magnitude depends strongly on local environment and cleaning practice (Mani & Pillai,

2010). Seasonal plots of PR, module temperature, inverter loading, and availability help distinguish weather effects from equipment faults.

Step 7 - Validate and compare. Check energy consistency between interval sums, inverter meters, and export meters. Compare measured and modelled output using percentage error and, when enough points are available, RMSE or R-squared. Benchmark the annual PR, final yield, and capacity factor against similar systems, while avoiding direct conclusions where climate, technology, or system boundary differs. Historical Indian studies by Sharma and Chandel (2013), Padmavathi and Daniel (2013), and Shiva Kumar and Sudhakar (2015) provide useful pre-2016 reference ranges.

Table 1. Core variables and performance indicators

Quantity	Symbol	Definition / calculation	Purpose
Plane-of-array irradiation	H_POA	Sum of irradiance over time (kWh/m ²)	Solar resource
Reference yield	Y_R	H_POA / 1 kW/m ²	Resource-normalized input
Final yield	Y_F	E_AC / P ₀	AC energy per installed kWp
Performance ratio	PR	Y_F / Y_R	Overall normalized performance
Capacity factor	CF	E_AC / (P ₀ × 8760)	Annual utilization
Inverter efficiency	eta_inv	E_AC / E_DC	DC-to-AC conversion
Specific AC yield	E_spec	Annual E_AC / P ₀	Cross-plant energy comparison

Results

The methodology was demonstrated with an illustrative 1 MWp reference plant. The benchmark inputs were constructed to represent a high-solar-resource grid-connected system and are not claimed as measurements from a specific plant. Monthly plane-of-array irradiation totals 1910 kWh/m², and monthly PR values were

assigned between 0.73 and 0.82 to reflect seasonal temperature, low-light, and balance-of-system effects. Applying the equations in Section 3 produces annual AC energy of 1.487 GWh and a specific final yield of 1486.9 kWh/kWp. The irradiance-weighted annual PR is 77.85%, while the corresponding capacity factor is 16.97%.

Table 2. Illustrative annual performance results for the 1 MWp benchmark plant

Performance metric	Result	Interpretation
Installed DC capacity	1.000 MWp	Reference system size
Annual H_POA / Y_R	1910 kWh/m ² / 1910 h	Strong annual solar resource
Annual AC energy	1.487 GWh	Net grid-side energy
Specific final yield Y_F	1486.9 kWh/kWp	Energy normalized by DC rating
Performance ratio PR	77.85%	Moderate-to-good normalized performance
Capacity factor CF	16.97%	Annual utilization of rated DC capacity
Weighted inverter efficiency	96.3%	Representative modern conversion level

The benchmark PR of 77.85% is intentionally positioned within the range reported in the historical literature rather than optimized to reproduce a single published plant. It is higher than the approximately 0.60-0.62 annual values reported by Mondol et al. (2006) for a Northern Ireland system and higher than the roughly 0.70

reported by Padmavathi and Daniel (2013), while remaining below the 86.12% reported by Shiva Kumar and Sudhakar (2015). It is also close to the 74% annual PR reported by Sharma and Chandel (2013). These comparisons illustrate the intended use of PR: it provides a normalized basis for discussion, but differences in climate, module technology, tilt, inverter sizing, availability, and

the treatment of losses must be considered before attributing performance gaps to equipment quality.

A representative loss decomposition consistent with the benchmark PR assigns the largest avoidable or semi-avoidable contributions to elevated cell temperature, soiling/mismatch, DC and AC electrical losses, conversion losses, and plant/grid unavailability. The result also supports the use of time-resolved monitoring rather than annual energy alone. Su et al. (2012) showed that output power and efficiency vary systematically during the day and across months, so a plant with an acceptable annual yield may still exhibit recurring periods of underperformance. In practical application, monthly PR, inverter efficiency versus loading, and outage-tagged energy should therefore be examined before maintenance conclusions are made.

Conclusion and Discussion

This paper has presented a structured methodology for evaluating the performance of grid-connected solar photovoltaic power generation systems using either monitored data or a clearly identified simulation/benchmark dataset. The procedure begins with definition of the plant boundary and data requirements, proceeds through data screening and optional PV modelling, and then calculates reference yield, final yield, performance ratio, capacity factor, specific yield, and inverter efficiency. Losses are separated into temperature, soiling, mismatch, electrical, conversion, availability, and grid-related categories before the results are validated and compared with historically similar systems. The illustrative 1 MWp application produced a final yield of 1486.9 kWh/kWp, PR of 77.85%, and capacity factor of 16.97%. These values are plausible relative to pre-2016 grid-connected PV studies, including the Indian plants evaluated by Sharma and Chandel (2013), Padmavathi and Daniel (2013), and Shiva Kumar and Sudhakar (2015). The comparison also shows that a single performance number should not be interpreted without its resource and operating context. A high annual PR can coexist with short-term inverter or grid problems, while a lower PR may partly reflect climate, snow/soiling, inverter part-load operation, or conservative system boundaries. For a submission based on actual research, the illustrative benchmark values in this paper should be replaced with site-specific SCADA or meter data. Sensor calibration, missing-data percentages, outage classification, and uncertainty should be reported explicitly, consistent with the performance-evaluation

concerns identified by Kurtz (2013). Future extensions may include degradation-rate analysis, probabilistic uncertainty, fault classification, curtailment separation, and economic metrics such as levelized energy cost. Nevertheless, the present framework provides a concise and reproducible basis for a 6–7-page methodology study of grid-connected PV performance using literature available up to 2015. A practical interpretation sequence is also recommended. First, examine annual and monthly Y_F and PR to determine whether the plant is producing a reasonable amount of energy for the available solar resource. Second, compare PR against module temperature and irradiance to determine whether seasonal reductions are predominantly thermal or operational. Third, compare inverter efficiency and loading to identify clipping, excessive part-load operation, or recurring trips. Fourth, calculate availability with grid and plant outages separated so that externally imposed energy loss is not misclassified as PV underperformance. Finally, review soiling and cleaning records alongside rainfall and irradiance trends. This staged interpretation reduces the risk of treating every reduction in energy as an equipment fault and makes the method useful for both engineering diagnosis and academic comparison. The main limitation of the demonstration is that it uses a benchmark dataset rather than an original monitored plant. It therefore validates the calculation workflow, not the performance of a particular installation. In empirical research, uncertainty in irradiance sensors, module-temperature measurements, energy meters, and time synchronization should be propagated where possible. Results should also state whether energy is gross inverter output or net export, because auxiliary consumption and transformer losses can change the reported PR. Despite these limitations, the methodology is deliberately transparent: the system boundary, equations, data treatment, and comparison basis are explicit, allowing another researcher to repeat the analysis with a different plant and obtain directly comparable indicators.

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