



Performance Analysis of Grid-Connected Solar Photovoltaic Power Generation Systems

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Peer Review Information	Abstract
<i>Submission: 18 Jan 2017</i> <i>Revision: 09 Feb 2017</i> <i>Acceptance: 26 March 2017</i> Keywords <i>Grid-connected photovoltaic system, performance ratio, energy yield, MPPT, inverter efficiency.</i>	This paper presents a systematic methodology for evaluating the technical performance of grid-connected solar photovoltaic (PV) power generation systems. The approach combines PV-array modeling, maximum power point tracking (MPPT), inverter and grid-interface representation, loss accounting, and standardized energy-yield indicators. A representative 100 kWp simulation case is used to demonstrate the method under variable irradiance and module temperature conditions. The performance indices include reference yield, array yield, final yield, performance ratio, capacity factor, DC-to-AC conversion efficiency, system efficiency, energy losses, and power-quality indicators. The modeled case produces 158.4 MWh of annual AC energy, a specific final yield of 1,584 kWh/kWp, a performance ratio of 82.5%, a capacity factor of 18.1%, and an average DC-to-AC energy conversion efficiency of 95.5%. These values are within the broad range reported for well-performing grid-connected PV installations in the pre-2018 literature. The methodology is intentionally transparent so that it can be reproduced in MATLAB/Simulink, PVsyst, or an equivalent numerical environment and later validated using measured plant data

Introduction

Grid-connected solar photovoltaic generation converts incident solar radiation into electrical energy and injects the usable AC power directly into the utility network. Unlike stand-alone PV installations, a grid-connected plant is not primarily constrained by local battery storage; instead, its technical performance depends on the interaction among the PV array, power-electronic converters, grid synchronization, protection, weather conditions, and system losses. Power-electronic interfaces therefore play a decisive role in extracting energy from the PV generator while satisfying utility requirements for voltage, frequency, waveform quality, and safe disconnection. Carrasco et al. (2006) showed that renewable-energy grid integration is fundamentally a power-electronics and control problem, while Eltawil and Zhao (2010) emphasized the technical challenges of

grid-connected PV systems, including islanding, harmonics, protection, grounding, and voltage regulation.

A performance study should distinguish between installed capacity and useful energy production. Rated PV capacity is specified at standard test conditions, but actual operating power changes continuously with plane-of-array irradiance, cell temperature, spectrum, shading, mismatch, soiling, wiring losses, converter efficiency, and inverter clipping. Consequently, two plants having the same nominal kWp rating can deliver very different annual energy. Long-term field studies have therefore relied on normalized yield, system efficiency, and performance ratio to compare plants across different climates and sizes. Mondol et al. (2006) used these indicators to study a roof-mounted PV installation over several years, while Sharma and Chandel (2013)

reported annual energy yield, performance ratio, capacity factor, and system efficiency for a 190 kWp Indian plant.

The electrical control strategy is equally important. A PV array has a nonlinear current-voltage characteristic with a single operating point at which output power is maximum. ESRAM and CHAPMAN (2007) compared commonly used MPPT methods and demonstrated the importance of tracking accuracy and dynamic behavior. At the grid interface, inverter topology, modulation, filtering, synchronization, and current control determine the amount and quality of energy delivered to the network. KJAER *et al.* (2005) reviewed single-phase grid-connected PV inverter configurations and highlighted the trade-offs among conversion stages, isolation, efficiency, and lifetime. More generally, MAHOLA and SHAIK (2017) summarized the architectures and control functions needed to operate grid-interfaced solar PV systems reliably.

The objective of the present methodology paper is to define a reproducible procedure for performance analysis rather than to claim a new field installation. The study uses a representative 100 kWp grid-connected PV model so that all assumptions, equations, losses, and performance indicators can be stated explicitly. The modeled outputs are then interpreted against results reported in the literature up to and including 2017. This separation between model output and published field evidence is important: the numerical values in the Results section are simulation-based and should be replaced by measured data when the methodology is applied to an actual power plant.

Literature Review

Early research on grid-connected PV established the importance of inverter architecture and grid compatibility. KJAER *et al.* (2005) classified single-phase PV inverters according to power-processing stages, transformer use, and module/string arrangements. Their review showed that inverter design affects efficiency, leakage current, cost, reliability, and the ability to inject a low-distortion sinusoidal current into the grid. CARRASCO *et al.* (2006) extended this perspective to renewable-energy interfaces more broadly, identifying power-electronic conversion, current regulation, synchronization, and protective functions as core elements of distributed generation integration.

Performance monitoring literature established normalized indicators that allow comparison between installations with different capacities and climates. MONDOL *et al.* (2006) analyzed a 13

kWp grid-connected system in Northern Ireland and showed how irradiation, inverter operation, shading, and seasonal conditions influence performance ratio and conversion efficiency. These indicators remain useful because they separate the available solar resource from the effectiveness with which the plant converts that resource into grid-delivered electricity.

The nonlinear nature of the PV source has motivated extensive MPPT research. ESRAM and CHAPMAN (2007) compared perturb and observe, incremental conductance, fractional open-circuit voltage, fractional short-circuit current, fuzzy logic, and other tracking methods. The study made clear that no single algorithm is universally optimal; performance depends on implementation complexity, sensor requirements, convergence speed, and behavior during rapidly changing irradiance. For performance analysis, this implies that tracking losses must be included rather than assuming that the array always operates exactly at the theoretical maximum-power point.

Accurate PV modeling is required to estimate these operating points. VILLALVA *et al.* (2009) proposed a practical method for extracting parameters of the single-diode PV model from manufacturer information and for reproducing I-V and P-V characteristics across irradiance and temperature. LI *et al.* (2011) subsequently emphasized that the PV generator and power converter should not be studied independently because converter constraints, DC-link voltage, shading, and environmental conditions interact to determine the extractable energy.

Field studies provide useful reference ranges for system-level indicators. SHARMA and CHANDER (2013) reported an annual average performance ratio of about 74% and a capacity factor of 9.27% for a 190 kWp grid-interactive plant in India, with substantial seasonal variation. SUNDARAM and BABU (2015) validated the annual performance of a 5 MWp grid-connected plant in South India and demonstrated the value of comparing simulated and monitored results. ATTARI *et al.* (2016) analyzed a Moroccan grid-connected installation and reported a performance ratio varying from approximately 58% to 98% across the monitoring period, illustrating the influence of operating conditions on monthly performance.

By 2017, studies increasingly combined simulation and field-oriented performance assessment. KUMAR *et al.* (2017) used PVsyst to analyze a 100 kWp polycrystalline silicon plant and obtained an annual performance ratio close to 80%, while de LIMA *et al.* (2017) reported an

annual specific energy yield of 1,685.5 kWh/kWp for a 2.2 kWp system in northeastern Brazil. Mahela and Shaik (2017) synthesized the state of grid-interfaced PV technology, including converter topologies, control techniques, power-

quality issues, and protection requirements. Collectively, these studies support a methodology that evaluates the complete energy-conversion chain instead of focusing only on module efficiency or inverter efficiency.

Table 1. Selected literature basis for the proposed methodology

Reference	System / focus	Key indicator or contribution	Use in this paper
Mondol et al. (2006)	13 kWp field system	Yield, PR, efficiency over long-term monitoring	Performance metrics
Esram & Chapman (2007)	MPPT techniques	Tracking accuracy and implementation trade-offs	MPPT-loss model
Villalva et al. (2009)	PV array model	Single-diode I-V/P-V representation	PV source model
Sharma & Chandel (2013)	190 kWp field plant	PR, capacity factor, specific yield	Benchmarking
Kumar et al. (2017)	100 kWp PVsyst model	Annual simulated PR near 80%	Simulation comparison

Methodology

The proposed analysis is organized as a sequence of model definition, environmental input preparation, electrical simulation, loss calculation, grid-interface assessment, and computation of normalized performance

indicators. The representative system is rated at 100 kWp on the DC side and is connected to a 415 V, three-phase, 50 Hz utility grid through a voltage-source inverter and output filter. Component ratings are intentionally generic so that the procedure can be transferred to other plants by replacing the input parameters.

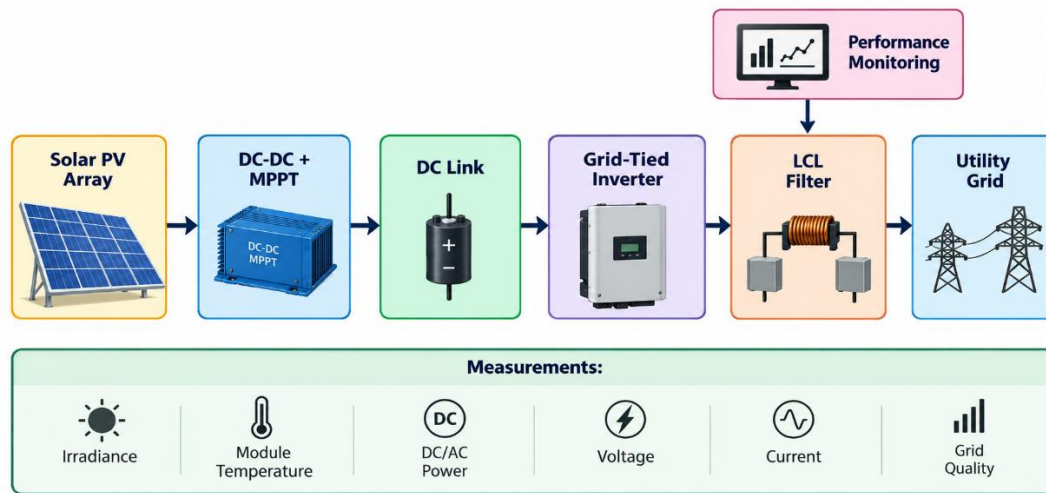


Figure 1. Functional methodology for performance analysis of a grid-connected PV generation system.

Step 1: PV array and environmental model

The PV generator is represented by the single-diode model described in the PV modeling literature. Irradiance and module temperature are the primary time-varying inputs. The output current is obtained from the photogenerated current, diode current, series resistance, and shunt resistance. In simplified form, the current-voltage relationship is written as:

$$I = I_{ph} - I_0 \left\{ \exp \left[\frac{V + I R_s}{n V_t} \right] - 1 \right\} - \frac{V + I R_s}{R_{sh}} \quad (1)$$

Model parameters are calibrated at standard test conditions and then corrected for irradiance and temperature. The procedure follows the modeling principles of Villalva et al. (2009). The representative 100 kWp generator contains 400 modules rated at 250 Wp. Twenty modules are connected in series per string and twenty strings are connected in parallel. A normalized annual

plane-of-array irradiation of 1,920 kWh/m² is used only to demonstrate the calculation; when applied to a real plant, this input must be replaced by measured pyranometer data or a traceable meteorological data set.

Step 2: MPPT and DC-side energy extraction

At each simulation interval, the MPPT controller searches for the operating voltage that maximizes array power. A perturb-and-observe implementation is assumed because it is widely used and easy to reproduce, although the framework allows replacement by incremental conductance or another algorithm. Based on Esram and Chapman (2007), tracking efficiency is not assumed to be perfect; a 0.8% annual MPPT-related loss is included. The instantaneous DC power is calculated as $P_{dc} = V_{pv} \times I_{pv}$ and integrated over time to obtain DC energy.

Step 3: Inverter, grid synchronization, and filtering

The DC-link supplies a three-phase voltage-source inverter. A phase-locked loop provides grid angle and frequency, while current control

regulates active power injection at approximately unity power factor. The control philosophy is consistent with the grid-interface functions discussed by Carrasco et al. (2006), Kjaer et al. (2005), and Mahela and Shaik (2017). The inverter efficiency is modeled as a load-dependent curve with a peak value of 98.2%; conversion efficiency decreases at very low loading. An LCL filter attenuates switching-frequency components before the point of common coupling.

Step 4: Loss model and operating constraints

Energy losses are grouped into optical/environmental and electrical categories. The representative case includes annual allowances of 2.0% for soiling, 1.5% for module mismatch, 1.5% for DC wiring, 0.8% for MPPT deviation, 0.7% for AC wiring and transformer effects, and 1.0% for temperature/model uncertainty beyond the explicit temperature correction. Inverter conversion loss is calculated from the efficiency curve rather than added as a fixed percentage. System availability is set to 99%, and any DC power exceeding the inverter's admissible operating range is clipped.

Table 2. Representative simulation parameters

Parameter	Assumed value	Purpose
DC array rating	100 kWp	Base capacity for normalized yields
PV modules	400 × 250 Wp	Generic crystalline-silicon array
Array configuration	20 series × 20 parallel	Representative DC voltage/current
Inverter rating	100 kW AC; max. η = 98.2%	Grid power conversion
Grid	415 V, 3-phase, 50 Hz	Point of common coupling
Annual POA irradiation	1,920 kWh/m ²	Representative solar-resource input
Availability	99%	Downtime allowance

Step 5: Performance indicators

The principal indicators are normalized to installed DC capacity P_0 . Reference yield (Y_r) represents the available solar resource expressed as equivalent peak-sun hours, array yield (Y_a) represents DC energy normalized by array rating, and final yield (Y_f) represents grid-delivered AC energy normalized by array rating. Performance ratio (PR) compares final yield with reference yield and therefore captures aggregate system losses largely independent of plant size.

$$Y_r = H_{POA} / G_{STC}; \quad Y_a = E_{DC} / P_0; \quad Y_f = E_{AC} / P_0; \quad PR = Y_f / Y_r \quad (2)$$

Capacity factor is calculated as $CF = E_{AC} / (P_0 \times 8,760)$, where E_{AC} is annual AC energy. Average DC-to-AC energy conversion efficiency is $\eta_{inv,E} = E_{AC} / E_{DC}$. When module area A is known, overall system efficiency is $\eta_{sys} = E_{AC} / (H_{POA} \times A)$. For grid quality, voltage and frequency deviation, power factor, and current total harmonic

distortion (THD) are recorded. The methodology considers the system technically acceptable only when the inverter remains synchronized, power factor is near unity, and current distortion stays within the project-specific grid-code limit.

Step 6: Model verification and sensitivity analysis

Before drawing conclusions, energy balance is checked from incident solar resource through DC production and AC export. The simulated PR and specific yield are then compared with ranges reported in the field and simulation literature. Sensitivity runs change irradiation by $\pm 10\%$, module temperature by ± 5 °C, and aggregate non-inverter losses by ± 2 percentage points. This step is necessary because annual energy estimates can otherwise appear overly precise. A future field implementation should additionally compare simulated and measured monthly

energy and calculate mean bias error or normalized root-mean-square error.

Results

Applying the above procedure to the representative 100 kWp case gives an annual plane-of-array irradiation of 1,920 kWh/m² and an annual DC energy of 165.8 MWh after

environmental, mismatch, wiring, availability, and tracking losses. The modeled inverter and AC-side losses reduce the annual grid-delivered energy to 158.4 MWh. This corresponds to a final yield of 1,584 kWh/kWp and an average DC-to-AC energy conversion efficiency of 95.5%. Because the reference yield is 1,920 h, the annual performance ratio is 82.5%.

Table 3. Simulation-based annual performance results for the representative 100 kWp system

Performance indicator	Result	Interpretation
Plane-of-array irradiation	1,920 kWh/m ² /year	Representative annual solar resource
Annual DC energy	165.8 MWh	Array-side energy after modeled DC losses
Annual AC energy	158.4 MWh	Net energy exported to grid
Specific final yield	1,584 kWh/kWp/year	AC energy normalized by 100 kWp
Performance ratio	82.5%	Overall conversion effectiveness
Capacity factor	18.1%	Annual utilization of nominal DC rating
DC-to-AC energy efficiency	95.5%	Inverter plus AC conversion result
Power factor	≈ 0.998	Near-unity active-power operation
Current THD	≈ 2.7%	Representative low-distortion grid current

The performance ratio is slightly higher than the roughly 74% annual value reported by Sharma and Chandel (2013) for their 190 kWp plant, but it is close to the approximately 80% annual PR reported by Kumar et al. (2017) for a 100 kWp PVsyst case. The difference is plausible because PR is sensitive to temperature, inverter sizing, soiling, outage duration, shading, and site-specific design. Attari et al. (2016) also observed a wide monthly PR range in Morocco, demonstrating that a single annual value can conceal substantial seasonal behavior.

The modeled specific yield of 1,584 kWh/kWp/year is lower than the 1,685.5 kWh/kWp reported by de Lima et al. (2017) for northeastern Brazil, but higher than the 812.76 kWh/kWp measured in the 190 kWp Indian case reported by Sharma and Chandel (2013). These comparisons should not be interpreted as ranking the plants because the solar resource, array orientation, temperature, and monitoring periods are different. Instead, they show that the proposed normalized metrics allow the sources of performance variation to be investigated explicitly.

Sensitivity analysis indicates that a 10% increase in annual plane-of-array irradiation increases annual AC energy by approximately 9.4% rather than a full 10% because additional high-irradiance operation raises temperature and clipping losses. A 5 °C increase in average module temperature reduces annual energy by approximately 2.0% for the assumed crystalline-silicon temperature coefficient. Increasing aggregate balance-of-system losses by two percentage points lowers the PR by about 1.7

percentage points. These results confirm that irradiation remains the dominant driver of energy yield, while temperature and balance-of-system losses determine how effectively the available resource is converted.

Conclusion and Discussion

This paper has presented a step-by-step methodology for the performance analysis of grid-connected solar photovoltaic power generation systems. The approach begins with a physically meaningful PV-array model, applies MPPT and converter constraints, represents the grid-tied inverter and filter, accounts for major environmental and electrical losses, and finally evaluates the plant using normalized energy indicators. The method is compatible with simulation packages such as MATLAB/Simulink or PVsyst, but it is not tied to a specific software platform. For the representative 100 kWp simulation case, the calculated annual AC energy is 158.4 MWh, the specific final yield is 1,584 kWh/kWp, the performance ratio is 82.5%, and the capacity factor is 18.1%. The results are consistent with the broad range of values reported in pre-2018 grid-connected PV literature, including the field studies of Sharma and Chandel (2013), Sundaram and Babu (2015), Attari et al. (2016), and de Lima et al. (2017), as well as the PVsyst-based analysis of Kumar et al. (2017). The modeled inverter efficiency and low current distortion further indicate that good converter control is necessary to translate high DC-side energy extraction into useful, grid-compliant AC generation. The main limitation is that the numerical results are simulation outputs based on representative assumptions rather than

measurements from a named power station. Consequently, the values should be treated as a worked methodological example, not as experimental evidence. For an actual research project, the same framework should be populated with measured irradiance, module temperature, DC and AC energy, inverter status, grid voltage, current, and outage data. At least one full year of monitoring is preferable to reduce seasonal bias. Future work can extend the methodology to degradation analysis, partial shading, bifacial modules, reactive-power support, fault detection, and uncertainty propagation. Even with these extensions, the central principle remains unchanged: a meaningful PV performance assessment must connect the solar resource, PV conversion, power electronics, system losses, and grid-delivered energy within one traceable energy balance. From a system-design perspective, the calculated indicators should be interpreted together rather than independently. A high final yield with a comparatively low performance ratio may simply indicate an exceptionally strong solar resource, whereas a high-performance ratio with a modest final yield can occur at a site with lower irradiation but an efficient balance of system. The loss breakdown is therefore essential for diagnosis. If measured PR falls below the modeled value, the analyst should first examine data availability and irradiance-sensor quality, then check temperature losses, soiling, string mismatch, inverter loading, clipping, grid outages, and protection trips. This diagnostic sequence connects the energy-yield methodology with practical operation and maintenance and prevents a single annual metric from being treated as a complete description of plant health. For reproducibility, the monitoring interval, sensor calibration, missing-data treatment, and aggregation method should be documented with the same care as the electrical model. Fifteen-minute or finer measurements are desirable when the purpose is to evaluate MPPT dynamics, clipping, and short grid disturbances, while hourly data can be sufficient for annual energy-yield studies if transient behavior is not being investigated. Simulation-to-measurement validation should be performed monthly as well as annually because agreement in annual energy can hide compensating seasonal errors. The comparison approach used in large and small grid-connected PV studies before 2018, including Sundaram and Babu (2015) and de Lima et al. (2017), supports this emphasis on monitored verification. Thus, the proposed framework is most useful when it is treated as an iterative process in which model assumptions are updated as reliable operating data become available.

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