Comparative Technical and Economic Performance of Four Inverter Architectures in Urban PV Microgeneration Systems

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***Abstract*—This article presents a comprehensive technical and financial assessment of four grid-connected photovoltaic (PV) systems in Manaus, Brazil, each employing a distinct inverter configuration: SolarEdge module-level power optimizers (MLPO), Growatt string inverter (SI), and Deye and Hoymiles microinverters (MI, considered as a single technology). In contrast to previous studies, which were mainly based on simulations or conducted outside of Brazil, this work provides the first empirical comparative analysis in the Brazilian Amazon, integrating twelve months of real operational data. Technical performance was evaluated using the Performance Ratio (PR) and Capacity Utilization Factor (CUF). At the same time, economic viability was assessed through the Payback Period (PP), Net Present Value (NPV), Internal Rate of Return (IRR), and Return on Investment (ROI), all normalized to facilitate a fair comparison. The results reveal architecture-specific responses to tropical conditions: the MLPO system demonstrated the strongest combined performance, with a CUF of 15.30%, a PP of 2 years, an NPV of $160,197.97, an IRR of 56.24%, and an ROI of 1,334.95%, while the MI system achieved the highest PR of 78.80%, but showed limited profitability due to its smaller scale and higher normalized cost. These findings establish empirical benchmarks for PV systems in the Amazon region and demonstrate that inverter architecture significantly influences not only energy efficiency, but also long-term economic performance.**

***Index Terms*—Energy performance, Performance Ratio (PR), Capacity Utilization Factor (CUF), microinverters, power optimizers.**

I. Introduction

The comparative performance of photovoltaic (PV) inverter architectures in real-world humid equatorial climates, especially in the Amazon region, remains insufficiently documented in the scientific literature. While similar climates exist in Africa and Oceania, no empirical studies with measured data have been reported for PV systems in the Amazon or Brazil. Most available works focus on simulated data or isolated communities, not on urban-grid connected systems.

This study addresses the knowledge gap by presenting the first systematic and empirical comparison of three inverter technologies—string inverters, module-level power optimizers, and microinverters (from two manufacturers, considered as a single technology)—operating simultaneously under identical climatic conditions in urban Manaus, the capital of Amazonas state, Brazil. Although geographically close to studies on energy access in remote Amazonian communities [1]–[3], the present work differs substantially in its technical context, focusing on urban, grid-connected PV microgeneration.

PV system operational efficiency is commonly evaluated using performance indicators such as the Performance Ratio (PR) and Capacity Utilization Factor (CUF), which measure how effectively the available solar resource is converted into usable electricity [4]–[7]. Prior studies conducted in various climates report significant differences between estimated and actual PR and CUF values, often attributed to site-specific losses such as thermal effects, shading, and grid interruptions [6]–[14].

For example, Ates and Singh [6] reported a PR of 83.61% and CUF of 17.35% for a 30 kWp system in Turkey, noting thermal and grid losses. Sekyere et al. [7] found a measured PR of 72.8% in Ghana, with differences from simulated values mainly due to solar variability and operational faults. Similar benchmarking by other authors confirms that PR and CUF are robust for assessing cross-technology and cross-climate performance [15]–[18].

In this context, we present a comparative analysis of four PV systems in Manaus, each with a distinct inverter implementation: (i) module-level power optimizers (SolarEdge), (ii) string inverter (Growatt), and (iii) microinverters (Deye and Hoymiles). The systems' nominal capacities are 83.39 kWp, 13.78 kWp, 17.60 kWp, and 8.96 kWp, respectively.

The evaluation utilizes twelve months of measured energy generation for each system, calculating PR and CUF, and comparing them with theoretical values derived from system sizing and local irradiance. In parallel, a financial assessment is performed using normalized investment costs (USD/kWp), historical exchange rates, and the indicators: payback period, Net Present Value (NPV), Internal Rate of Return (IRR), and Return on Investment (ROI).

The primary hypothesis is that the architecture of the inverter significantly influences the technical and economic performance of PV systems in humid Amazonian climates, with module-level power electronics expected to outperform traditional string solutions under conditions of partial shading and high humidity. The main original contributions of this work are: (i) establishment of empirical benchmarks for three inverter technologies under Amazonian urban conditions; (ii) quantification of architectural-specific technical responses to environmental stressors; (iii) integration of technical and financial performance metrics; and (iv) practical recommendations for the design and selection of solar systems in the Amazon and similar regions.

II. System Description

This study analyzes four grid-connected photovoltaic (PV) systems in Manaus, Brazil: three residential and one commercial (educational institution). Brazil has excellent solar potential, with direct normal irradiance from 3 to 6 kWh/m^2.day [9]. The systems—A (83.39 kWp), B (13.78 kWp), C (17.60 kWp), and D (8.96 kWp)—use Tier 1 monocrystalline PV modules and are illustrated in Fig. 1.

Fig. 1. From top, left to right: A (83.39 kWp), B (13.78 kWp), C (17.60 kWp), D (8.96 kWp).

The average global monthly irradiance in Manaus ranges from 3.89 to 5.11 kWh/m^2.day, with an annual mean of 1,613 kWh/m^2.year [19], based on CRESESB SunData (central Manaus) and validated by local stations. For privacy, installation locations are not disclosed.

PV module nominal powers/efficiencies: A: 545 Wp (21.1%), B: 530 Wp (20.7%), C: 550 Wp (21.3%), D: 560 Wp (21.67%).

System A: SolarEdge SE75K inverter + 81 S1200 optimizers, 153 JA Solar 545 Wp modules (9 strings of 17), module-level monitoring (MySolarEdge). System B: Growatt MIN 10000TL-X string inverter, 26 Jinko 530 Wp modules (2×9 + 8 modules on dual MPPT), monitored via ShinePhone. System C: 8 Deye SUN2000 microinverters (4 MPPT each), 32 JA Solar 550 Wp modules, monitored via Solarman Business. System D: 4 Hoymiles HMS-2000-4T microinverters, 16 Leapton 560 Wp modules (individual MPPT), monitored with the S-Miles Installer.

III. Performance Indicators Calculation

This section describes the calculation of the two main performance indicators used to evaluate the photovoltaic systems: *Performance Ratio* (PR) and *Capacity Utilization Factor* (CUF). Both metrics are recommended by the IEC 61724 standard [18] to assess the productivity and efficiency of the photovoltaic system. Calculations in this work are based exclusively on measured annual energy generation data and nominal installed capacity, ensuring the results reflect the real operating conditions of the systems in the Amazon region.

A. Performance Ratio (PR)

The *performance ratio* (PR) is a dimensionless percentage metric that evaluates the overall efficiency of a photovoltaic system by accounting for all losses, including those due to temperature, shading, soiling, inverter inefficiency, equipment failures, and module degradation [18], [19]. PR enables a direct comparison of system performance, regardless of location or technology, and is a key indicator for maintenance and performance monitoring [15], [17]. According to IEC 61724 [18], regular monitoring of PR helps detect degradation or operational faults.

The PR is calculated as follows [17]:

$$PR = \frac{Y_f}{Y_r} \times 100 \tag{1}$$

where:

- $Y_f = \frac{E_{AC}}{P_{STC}}$ is the final yield (kWh/kWp), with E_{AC} being the measured AC energy generated and P_{STC} the nominal installed capacity,
- Y_r is the reference yield, based on the total incident global irradiance.

Alternatively, PR can be expressed by:

$$PR = \frac{E_{AC}}{P_{STC} \cdot G_t} \times 100$$

where G_t is the annual global solar irradiance (kWh/m^2).

B. Capacity Utilization Factor (CUF)

The *Capacity Utilization Factor* (CUF) measures the extent to which a PV system's installed capacity is utilized over a given period. It is the ratio of actual energy generated to the maximum possible energy output if the system operated at full capacity continuously [14]:

$$CUF = \frac{E_{AC}}{P_{STC} \cdot t} \times 100 \tag{2}$$

where t is the total time interval in hours (typically 8,760 hours per year).

Reported CUF values for PV systems commonly range from 15% to 20%, depending on local climatic conditions, system availability, and maintenance [7], [13], [14].

In this study, the CUF is calculated for one year as:

$$CUF = \frac{E_{AC}}{P_{STC} \cdot 8760} \times 100$$

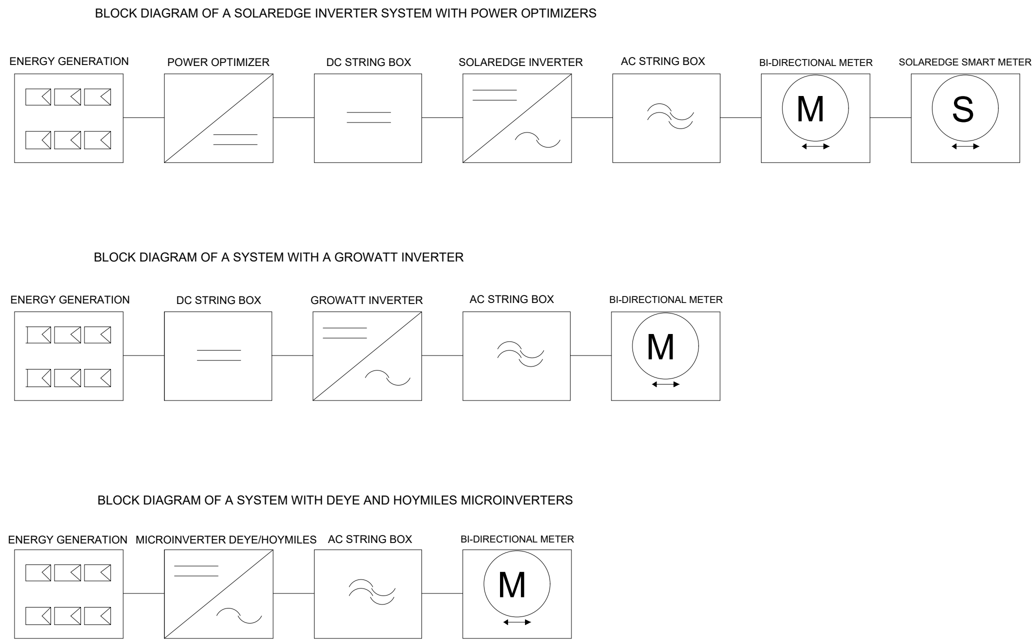

Fig. 2. Block diagrams of the photovoltaic systems: (top) A with SolarEdge optimizers; (middle) B with Growatt; (bottom) C and D with Deye and Hoymiles microinverters.

where all values are based on measured annual system output and installed capacity.

IV. Economic Performance Analysis

In addition to technical evaluation, financial analysis is crucial for determining the investment viability of photovoltaic systems [21], [22]. This study adopts four standard financial indicators: Payback Period, Net Present Value (NPV), Internal Rate of Return (IRR), and Return on Investment (ROI) [21].

All economic analyses were based on measured system generation over 12 months, normalized investment costs in USD/kWp, and historical exchange rates at the time of acquisition. The following assumptions were used for all systems:

- System lifetime: 25 years;
- Initial module degradation: 1% (year 1), then 0.7% per year;
- Operation and maintenance (O&M) costs: 1.09% of initial capital expenditure per year;
- Electricity tariff: USD 0.20/kWh;
- Annual electricity tariff inflation: 4.33%;
- Equipment price inflation: 7% per year;
- Inverter replacement in year 15 (USD 1,478.43 for string inverters, USD 5,057.29 for power optimizers);
- Weighted average cost of capital (WACC): 10%.

For microinverter systems, inverter replacement costs were not included due to their distributed architecture and extended expected lifespan.

A. *Payback Period*

The payback period is the time required to recover the initial investment through the accumulation of net cash flows. Shorter payback periods indicate faster capital recovery and reduced financial risk [21], [22]. System A (SolarEdge) achieved the shortest payback period of 2 years. System B (Growatt) followed with 3 years, while Systems C (Deye) and D (Hoymiles) both required 4 years to reach payback.

B. *Net Present Value (NPV)*

NPV is the sum of all projected cash flows discounted to present value. A positive NPV signifies a financially viable project [21], [22]. System A presented the highest NPV (USD 160,197.97), followed by Systems C (USD 21,397.25), B (USD 19,639.19), and D (USD 10,996.47). Although all projects show positive NPVs, the results confirm that larger systems with optimized architectures provide stronger financial outcomes.

C. *Internal Rate of Return (IRR)*

IRR is the discount rate that yields an NPV of zero, representing the expected annualized return. Higher IRR values correspond to more attractive investments [21]. System A obtained the highest IRR (56.24%), System B reached 36.51%, and Systems C and D had lower values (29.72% and 27.66%, respectively).

D. Return on Investment (ROI)

ROI is the ratio of total net profit to initial investment, expressed as a percentage. It quantifies the overall profitability of the project [21]. System A recorded the highest ROI (1,334.95%), followed by System B (800.66%), System C (637.38%), and System D (583.39%). These results indicate that although all systems are financially viable, inverter architecture and system scale significantly influence profitability.

E. Technical Performance Analysis

Table I summarizes the actual and estimated values of the performance indicators *Performance Ratio* (PR) and *Capacity Utilization Factor* (CUF) for the four photovoltaic systems evaluated. Estimated values were calculated using the regional average annual solar irradiance (1,613 kWh/m^2.year) and the nominal system capacities. Actual values were derived from cumulative generation data recorded by the respective monitoring platforms of each system.

The observed performance variations can be attributed to several architecture-specific factors operating under tropical conditions. System A, utilizing SolarEdge power optimizers and module-level monitoring, achieved the highest performance indicators, with a PR of 83.07% and CUF of 15.30%. These superior results reflect the system's ability to mitigate localized shading losses common in urban environments and compensate for module-level mismatches exacerbated by high-humidity and temperature cycling. Individual MPPT control effectively maintains optimal operating points despite environmental variations.

System B, with a traditional Growatt string inverter, also performed well (PR of 79.92%, CUF of 14.72%), demonstrating that centralized architectures can achieve competitive efficiency when properly configured with dual MPPT inputs to minimize string-level mismatches. However, its performance remains more susceptible to partial shading effects than module-level solutions.

System C, employing Deye microinverters, achieved a PR of 70.91% and CUF of 13.06%, indicating consistent, but moderate technical performance. The lower values compared to other systems may result from thermal stress effects on the microinverter electronics under high ambient temperatures and humidity levels characteristic of the tropical climate.

System D (Hoymiles) outperformed System C in technical indicators, presenting higher PR and CUF values (78.80% and 14.51%, respectively), suggesting better thermal management and power conversion efficiency under tropical conditions. However, its smaller scale and higher cost per kWp limited overall profitability, despite the strong technical performance.

The consistent pattern of measured performance exceeding theoretical estimates in all systems (performance gaps ranging from 0.42% to 12.68%) indicates that standard performance models may underestimate the capabilities of the photovoltaic system in tropical environments with high radiation. This finding has important implications for project feasibility assessments in similar climatic zones.

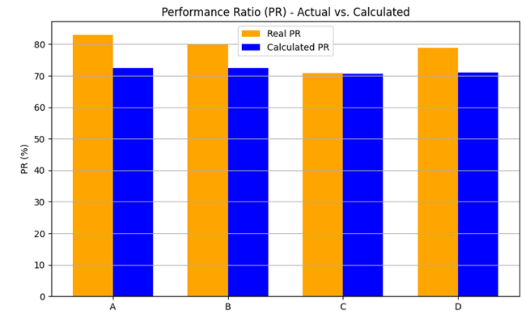

Fig. 3. Comparison between measured and estimated Performance Ratio (PR) values for systems A, B, C, and D.

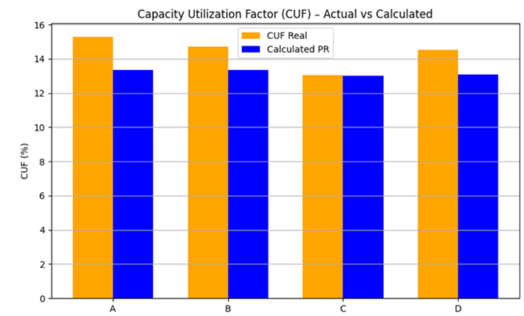

Fig. 4. Comparison between measured and estimated Capacity Utilization Factor (CUF) values for systems A, B, C, and D.

F. Financial Performance Analysis

To assess the economic feasibility of each photovoltaic system, three financial indicators were calculated based on 25 years of projected operation: Net Present Value (NPV), Internal Rate of Return (IRR), and Return on Investment (ROI). Since the systems have different installed capacities, all costs were normalized by system size, using USD/kWp as a comparison metric.

1) Currency Conversion Methodology: All investment values were originally expressed in Brazilian Reais (BRL) and were converted to U.S. Dollars (USD) using the commercial exchange rate valid at the time of equipment acquisition. This approach preserves the financial context of each system, avoiding distortions caused by exchange rate fluctuations over time. The following historical rates were applied, based on official records from Ideal Softwares [23]–[25]:

- System A (February 20, 2024): 1 USD = 4.94 BRL
- System B (July 12, 2022): 1 USD = 5.41 BRL
- System C (January 30, 2023): 1 USD = 5.10 BRL
- System D (July 4, 2023): 1 USD = 4.81 BRL

The final cost in dollars was obtained by dividing the total BRL investment by the corresponding exchange rate. All resulting values were then divided by the installed capacity (in kWp) to compute the normalized cost per watt-peak (USD/kWp), ensuring proportional comparison between systems of different scales.

System A achieved the best financial results, with a payback period of 2 years, NPV of $160,197.97, IRR of 56.24%, and

TABLE I
COMPARISON OF PR AND CUF INDICATORS: ACTUAL VS ESTIMATED VALUES.

System	P_{STC} (kWp)	E_{Actual} (kWh)	$E_{Estimated}$ (kWh)	PR_{Actual} (%)	$\text{PR}_{Estimated}$ (%)	CUF_{Actual} (%)	$\text{CUF}_{Estimated}$ (%)
A	83.39	111,730.00	97,572.30	83.07	72.54	15.30	13.36
B	13.78	17,763.70	16,123.59	79.92	72.54	14.72	13.36
C	17.60	20,130.00	20,044.85	70.91	70.61	13.06	13.00
D	8.96	11,388.95	10,278.98	78.80	71.12	14.51	13.10

ROI of 1334.95%. Despite the high absolute cost, it had the lowest normalized investment at \$685.49/kWp, indicating high cost-efficiency in larger-scale systems with power optimizers.

System B reached a payback period of 3 years, with an NPV of \$19,639.19, IRR of 36.51%, and ROI of 800.66%. The normalized cost was \$813.97/kWp, demonstrating that well-designed string inverter systems can yield favorable returns with moderate investment.

System C, based on Deye microinverters, had a payback of 4 years, NPV of \$21,397.25, IRR of 29.72%, and ROI of 637.38%. Its higher cost of \$895.73/kWp is offset by the operational benefits of independent MPPT tracking.

System D, with Hoymiles microinverters and the smallest capacity (8.96 kWp), showed the lowest financial performance: payback of 4 years, NPV of \$10,996.47, IRR of 27.66%, and ROI of 583.39%. Its normalized cost reached \$1004.22/kWp, confirming the impact of scale on financial outcomes.

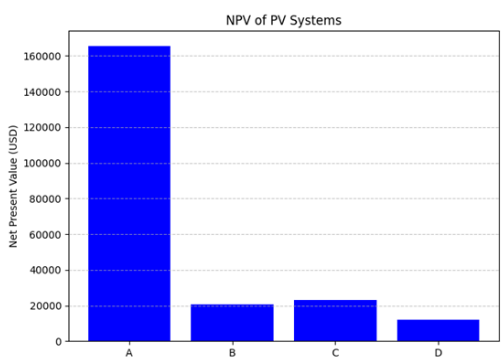

Fig. 5. Net Present Value (NPV) for systems A, B, C, and D.

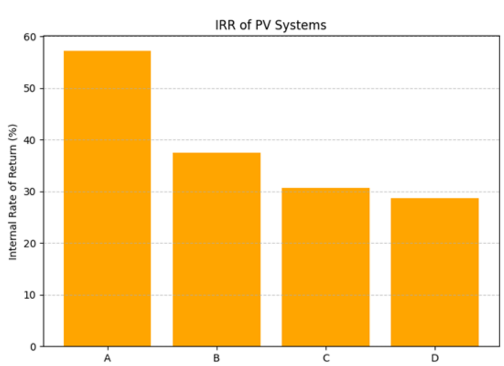

Fig. 6. Internal Rate of Return (IRR) for systems A, B, C, and D.

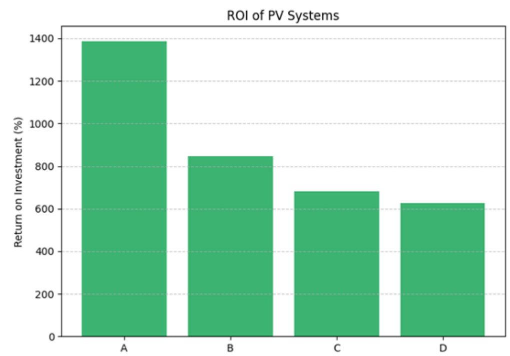

Fig. 7. Return on Investment (ROI) for systems A, B, C, and D.

V. RESULTS AND CONCLUSION

This study conducted an empirical evaluation of four grid-connected PV systems in Manaus, Brazil, each employing a distinct inverter architecture: power optimizers (System A), a string inverter (System B), and two microinverter-based systems (Systems C and D). To ensure comparability, financial indicators were normalized in USD/kWp.

System A (SolarEdge with optimizers) achieved the strongest overall performance, combining the highest CUF (15.30%) and PR (83.07%) with the most favorable financial results (two-year payback and ROI of 1387.6%). These results confirm the effectiveness of module-level MPPT in mitigating shading and mismatch losses common in dense urban Amazonian environments. System B (Growatt string inverter) also performed competitively (PR 79.92%, CUF 14.72%), showing that well-designed string systems can balance cost and efficiency despite lower resilience to partial shading.

Microinverter-based systems showed divergent results. System C (Deye) reached moderate values (PR 70.91%, CUF 13.06%), likely due to thermal stress and higher normalized costs. System D (Hoymiles) demonstrated stronger technical indicators (PR 78.80%, CUF 14.51%), but its smaller scale limited economic viability (ROI 626.8%). These findings suggest that while microinverters are technically robust under Amazonian conditions, their cost-effectiveness depends strongly on system scale.

Across all systems, measured PR and CUF consistently exceeded theoretical estimates, indicating that conventional simulation models may underestimate PV performance in high-irradiance tropical climates. This highlights the importance of locally measured datasets for accurate feasibility assessments.

TABLE II
COMPREHENSIVE FINANCIAL METRICS FOR THE PV SYSTEMS.

System	Size (kWp)	Cost (USD/kWp)	Payback (yrs)	NPV (USD)	IRR (%)	ROI (%)
A	83.39	685.49	2	$160,197.97	56.24	1,334.95
B	13.78	813.97	3	$19,639.19	36.51	800.66
C	17.60	895.73	4	$21,397.25	29.72	637.38
D	8.96	1,004.22	4	$10,996.47	27.66	583.39

Overall, module-level solutions (optimizers and microinverters) demonstrated superior technical resilience, whereas string inverters offered a balanced cost–benefit alternative. Economies of scale proved decisive, reducing normalized costs and accelerating the payback period. This work establishes the first empirical benchmarks for the technical and financial performance of PV systems in the Brazilian Amazon, providing practical guidance for technology selection, system sizing, and investment strategies in tropical regions.

Some limitations remain: the analysis was based on one year of data, which may not fully capture interannual variability or long-term reliability; plane-of-array irradiance sensors were unavailable, restricting loss attribution; and O&M costs were estimated rather than measured directly. Future research should extend to multi-year monitoring, high-resolution diagnostics (e.g., I–V curve tracing, module-level temperature sensing), and the assessment of hybrid PV+BESS solutions. Comparative studies in other tropical regions, such as Africa and Oceania, would help test the generality of the trends observed in Manaus.

Lastly, the findings provide actionable insights for policymakers and investors: targeted incentives could accelerate the adoption of high-performance module-level solutions. At the same time, economies of scale remain essential for maximizing financial returns in tropical urban contexts.

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