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COMPARATIVE ASSESSMENT OF MICROINVERTER, STRING-INVERTER AND POWER-OPTIMIZER ARCHITECTURES FOR PHOTOVOLTAIC SYSTEMS

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Abstract
Photovoltaic (PV) system performance depends not only on module characteristics but also on the selected power-conversion architecture. This paper presents a structured comparison of conventional string inverters, string inverters with module-level DC power optimizers, and microinverters. The objective is to identify the most suitable architecture for three representative applications: uniform commercial roofs, shade-prone residential roofs, and retrofit or geometrically complex installations. A transparent multi-criteria screening model combines uniform-condition efficiency, mismatch and shading resilience, fault containment, monitoring and safety capability, modularity, and cost/complexity. Literature-supported architectural ratings are combined with application-dependent weights. Under the declared assumptions, the string inverter obtains the highest screening score for uniform commercial arrays (3.95/5), whereas microinverters lead in shade-prone residential (4.25/5) and retrofit/complex-roof cases (4.50/5). Power optimizers form an intermediate solution and become preferred over microinverters when cost/complexity receives sufficiently high weight. The results support application-specific selection rather than a universal ranking of PV inverter architectures.

Keywords: microinverter, photovoltaic systems, power optimizer, string inverter, module-level power electronics.

INTRODUCTION

Grid-connected photovoltaic systems commonly use one of three power-conversion architectures: a central or string inverter, a string inverter assisted by module-level DC optimizers, or module-level microinverters. The architectures differ in the location of maximum-power-point tracking (MPPT), the number of power-electronic conversion stages, fault concentration, monitoring granularity, installation complexity and sensitivity to module mismatch. Partial shading is especially important because series-connected modules can transfer the effect of one underperforming module to the operating point of an entire string [1]. Module-level power electronics (MLPE) reduce this coupling by allowing independent module operation, but they add rooftop electronics, conversion losses and investment cost [1,2].

Recent evidence does not support a universal rule that MLPE always increases annual yield. The IEA PVPS assessment of partially shaded generators reports that conventional string inverters can remain competitive when shading is light and realistic optimizer losses are included [2]. Reliability must also be treated separately from energy yield: accelerated tests have reported long-life potential for

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microinverters [3], while DC optimizer studies show that cyclic thermal stress can materially change lifetime projections [4]. Modern grid-connected inverter design must additionally satisfy power-quality, control and grid-code requirements [5]. These observations motivate an application-specific rather than technology-first selection procedure.

The purpose of this work is to provide a compact decision framework for selecting among the three architectures for low- and medium-power rooftop PV systems. It extends earlier system-sizing work by the authors [7] and complements previous studies on PV module configuration and energy-yield improvement [8]. The contribution is a transparent multi-criteria comparison that separates architectural advantages from project-dependent preferences. The study is a screening analysis; it does not replace manufacturer-specific yield simulation, site measurements or lifecycle cost quotations.

COMPARISON METHODOLOGY

Figure 1 summarizes the conversion paths. In a string-inverter system, several modules share the same DC string and one grid-connected inverter. In the optimizer architecture, each module is equipped with a DC–DC stage and the optimized outputs feed a common string inverter. In the microinverter architecture, each module has its own DC–AC converter and the outputs are paralleled on the AC side. The latter two approaches provide module-level MPPT, while only the microinverter removes the central DC–AC conversion point.

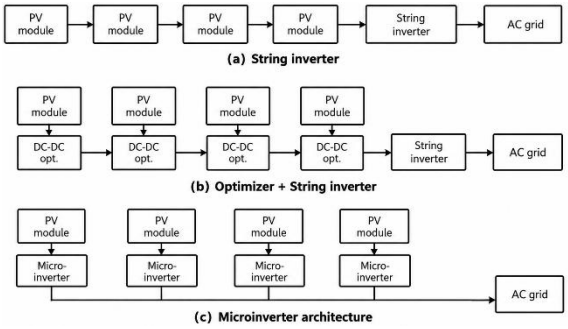


Fig. 1. *Simplified power-conversion architectures considered in the comparison.*

The comparison uses six criteria rated on a five-level ordinal scale, where 1 denotes an unfavorable and 5 a favorable architectural property: (C_1) conversion efficiency under uniform conditions, (C_2) mismatch/shading resilience, (C_3) fault containment, (C_4) monitoring and safety capability, (C_5) modularity and expansion, and (C_6) cost and hardware complexity. The adopted architecture ratings are String = [5, 2, 2, 2, 2, 5], Optimizer + String = [4, 5, 3, 5, 3, 3], and Microinverter = [4, 5, 5, 5, 5, 1]. The values are literature-informed engineering screening ratings rather than measured efficiencies or market prices. In particular, MLPE ratings reflect their module-level control benefits [1,6], while the reliability criteria acknowledge the different failure structures reported for microinverters and optimizers [3,4].

$$S_a = \sum_{j=1}^{m} w_j \, r_{a,j}, \quad \sum w_j = 1. \tag{1}$$

In (1), S_a is the total screening score of architecture a, $r_{a,j}$ is its rating for criterion j, w_j is the application-specific criterion weight, and $m = 6$ is the number of criteria. Three profiles are evaluated. For a uniform commercial roof, the weights [0.30, 0.05, 0.10, 0.05, 0.15, 0.35] emphasize conversion efficiency and cost. For a shade-prone residential roof, [0.15, 0.30, 0.15, 0.15, 0.10, 0.15] emphasizes mismatch resilience. For retrofit or complex roofs, [0.10, 0.25, 0.15, 0.15, 0.25, 0.10] gives additional importance to modularity. The weights in each profile sum to unity. The resulting technology-specific ratings are summarized in Table 1, which provides the fixed architectural input for the multi-criteria evaluation.

Table 1. *Architectural screening ratings used in the multi-criteria model.*

Criterion	**String inverter**	**Optimizer + String**	**Microinverter**
C1 Uniform-condition efficiency	5	4	4

C2 Mismatch/shading resilience	2	5	5
C3 Fault containment	2	3	5
C4 Monitoring and safety	2	5	5
C5 Modularity and expansion	2	3	5
C6 Cost and complexity	5	3	1

The ratings represent relative architectural properties for preliminary screening and should be replaced by manufacturer- and project-specific data when available.

Architecture summary: String inverter—high uniform-condition efficiency and low device count, but string-level mismatch coupling and a central failure point. Optimizer + string inverter—module MPPT and monitoring with a common inverter, but two conversion levels and rooftop DC electronics. Microinverter—module-level MPPT and DC–AC conversion with strong fault containment and expansion flexibility, but the highest number of conversion devices and typically higher initial cost.

RESULTS AND DISCUSSION

The calculated scores are given in Table 2. For the uniform commercial profile, the string inverter reaches 3.95/5 and is preferred because the weighting rewards conversion efficiency, low component count and cost. This result is consistent with the observation that extra module-level electronics do not automatically improve annual yield when shading and mismatch are small [1,2]. The optimizer architecture scores 3.50/5 and the microinverter 3.30/5 under this profile.

Table 2. *Calculated scores.*

Application	String	Optimizer	Microinverter
Uniform commercial roof	3.95	3.50	3.30
Shade-prone residential	2.90	4.05	4.25
Retrofit / complex roof	2.60	3.90	4.50

In the shade-prone residential profile, module-level MPPT changes the ranking. The optimizer system reaches 4.05/5 and the microinverter 4.25/5, while the string system falls to 2.90/5. The advantage is not interpreted as a universal energy-yield percentage. It expresses that individual module control, monitoring and fault containment become more valuable when roof geometry, vegetation, chimneys, module aging or orientation differences create persistent mismatch. Detailed energy gains remain dependent on the shading pattern and converter efficiency maps [1,2].

The retrofit/complex-roof profile strengthens the modularity criterion and produces the clearest separation: 4.50/5 for microinverters, 3.90/5 for optimizers and 2.60/5 for a conventional string inverter. However, a sensitivity check shows that the residential ranking is not invariant to economics. When the cost/complexity weight is increased while the other five weights are rescaled proportionally, the optimizer and microinverter scores become equal at a cost weight of approximately 0.227. Above this point, the optimizer architecture becomes the preferred MLPE solution. Thus, small changes in project priorities can legitimately change the selected architecture.

Screening scores (String / Optimizer / Microinverter): uniform commercial roof = 3.95 / 3.50 / 3.30; shade-prone residential roof = 2.90 / 4.05 / 4.25; retrofit or complex roof = 2.60 / 3.90 / 4.50.

Reliability also prevents a simple ranking. A string inverter concentrates failure consequences in one device, but the device is usually accessible and the rooftop electronics count is low. Microinverters distribute the failure consequence to individual modules, and accelerated testing has demonstrated favorable long-duration behavior for the evaluated units [3]. Optimizers similarly localize MPPT and monitoring, but accelerated tests show that cyclic thermal mechanisms can reduce lifetime estimates under some stress models [4]. These results should be used as evidence about failure mechanisms, not as universal service-life values for all commercial products.

SENSITIVITY ANALYSIS

Because the screening results depend on the application-specific weighting vector, a sensitivity analysis was performed to examine the robustness of the architecture selection. The cost/complexity criterion C_6 was progressively increased while the remaining five criterion weights were rescaled proportionally so that the total weight remained equal to unity. For the shade-prone residential profile, the baseline cost weight is 0.15. Under this condition, the microinverter architecture achieves a score of 4.25/5 compared with 4.05/5 for the optimizer-assisted string architecture.

As the importance of cost and hardware complexity increases, the microinverter score decreases more rapidly because of its lower C_6 rating. The two MLPE architectures reach approximately equal scores when the cost/complexity weight approaches 0.227. Above this threshold, the optimizer-assisted string configuration becomes the higher-scoring MLPE alternative. This result demonstrates that the preferred architecture is not determined exclusively by technical performance but can change when project economics are given greater importance.

The sensitivity analysis also indicates that the conventional string inverter remains attractive when uniform operating conditions and cost dominate the decision, whereas microinverters remain comparatively robust when mismatch resilience, modularity and fault containment receive higher weights. Consequently, the proposed model is more appropriately interpreted as a decision-support tool than as a fixed technology ranking.

Figure 2 illustrates the sensitivity of the screening scores to the cost/complexity weight w_{C6} for the shade-prone residential profile. As w_{C6} increases, the score of the microinverter architecture decreases more rapidly because of its lower rating for cost and hardware complexity, while the optimizer-assisted string architecture is less sensitive to this change. The two MLPE alternatives reach approximately equal screening scores at $w_{C6} \approx 0.227$, which marks the transition point beyond which the optimizer-assisted architecture becomes the preferred MLPE solution under the adopted weighting scheme.

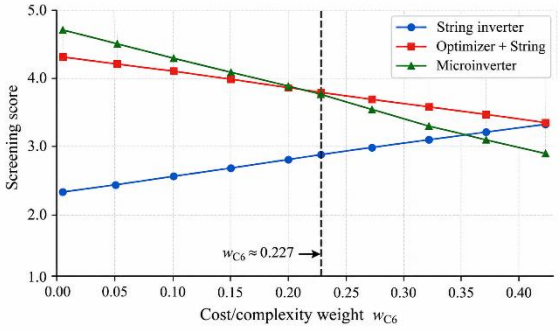


Fig. 2. *Sensitivity of the screening score to the cost/complexity weight for the shade-prone residential profile.*

From a design perspective, the three architectures therefore occupy different application domains. String inverters remain strong for uniform arrays with low mismatch and strong cost pressure. Optimizers are attractive when module-level control is needed but a central inverter remains acceptable. Microinverters are strongest when modularity, fault containment and irregular roof conditions dominate the decision. Manufacturer-specific efficiency maps, warranty terms, grid-support functions, shutdown requirements and

replacement access should be added before a final procurement decision [5,6].

PRACTICAL DESIGN IMPLICATIONS

The screening results can be translated into several practical design rules. Conventional string inverters are particularly suitable for relatively uniform PV fields with similar module orientation, limited shading and easy access to the central inverter. Their low component count, mature technology and favorable cost structure make them attractive for commercial roofs and other installations where mismatch losses are expected to remain small.

Optimizer-assisted string systems provide a compromise between centralized and fully distributed conversion. They are suitable when module-level MPPT and monitoring are required but retaining a central inverter is acceptable. Typical applications include residential or commercial roofs with moderate shading, multiple orientations, or a need for enhanced module-level diagnostics.

Microinverters are most advantageous when installation geometry is highly irregular, modules experience different irradiance conditions, or future expansion is expected. Because each module operates independently, a localized converter or module fault has limited influence on the remaining array. The architecture is therefore attractive for small residential installations, retrofit projects, and roofs with multiple azimuths or frequent partial shading. However, the increased number of rooftop electronic devices and typically higher initial cost should be included in lifecycle and maintenance assessments.

In practical engineering design, the architecture should therefore be selected after evaluating not only peak conversion efficiency but also roof geometry, shading distribution, expected maintenance access, monitoring requirements, grid-support functions, warranty conditions and lifecycle cost.

LIMITATIONS

The present study is intended as an architectural screening analysis and therefore has several limitations. First, the criterion ratings are literature-informed engineering assessments and are not derived from measurements of a single commercial product family. Actual conversion efficiency, reliability, cost and monitoring functionality vary between manufacturers and inverter generations.

Second, the model does not explicitly simulate hourly irradiance, temperature, shading geometry, module degradation or inverter efficiency curves. Consequently, the calculated scores should not be interpreted as predicted annual energy yields. Third, economic performance is represented through a relative cost/complexity criterion rather than a full lifecycle-cost model including installation, replacement, downtime and maintenance expenses.

Finally, the weighting factors reflect representative application profiles rather than universally applicable project priorities. Different stakeholders may assign different importance to efficiency, reliability, safety, monitoring, modularity and cost. Future work should therefore combine the proposed screening framework with measured irradiance profiles, manufacturer-specific efficiency maps, probabilistic reliability models and discounted lifecycle-cost analysis.

CONCLUSION

This study presented a transparent multi-criteria framework for comparing string inverters, optimizer-assisted string inverters, and microinverters for rooftop PV applications. The results demonstrate that no architecture is universally preferable. Under the adopted assumptions, the conventional string inverter achieved the highest score for uniform commercial roofs (3.95/5), whereas microinverters achieved the highest scores for shade-prone residential (4.25/5) and retrofit or geometrically complex roofs (4.50/5).

The sensitivity analysis further showed that architecture selection is strongly dependent on project priorities. For the residential profile, increasing the cost/complexity weight to approximately 0.227 changes the preferred MLPE solution from the microinverter to the optimizer-assisted architecture. This confirms that technical performance, reliability, monitoring, modularity, and economic constraints should be evaluated jointly rather than independently.

The proposed framework is intended for preliminary engineering decision support rather than manufacturer-specific system design. Future work will integrate measured irradiance profiles, converter efficiency maps, probabilistic reliability models, and lifecycle-cost data to extend the screening model toward quantitative techno-economic optimization.

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