

Editorial

Advancements in Photovoltaic System Operation and Intelligence: Innovations for Enhanced Energy Conversion and Efficiency

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Photovoltaic (PV) energy continues to expand its role in modern power systems, accompanied by growing requirements for higher conversion efficiency, more effective energy extraction, accurate power forecasting, reliable grid integration, and improved operation and maintenance. As PV installations increase in scale and penetration, system performance can no longer be considered solely in terms of the conversion efficiency of photovoltaic modules. Environmental variability, partial shading, converter control, grid conditions, prediction uncertainty, and equipment faults all influence the amount, quality, and reliability of the energy ultimately delivered by a PV system.

Within this editorial, the term photovoltaic technologies is used deliberately at the system and operational level rather than as a comprehensive survey of PV materials, cell architectures, module manufacturing, or emerging absorber technologies. The seven papers accepted in the Special Issue are concentrated on the conversion and management chain downstream of the PV module: maximum power extraction, performance enhancement and assessment, power forecasting, inverter–grid interaction, and intelligent fault diagnosis. The editorial therefore synthesizes advances represented by this specific collection, while recognizing that contemporary PV technology also includes major developments in cells, modules, materials, manufacturing, degradation science, and balance-of-system hardware that lie outside the evidentiary scope of these seven contributions.

This system-level interpretation is technically relevant because the energy ultimately delivered by a PV installation is determined not only by cell or module conversion efficiency, but also by how effectively the operating point is tracked, how environmental variability is anticipated, how converter and inverter controls respond, how enhancement measures are evaluated, and how faults and degradation are detected. Accordingly, the unifying theme of the Special Issue is not the full photovoltaic technology landscape, but the set of operational and control technologies that convert module-level potential into reliable, grid-compatible and maintainable electrical energy output.

The Special Issue “Advancements in Photovoltaic Technologies: Innovations for Enhanced Energy Conversion and Efficiency” brings together seven contributions that address this system-level transition. Collectively, they examine how photovoltaic systems can extract energy more effectively, evaluate performance improvements more consistently, anticipate variations in generation, interact more reliably with power grids, and use emerging artificial intelligence methods to support operation and maintenance. The discussion below is therefore structured around the technological scope represented by these seven papers rather than presented as an exhaustive review of all branches of photovoltaic research.



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Maximum power extraction remains a fundamental requirement for efficient PV operation. Because the electrical characteristics of photovoltaic modules vary with environmental conditions, MPPT algorithms must continuously adapt the operating point of the system. Singh, Singh, and Verma [1] address this challenge through a learning-modified perturb and observe (LMPO) MPPT technique combined with adaptive control in a two-stage grid-integrated photovoltaic system. The proposed approach achieved an operating efficiency of 99.68% under the investigated conditions, while the grid current total harmonic distortion was reported as 2.60%. The study also demonstrated DC-link voltage regulation and active and reactive power control under changing meteorological conditions.

The MPPT challenge becomes more difficult when partial shading creates multiple peaks in the PV power–voltage characteristic. Under these conditions, identifying the global maximum power point while maintaining rapid and stable tracking becomes particularly important. Xiong, Han, Qin, and Li [2] propose the IWMA-VINC strategy, combining an Improved Whale Migration Algorithm with variable-step incremental conductance. The method uses global exploration to locate the region of the global maximum power point and local refinement to improve tracking performance. The reported tracking accuracies reached 99.74% under static partial shading conditions and 99.44% under dynamic conditions, with improved convergence and reduced variability compared with the methods evaluated in the study.

Together, these contributions illustrate the increasing sophistication of MPPT research, but they also reveal an important remaining challenge. Improvements in tracking accuracy and dynamic response must ultimately be reconciled with computational complexity, implementation requirements, and robustness in physical systems. This is particularly relevant for advanced optimization-based methods. Indeed, Contribution 2 identifies hardware prototypes, real-time embedded implementation, larger PV arrays, different system topologies, grid-side constraints, thermal effects, and long-term aging as areas requiring further investigation.

Photovoltaic performance can also be improved through techniques that modify the operating environment of the PV module. Cooling systems, reflectors, and related enhancement approaches can increase power output, but their comparison requires indicators capable of expressing the significance of the achieved improvement. Sultan and Tso [3] address this issue through the Power Effectiveness Factor (FPE), which provides a normalized measure of the improvement achieved by an enhancement technique relative to the maximum rated power of the photovoltaic module. The approach offers a common perspective for comparing enhancement techniques whose absolute power gains may otherwise be difficult to interpret.

This contribution also highlights a broader issue in PV performance assessment. The technical benefit of an enhancement method should ultimately be considered in relation to the overall resources required to achieve it. Future evaluation frameworks could therefore extend beyond instantaneous power improvement toward more comprehensive consideration of operating conditions, auxiliary requirements, durability, and long-term performance.

A second major theme of the Special Issue concerns photovoltaic power forecasting. Variability in solar resources creates uncertainty in PV generation, making accurate prediction increasingly relevant to planning and operation. Two contributions address this challenge at different forecasting horizons and through different computational approaches.

Chen, Liu, Liu, Liu, and Zhang [4] propose a long-term PV power prediction model based on stacked generalization. Their framework combines several base learners—GMDH, LSSVM, RBFNN, and ENN—with a backpropagation neural network operating as the meta-learner. The approach seeks to exploit the complementary capabilities of different forecasting models rather than relying on a single prediction method. The work demonstrates the

potential of model combination for improving long-term photovoltaic power prediction while also drawing attention to the dependence of data-driven forecasting performance on the characteristics of the available dataset.

Qin, Wei, Deng, Zhang, and Wang [5] investigate photovoltaic power forecasting through a different hybrid architecture that combines Variational Mode Decomposition, the Zebra Optimization Algorithm, and a Long Short-Term Memory network. Environmental factors including solar irradiance, component temperature, air humidity, and wind speed are incorporated into the prediction framework. The proposed VMD-ZOA-LSTM model achieved the lowest RMSE and MAE and the highest R^2 among the models evaluated in the study, reducing overall prediction errors by more than 50% and maintaining strong performance under both clear-sky and non-clear-sky conditions.

The forecasting contributions reveal an important direction for future research. Increasing model complexity can improve prediction performance, but reliable deployment requires models that remain effective across different locations, seasons, weather patterns, and operating environments. Qin [5] explicitly proposes incorporating additional variables such as cloud coverage and atmospheric pressure and extending validation to datasets from multiple regions and seasons. The study also identifies potential applications in photovoltaic-powered electric vehicle charging, energy storage dispatch, charging scheduling, and vehicle-to-grid operation. Future forecasting research should therefore increasingly consider not only prediction accuracy but also generalization and the operational value created by improved forecasts.

Increasing photovoltaic penetration introduces another challenge: the relationship between PV generation and power system stability. As the share of inverter-based generation grows, photovoltaic inverters increasingly influence voltage behavior during normal operation and system disturbances. Their role is therefore expanding from energy conversion and injection toward active participation in maintaining reliable grid operation.

Sun, Wang, Yao, Cui, Li, Zhang, Wang, and Sun [6] investigate voltage adaptability in an AC/DC hybrid receiving-end power grid with high PV penetration. The study analyzes the coupling between reactive power and transient voltage and proposes a hierarchical optimization strategy for low-voltage and high-voltage ride-through control parameters. Following optimization, the transient voltage peak in the investigated system was reduced from 1.263 p.u. to 1.098 p.u., and post-fault voltages were maintained within the required range.

This work illustrates the increasing importance of coordinating photovoltaic operation with grid requirements. Future PV control strategies will need to consider not only energy harvesting but also voltage support and system behavior during disturbances. Contribution 6 identifies intelligent optimization of inverter parameters using approaches such as machine learning or genetic algorithms, together with coordinated optimization involving other reactive power compensation devices, as areas for further investigation.

The final contribution extends the Special Issue into the emerging area of multimodal artificial intelligence for photovoltaic operation and maintenance. As PV installations become larger and more geographically distributed, fault diagnosis must process increasing amounts of heterogeneous information. Wu, Chen, Min, Chen, Zhao, and Ye [7] propose PV-FaultExpert, a domain-adaptive multimodal large language model for PV equipment fault diagnosis based on Dynamic LoRA routing. The study develops a dataset containing more than 35,000 samples and combines heterogeneous visual information with diagnostic reports. The proposed routing mechanism enables specialized adaptation according to the input modality.

This work demonstrates how multimodal artificial intelligence may expand the capabilities of photovoltaic condition monitoring. At the same time, it highlights challenges

that will become increasingly important as such models move toward practical use. Diagnostic systems must remain reliable when applied to different equipment, operating environments, and fault conditions. Dataset quality, validation, model generalization, and the reliability of diagnostic recommendations will therefore require continued attention.

Viewed collectively, the seven contributions reveal a first major gap between algorithmic performance and deployable engineering. For MPPT, advanced hybrid and meta-heuristic methods must execute within converter sampling and switching constraints, using finite-resolution voltage and current measurements and limited processor memory and computation. Their benefits can be reduced by sensor noise, quantization, converter losses, duty-cycle limits, delays, rapidly moving irradiance patterns, module mismatch, soiling, temperature transients, and component aging. Recent MPPT reviews likewise emphasize computational demand, sensor requirements, cost, hardware constraints, and environmental adaptability as practical selection criteria [8,9]. Hardware-in-the-loop testing, embedded-controller implementation, long-duration outdoor experiments, and reporting of execution time, memory use, sensor burden, energy overhead, and net energy gain are therefore needed alongside tracking accuracy.

Comparable implementation constraints arise in forecasting and intelligent diagnosis. Forecasting models depend on the quality, synchronization, resolution, and availability of meteorological and plant measurements; missing data, sensor drift, numerical weather prediction bias, seasonal distribution shifts, and transfer between sites can degrade models that perform well on a single historical dataset. Computational latency also matters when forecasts are intended to support dispatch or real-time control. Recent reviews identify adaptability, data quality, computational efficiency, cross-region generalization, uncertainty treatment, and operational integration as continuing challenges [10,11]. In fault diagnosis, field deployment additionally requires reliable labels, representative rare-fault samples, calibration across cameras and sensors, robustness to illumination, temperature, dust and equipment differences, and explicit management of false alarms and missed detections. Wider reviews of PV prognostics and predictive maintenance similarly highlight heterogeneous data, data standardization, experimental validation, and transfer from laboratory datasets to engineering applications [12,13].

A second and potentially more consequential gap is architectural integration. Forecasting, MPPT, inverter control, and fault diagnosis are usually developed as separate functions, although they observe and influence the same physical system. A practical integrated PV-management architecture could contain four interacting layers. A sensing and state-estimation layer would combine irradiance, temperature, voltage, current, DC-link, inverter, grid, weather forecast, and inspection data. A prediction and health layer would produce short- and longer-horizon power forecasts, uncertainty bounds, anomaly indicators, fault probabilities, and degradation estimates. A supervisory optimization layer would translate these outputs into operating objectives and constraints for MPPT, active/reactive power scheduling, reserve provision, curtailment, thermal or component protection, and maintenance prioritization. Finally, fast local controllers would execute converter and inverter commands within certified protection and grid-code limits.

The information exchange between these layers is central to the proposed integration. Forecasts of irradiance and expected power can provide feed-forward information to MPPT and energy-management functions, reducing unnecessary search during predictable transients and informing reserve or curtailment decisions. MPPT and inverter telemetry can return actual operating point, DC-link, and power quality information to forecasting and diagnostic modules. Diagnostic confidence scores can impose derating limits, block unsafe operating regions, trigger inspection, or modify the expected available-power baseline used by the forecaster. Grid voltage, frequency, reactive power demand, and fault-ride-through

states can constrain both active power extraction and inverter set-points. A supervisory controller can then reconcile potentially competing objectives—maximum energy capture, thermal stress, grid support, component health, and maintenance risk—while retaining fast protection functions locally. This closed information loop provides a stronger unifying research direction than optimizing each function independently [9].

The most important unresolved challenge is therefore validation of such methods as complete cyber–physical PV systems rather than isolated algorithms. Priority should be given to experiments that combine embedded implementation, realistic sensing, converter and inverter dynamics, communication delays, weather variability, faults, aging, and grid disturbances. Common benchmark scenarios and interoperable data interfaces would make it possible to compare not only accuracy but also robustness, latency, computational burden, energy overhead, safety margins, and lifecycle benefit. For inverter-dominated networks, the recent PV-focused literature also points toward grid-forming and adaptive control, multi-inverter coordination, large-disturbance ride-through, and protection integration as emerging system-level priorities [14].

These observations also change how future advances should be evaluated. A higher MPPT tracking percentage is not sufficient if the required computation, sensing, or control activity reduces net energy yield or exceeds embedded hardware capability. A lower forecasting error is most valuable when it improves dispatch, reserve allocation, curtailment, storage scheduling, or grid support. A diagnostic model should be judged not only by classification accuracy but also by calibration, false alarm cost, missed-fault risk, inference latency, and transfer across equipment and sites. Likewise, inverter control improvements should be assessed against stability, power quality, semiconductor stress, protection coordination, and compliance under representative disturbances. This system-oriented evaluation framework connects the seven contributions to a wider body of recent PV research and clarifies where laboratory performance must be converted into operational value [15].

Conclusions

The seven contributions in this Special Issue show that an important frontier of photovoltaic development lies in the operational technologies that determine how effectively module output is converted into usable, reliable, and grid-compatible energy. The papers span MPPT under meteorological variation and partial shading, evaluation of enhancement techniques, long- and short-term forecasting, inverter voltage adaptability, and multimodal fault diagnosis. Their collective contribution is therefore best understood as a system-level perspective on PV energy conversion and operation, complementary to—rather than a substitute for—parallel advances in photovoltaic materials, cells, and modules.

Four research priorities emerge most clearly. First, advanced algorithms must be demonstrated on embedded hardware and in long-duration field operation, with computational burden, sensing uncertainty, latency, losses, and environmental variability reported explicitly. Second, forecasting and diagnostic methods require stronger cross-site, cross-season, and cross-equipment validation, together with uncertainty quantification and standardized datasets. Third, inverter research must increasingly address high-penetration operation, coordinated voltage and frequency support, ride-through, and protection constraints. Fourth, the presently separate functions of prediction, maximum power extraction, grid control, and condition monitoring should evolve toward interoperable supervisory architectures in which information is exchanged and operating objectives are coordinated.

The critical measure of progress is consequently not whether an individual method achieves a marginally higher accuracy under a defined test, but whether it produces repeatable system-level benefit under realistic constraints. Research that couples rigorous field validation with integrated control and health management is likely to have the greatest impact on the next generation of PV systems. This direction is consistent with the wider

recent literature on MPPT implementation, forecasting adaptability, intelligent maintenance, and inverter-dominated grid operation [8–15], and provides a focused roadmap extending beyond the seven papers collected here.

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