

ENVIRONMENTAL STRESS–PERFORMANCE COUPLING IN PEROVSKITE BIPV: OPERATING-REGIME TRANSITIONS UNDER SEMI-ARID OUTDOOR CONDITIONS

Shahzad Aman^{*1}, Dr. Adnan Daud Khan², Dr. Aimal Daud Khan³

^{*1}MS Student, Department of U.S Pakistan Center for Advanced Studies in Energy, University of Engineering and Technology Peshawar, Pakistan.

²Associate Professor, Department of U.S Pakistan Center for Advanced Studies in Energy, University of Engineering and Technology Peshawar, Pakistan.

³PhD Scholar, Department of U.S Pakistan Center for Advanced Studies in Energy, University of Engineering and Technology Peshawar, Pakistan.

^{*1}shahzadaman@uetpeshawar.edu.pk, ²adnan.daud@uetpeshawar.edu.pk

DOI: <https://doi.org/10.5281/zenodo.22914595>

Keywords

building integrated photovoltaics; perovskite solar modules; environmental stress; outdoor performance; relative humidity; irradiance; operating regimes; stability; semi-arid climate; IoT monitoring.

Article History

Received: 16 June 2026

Accepted: 07 September 2026

Published: 23 September 2026

Copyright @Author

Corresponding Author: *

Shahzad Aman

Abstract

The outdoor performance of perovskite-based building-integrated photovoltaics (BIPV) is a function of the combined effect of solar irradiance, temperature, relative humidity, module architecture, and progressive changes in material state. However, typical techniques assess environmental sensitivity over short time windows or aggregated performance indicators, and therefore have limited ability to identify transitions between different outdoor operating regimes. In this work, we investigate the environmental stress–performance coupling of two independently operated perovskite BIPV modules installed under semi-arid outdoor conditions in Peshawar, Pakistan. Electrical and environmental variables like voltage, current, operating power, irradiance, ambient temperature, relative humidity, and sunshine duration were recorded using a synchronized IoT-based monitoring framework. The analysis employs a continuous, matched, daily observational dataset over the autumn–winter transition and comprise a 300 cm² multi-cell configuration (Module A) and a 500 cm² single-module configuration (Module B). The results indicate a significant seasonal reduction in the environmental operating envelope. Irradiance dropped from about 49–60 mW cm⁻² in October to 32–35 mW cm⁻² in December, and relative humidity increased from about 25–36% to 65–66%. Although the irradiance partially recovered in January to about 35–37 mW cm⁻², the system did not recover to earlier levels of performance. The performance degradation and environment sensitivity of Module A was much more severe than that of Module B. The efficiency loss per month was from 4.4% to 2.3% for Module A while that of Module B was from 7.2–7.3% to 6.1%. This divergence was despite common outdoor exposure, suggesting a large architecture- and state-dependent component in the environmental response. This behavior is consistent with a transition from a regime of

operation controlled by irradiance under higher radiation and lower humidity conditions to a regime limited by humidity and constrained by stability during winter. This interpretation is consistent with the known sensitivity of metal halide perovskites to moisture, oxygen, thermal cycling, ion migration, interfacial reactions and poor encapsulation. "Outdoor testing of perovskite BIPV should move beyond simple reporting of overall efficiency and include environmental sensitivity analysis within context of the architecture and explicit identification of switching between operating regimes." Therefore, the experimental framework allows to separate short-term variability due to weather conditions from the performance limitations of emerging BIPV systems that are conditioned by the environment.

1. Introduction

The transition toward low-carbon buildings is increasingly shifting photovoltaic deployment from stand-alone electricity-generation assets toward technologies that can simultaneously perform architectural, optical, thermal, and energy-generation functions. Building-integrated photovoltaics (BIPV) represent this transition by incorporating photovoltaic elements into roofs, façades, skylights, windows, shading devices, and other components of the building envelope [1–4]. Unlike conventional rooftop photovoltaic systems, BIPV technologies operate simultaneously as energy-generating devices and building components; consequently, their performance is governed by interacting electrical, optical, thermal, architectural, and environmental requirements rather than by photovoltaic conversion efficiency alone [1–5]. Recent BIPV studies have emphasized that semi-transparent and bifacial photovoltaic technologies are particularly relevant to future building envelopes because electrical production must be considered alongside daylight transmission, solar heat management, façade orientation, thermal behavior, and building energy control [1–7].

The integration of photovoltaic technologies into glazing systems is particularly attractive because windows and façades constitute substantial areas of modern building envelopes and have traditionally served primarily architectural and environmental-control functions. Semi-transparent photovoltaics can transmit a fraction of incident visible radiation while converting another fraction into electricity, thereby creating

multifunctional building-envelope elements [3–7]. Recent studies have demonstrated that emerging semi-transparent photovoltaic technologies offer opportunities to balance visible transmittance, photovoltaic conversion, daylight utilization, and solar-heat control, making them particularly attractive for windows and façades where conventional opaque photovoltaic modules cannot provide the same architectural functionality [5–7]. Metal-halide perovskite photovoltaics are especially promising for this application because of their strong optical absorption, tunable bandgap, solution-processability, low-temperature fabrication potential, and compatibility with thin-film and semi-transparent architectures [6–10]. These characteristics have enabled photovoltaic structures that can be adapted to architecturally constrained surfaces and glazing systems while maintaining useful electrical output [5–10].

The advantages of perovskite BIPV, however, are accompanied by stringent requirements for stability and reliability. A photovoltaic element integrated into the building envelope cannot be evaluated solely by its initial conversion efficiency under controlled laboratory conditions. During practical operation, the photovoltaic component experiences continuously changing irradiance, temperature, humidity, atmospheric oxygen, thermal cycling, spectral variation, and other weather-related stresses. The environmental conditions therefore become an intrinsic component of the photovoltaic operating state rather than merely external disturbances [8–15]. This distinction is particularly important for

emerging photovoltaic technologies because laboratory-scale efficiency improvements have advanced considerably faster than evidence concerning long-duration, large-area, and climate-specific outdoor reliability [8], [12–16].

Metal-halide perovskites are particularly sensitive to environmental exposure because several degradation pathways can be activated simultaneously. Moisture, oxygen, temperature, illumination, ion migration, interfacial reactions, and mechanical stress can interact to alter the chemical, structural, and electronic state of the device [8], [13–16]. Moisture is especially important because water can interact with the perovskite absorber and adjacent interfaces, facilitating chemical transformations, defect formation, ionic redistribution, and non-radiative recombination. The severity of these effects depends on material composition, interface chemistry, encapsulation quality, environmental exposure, and operating history [8], [13], [14], [15], [16]. Recent studies have consequently identified moisture ingress and inadequate environmental barriers among the most important limitations to practical perovskite photovoltaic deployment [13–16].

Temperature represents another major environmental variable. Temperature influences bandgap, carrier transport, recombination, open-circuit voltage, ion migration, phase stability, interfacial behavior, and thermomechanical stress in multilayer photovoltaic structures [10], [17–20]. Under outdoor conditions, module temperature itself is coupled to incident solar irradiance, ambient temperature, wind, mounting configuration, optical absorption, and surrounding building materials. Consequently, temperature-related changes in photovoltaic output cannot necessarily be interpreted independently of the solar resource and other environmental conditions [10], [17–20]. Jošt *et al.* demonstrated that the performance and energy yield of outdoor perovskite photovoltaic modules exhibit significant temperature dependence. At the same time, Stoichkov *et al.* reported pronounced diurnal changes and reversible performance effects during outdoor operation of

perovskite mini-modules [17], [18]. Such findings demonstrate that the instantaneous electrical output of a perovskite photovoltaic device can depend on both its current environment and its recent operating history.

Solar irradiation introduces an additional dual role. Irradiance is the primary energy input responsible for photovoltaic electricity generation, but illumination can simultaneously activate or accelerate ion migration, phase redistribution, photochemical reactions, and interfacial degradation processes [20], [21]. Mixed-halide perovskites, for example, may undergo light-induced phase segregation, altering their local electronic properties and carrier dynamics [21]. Thus, higher irradiance cannot be interpreted simply as a beneficial input variable; under certain operating conditions, it can also contribute to long-term environmental stress. The resulting outdoor behavior is therefore multidimensional, with the measured output representing the combined effect of solar input, thermal conditions, atmospheric exposure, module architecture and evolving material state.

For this reason, outdoor field measurements are indispensable for establishing the realistic behavior of perovskite photovoltaic systems. Standardized laboratory measurements remain essential for controlled comparison. Still, they cannot fully replicate alternating illumination and darkness, seasonal temperature cycles, humidity fluctuations, the natural solar spectrum, and simultaneous environmental stressors encountered in the field [11], [17–19]. The International Summit on Organic Photovoltaic Stability (ISOS) consensus framework therefore emphasizes standardized reporting of stability-test conditions and environmental metadata, including illumination, temperature, relative humidity, and operating history [11]. Such reporting is necessary because outdoor results are inherently climate-, location-, season- and module-dependent, and because inconsistent environmental characterization can make results from different studies difficult to interpret or compare [11].

Recent field studies have further established the importance of realistic outdoor exposure. Outdoor perovskite modules have been shown to exhibit reversible daytime changes, overnight recovery, progressive performance loss, and climate-specific responses that cannot be reduced to a single degradation mechanism [18], [22–25]. Paraskeva *et al.* demonstrated, through extended outdoor monitoring, that perovskite module performance can exhibit distinct diurnal and longer-term components and that environmental variables can be incorporated into predictive analyses of photovoltaic output [23]. Other long-term studies have shown that different perovskite material formulations and module architectures can exhibit distinct outdoor performance trajectories despite being subjected to broadly comparable environmental conditions [24], [25]. Long-duration operation of perovskite/silicon tandem modules has similarly demonstrated the importance of realistic temperature, irradiance and spectral conditions in interpreting outdoor energy yield [25]. These findings collectively indicate that outdoor perovskite performance should be understood as a coupled environmental-response problem rather than as a simple time-dependent decline in efficiency.

This distinction is particularly important when environmental variables are strongly coupled. Under natural outdoor conditions, periods of high irradiance may coincide with higher temperature and lower relative humidity. In contrast, winter conditions can simultaneously produce lower irradiance, lower temperature, and substantially higher humidity. A strong statistical relationship between photovoltaic efficiency and one environmental parameter therefore does not necessarily indicate an independent causal influence of that parameter. Instead, the observed relationship may contain contributions from correlated environmental variables and from changes in the underlying material or module state. A rigorous field analysis must therefore examine the environmental envelope jointly rather than interpreting individual correlations in isolation.

The present study adopts an environmental stress-performance coupling framework to address this issue. In this framework, photovoltaic efficiency is considered a function of the contemporaneous environmental state and the evolving condition of the photovoltaic module:

$$\eta(t) = f[G(t), T(t), RH(t), S(t), M(t), A] \quad (1)$$

where G represents irradiance, T represents temperature, RH represents relative humidity, S represents solar-exposure or sunshine conditions, M represents the evolving module state, and A represents architecture-dependent characteristics. The inclusion of the module-state term is important because the same external environmental conditions may not produce the same electrical response at different stages of outdoor exposure. Moisture ingress, interfacial modification, ion redistribution, defect evolution and encapsulation deterioration can alter the subsequent sensitivity of the device to its surrounding environment [8], [13], [15], [20], [26–28].

This distinction provides a useful separation between weather-driven variability and state-conditioned response. Weather-driven variability refers to changes in photovoltaic output caused primarily by contemporaneous environmental conditions. State-conditioned response refers to a situation in which the environmental response changes due to cumulative exposure or an internal state change in the photovoltaic module. These processes can occur simultaneously and therefore cannot be adequately distinguished by beginning-to-end efficiency comparisons alone. Time-resolved environmental and electrical measurements are required to identify whether the relationship between environmental forcing and photovoltaic response remains approximately stationary or evolves during outdoor exposure.

The possibility of such evolution motivates the concept of operating-regime transitions adopted in this study. An operating regime is defined as a period during which the environmental envelope and the photovoltaic response exhibit comparatively consistent statistical behavior. A regime transition occurs when the relationship between environmental forcing and photovoltaic

performance changes sufficiently that the previous response function no longer adequately represents the observed operating condition. This approach is particularly useful for emerging photovoltaic technologies because it allows the analysis to distinguish a simple seasonal change in the solar resource from a change in the photovoltaic component's underlying environmental sensitivity.

The experimental dataset provides a suitable basis for investigating this question. The environmental measurements recorded across the field campaign show a substantial change in the outdoor operating envelope. October is characterized by comparatively high irradiance (approximately 48–60 mW cm⁻² in the supplied daily records), temperatures around 30–32 °C, and relative humidity generally within 25–36%. November shows a reduction in irradiance to approximately 41–44 mW cm⁻², while relative humidity increases to approximately the mid-40% range. December represents a markedly different environmental state, with irradiance reduced to approximately 32–35 mW cm⁻², temperatures near 13 °C, and relative humidity approaching approximately 65–66%. January subsequently shows a partial recovery in irradiance to approximately 35–37 mW cm⁻², while temperature remains close to 13 °C and relative humidity is approximately 58–60%. The January behaviour is particularly important because the partial recovery in solar resource does not correspond to a proportional return to the earlier operating-performance range, providing an empirical basis for examining whether the environmental-performance relationship has changed during the exposure period.

The photovoltaic measurements provide the complementary response dimension. The supporting INA219_1 dataset contains daily irradiance, sunshine duration, ambient temperature, relative humidity, voltage, current, operating power, power density, energy yield and efficiency for the 300 cm² configuration. The corresponding INA219_2 dataset provides the same principal variables as the first module and demonstrates a substantially different voltage-

current operating range and electrical response. The thesis describes the two configurations as independently operated modules with distinct active areas and electrical characteristics, enabling their environmental responses to be evaluated separately, even though they experienced the same external weather conditions.

The experimental arrangement is particularly useful because the external environmental forcing is approximately common to both modules, while their electrical operation remains independent. The thesis identifies the first configuration as a 300 cm² multi-cell arrangement and the second as a 500 cm² module configuration [28]. The architecture therefore introduces differences in active area, cell arrangement, electrical operating regime, and associated response characteristics while maintaining a common outdoor exposure environment. This makes it possible to examine whether environmental sensitivity is approximately shared between the modules or whether different module configurations exhibit systematically different responses to the same environmental forcing.

The geographical setting further strengthens the relevance of this investigation. A substantial fraction of the perovskite outdoor literature has originated from European, East Asian, Mediterranean, or other controlled climatic environments. At the same time, geographically specific evidence from South Asian semi-arid regions remains more limited [22], [24], [25]. The thesis identifies Peshawar, Khyber Pakhtunkhwa, as a relevant semi-arid environment characterized by substantial seasonal variation in irradiance, temperature, and humidity, and highlights the need for region-specific field data on perovskite BIPV behavior. The environmental dataset collected during the experiment directly captures this changing outdoor envelope, providing an empirical basis for relating photovoltaic behavior to the local climate rather than relying only on generalized meteorological assumptions.

The recently published *Results in Engineering* study from Peshawar further establishes the relevance of this geographic and technological context. That study experimentally demonstrated a scaled BIPV

platform employing semi-transparent perovskite photovoltaic windows and real-time IoT-based electrical and environmental monitoring. It reported measurable relationships between irradiance, temperature, humidity, and electrical output and emphasized the effects of module configuration and encapsulation on outdoor performance [29]. The study also demonstrated experimentally that module format and environmental exposure can produce markedly different electrical responses within a common building-integrated environment [29]. Its findings, therefore, provide relevant regional context for investigating relationships between environmental performance and other variables in Peshawar. At the same time, the present study focuses specifically on the evolution of environmental sensitivity across an extended seasonal field dataset.

Despite the expanding literature on perovskite outdoor stability and BIPV, three important gaps remain. First, synchronized long-duration datasets that include electrical and multiple environmental variables remain comparatively limited, especially for emerging BIPV configurations operating under geographically distinct climates [11],[17]–[25]. Second, environmental variables are frequently used as explanatory variables for observed changes in power or efficiency without explicitly testing whether their influence remains stable throughout the entire outdoor campaign. Third, comparatively limited attention has been paid to architecture-dependent environmental sensitivity under common outdoor exposure, particularly when independently operated modules experience the same environmental forcing yet exhibit different electrical operating conditions and evolving performance states [9], [16], [26], [29].

The present study addresses these gaps by using the complete, synchronized outdoor dataset from the Peshawar BIPV experiment to quantify environmental stress–performance coupling and identify empirically distinguishable operating-regime transitions. The study characterizes the environmental operating envelope in terms of irradiance, temperature, relative humidity and sunshine duration; quantifies the corresponding

temporal evolution of operating power, power density, efficiency and energy yield; evaluates module-specific relationships between photovoltaic performance and environmental variables; examines whether those relationships change across the observation period; compares the environmental responses of the two co-located perovskite configurations; and establishes whether the later operating state can be interpreted adequately using contemporaneous weather conditions alone or whether the response indicates increasing state dependence. These objectives directly reflect the original experimental aim of the thesis, which was to evaluate power, efficiency, energy yield and degradation behaviour under changing solar and climatic conditions using IoT-enabled multiparameter monitoring.

The principal contribution of this study is therefore a time-resolved environmental stress–performance framework for perovskite BIPV, in which the outdoor photovoltaic response is considered jointly as a function of environmental forcing, module architecture and evolving operating state. Rather than treating the seasonal change in efficiency as a single monotonic trend, the analysis examines whether the environmental–performance relationship itself changes during outdoor exposure. This distinction is consistent with emerging evidence from the field demonstrating that perovskite photovoltaics can exhibit both reversible environmental responses and persistent, state-dependent performance changes [18], [23–25]. The use of synchronized daily environmental and electrical measurements further enables the analysis to move beyond broad monthly averages toward matched-day relationships and period-resolved sensitivity.

Accordingly, the central research question addressed in this work is whether the environmental–performance relationship of perovskite BIPV remains approximately stationary during outdoor operation or whether it evolves as the environmental envelope changes and the photovoltaic modules undergo cumulative exposure. Resolving this question is relevant to climate-specific outdoor qualification, environmental sensitivity modelling,

encapsulation design, module architecture, reliability assessment and the development of predictive models for practical perovskite BIPV systems.

2. Materials and Methods

The experimental investigation was conducted using a dual-module perovskite building-integrated photovoltaic (BIPV) platform installed under real outdoor operating conditions at the University of Engineering and Technology (UET), Peshawar, Pakistan, at approximately 34.01°N and 71.58°E. The experimental platform was designed to reproduce the principal characteristics of a small building-integrated photovoltaic envelope while enabling independent monitoring of two dissimilar carbon-based perovskite photovoltaic configurations. The two configurations differed in

active area, electrical architecture, and spatial distribution of the photovoltaic elements, while remaining exposed to the same outdoor environmental conditions. This configuration enabled evaluation of module-specific electrical responses under a common environmental forcing field, without direct electrical coupling between the generators. The methodology integrated synchronized measurements of photovoltaic electrical variables and environmental conditions, enabling evaluation of operating power, power density, energy yield, and operating conversion efficiency together with incident irradiance, ambient temperature, relative humidity, wind speed, and sunshine duration. The complete experimental and analytical workflow is presented schematically in Fig. 1.

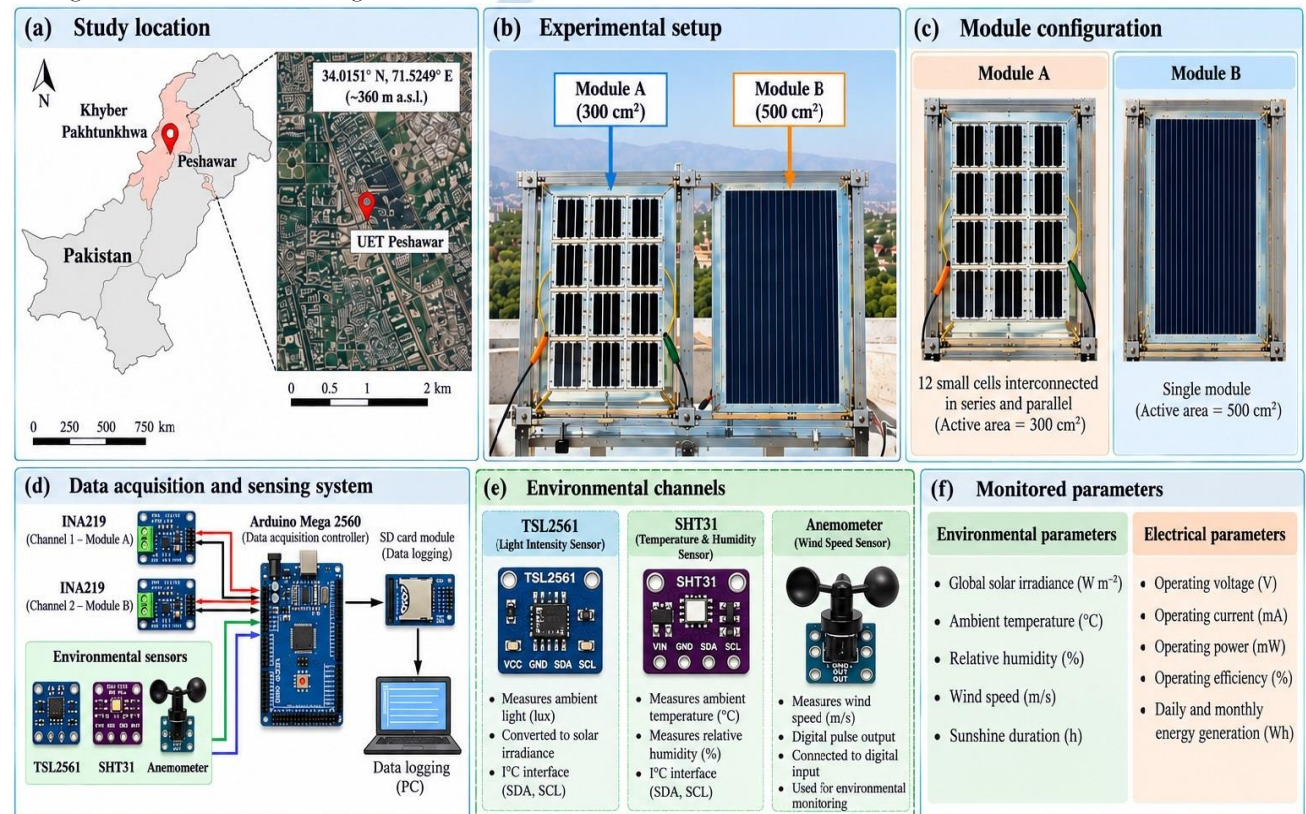


Fig. 1. Integrated experimental and analytical workflow for the outdoor evaluation of the two perovskite BIPV configurations, including module architecture, environmental and electrical sensing, data acquisition, synchronization, storage, photovoltaic-performance calculations, statistical analysis, and environmental operating-regime identification

The physical BIPV structure was fabricated primarily from 0.6-inch-thick melamine-faced

particleboard. The documented material properties included a thermal conductivity of

approximately $0.12 \text{ W m}^{-1} \text{ K}^{-1}$, a density of approximately 650 kg m^{-3} , a specific heat of approximately $1700 \text{ J kg}^{-1} \text{ K}^{-1}$, a thermal absorptance of 0.75, a visible absorptance of 0.65, and a solar absorptance of 0.70. A south-facing inclined roof was incorporated to provide a representative photovoltaic mounting surface, while window apertures were included to accommodate semi-transparent photovoltaic integration. The documented roof inclination was approximately 16.2° , due to differences in wall heights. The prototype therefore reproduced the principal geometric characteristics of a small building envelope while providing sufficient access for instrumentation, electrical integration, and module installation.

The photovoltaic subsystem comprised two carbon-based semi-transparent perovskite configurations. Module A, designated INA219_1, consisted of twelve individual $5 \times 5 \text{ cm}$ mini-

modules with a combined active photovoltaic area of 300 cm^2 . The twelve units were electrically interconnected in a 3-series $\times$ 4-parallel (3S4P) configuration, providing a nominal operating-voltage range of approximately 5–6 V while increasing current capability and distributing the effects of individual-unit mismatch. Module B, designated INA219_2, consisted of a larger monolithic carbon-based semi-transparent perovskite module with an active area of 500 cm^2 . Its internal series configuration resulted in a substantially higher operating-voltage range of approximately 18–20 V. The two configurations consequently provided an experimentally relevant contrast between a spatially distributed mini-module array and a larger single-module architecture. The principal experimental characteristics of both configurations and the common monitoring architecture are summarized in Table 1.

Table 1. Experimental configuration and variables used in the environmental stress–performance analysis

Parameter	Module A / Shared System	Module B / Shared System
Identifier	INA219_1	INA219_2
Active photovoltaic area	300 cm^2	500 cm^2
Photovoltaic configuration	$12 \times 5 \times 5 \text{ cm}$ semi-transparent mini-modules, 3S4P	Single larger-area semi-transparent module
Approximate electrical operating range	$\sim 5\text{--}6 \text{ V}$	$\sim 18\text{--}20 \text{ V}$
Experimental load	200Ω resistive load + green LED	$1 \text{ k}\Omega$ resistive load + red LED
Electrical sensor	INA219	INA219
Environmental channels	TSL2561, SHT31, anemometer	Same synchronized channels
Time synchronization	DS3231 RTC	Same synchronized time base
Data aggregation	ESP32	Shared ESP32
Data storage	SD card	Shared SD-card system
Daily photovoltaic variables	Voltage, current, operating power, power density, energy yield, efficiency	Voltage, current, operating power, power density, energy yield, efficiency
Common environmental variables	Irradiance, temperature, relative humidity, sunshine duration	Same

Field-analysis period	October 2025– January 2026	October 2025– January 2026
-----------------------	----------------------------	----------------------------

Both photovoltaic configurations utilized carbon-based perovskite architectures prepared on FTO-coated glass. The documented device stack comprised a compact TiO₂ electron-transport/blocking layer, a mesoporous TiO₂ scaffold, a ZrO₂ insulating spacer, a carbon electrode, silver current-collection contacts and a methylammonium lead iodide (MAPbI₃) absorber. The fabrication was realized by screen printing and thermal treatment processes. Thus, the two configurations differed not only in active area but also in electrical interconnection and spatial distribution of the active photovoltaic material, providing the architectural contrast necessary to evaluate environmental-performance coupling.

The photovoltaic elements were embedded in double-glazed window assemblies for mechanical protection and for minimizing the direct exposure of the active layer to moisture and oxygen. The photovoltaic structure was sandwiched between glass substrates using rubber spacers, the interior cavity being defined by a perimeter spacer of approximately 7 mm. ~95% optical transmittance upper glass sheet was mounted on the photovoltaic structure and bonded by butyl rubber and silicone rubber. A completed glazing unit was supported in an aluminum frame to provide structural support and to facilitate installation. The aim of this encapsulation architecture is to retain the semi-transparent BIPV function, while alleviating the direct environmental exposure to the perovskite active layer during outdoor operation.

The two photovoltaic configurations were kept as electrically independent generators during the experiment. Module A was operated through a resistive load of 200 Ω and green LED indicator while Module B was operated through a resistive load of 1 kΩ and a red LED indicator. The independent loading arrangement prevented direct series or parallel electrical coupling from masking differences in module voltage, current, architecture and operating state. This setup was

especially crucial for the environmental-sensitivity analysis as both setups were subjected to the same outdoor forcing conditions while maintaining their own electrical running paths. Electrical performance was measured using INA219 current-voltage monitors. For each INA219 sensor, measurements of bus voltage and current were obtained and operating electrical power was calculated as:

$$P = VI \quad (2)$$

Where P denotes operating electrical power (mW), V denotes measured voltage (V) and I denotes measured current (mA). With these units the resulting electrical power is given directly in mW. The INA219 sensors were interfaced with the ESP32 microcontroller using the I²C communication architecture.

Since both photovoltaic configurations were operated with fixed resistive loads, the measured electrical output represents the operating power under the prescribed experimental load conditions rather than a certified maximum power point (MPP) or rated maximum power (P_{max}) value. The experimental data given did not contain a complete current-voltage sweep or a specific dataset for maximum-power-point tracking. Therefore, in the present study the term operating power is consistently used rather than (MPP power) or (P_{max}) when referring to the measured electrical output.

Environmental monitoring was set up as a synchronized multi-sensor system. The incident light intensity was characterized using a TSL2561 digital light sensor and the environmental dataset used for the photovoltaic performance calculations included the corresponding irradiance values. Ambient temperature and relative humidity were measured with a SHT31 sensor, while wind-speed measurements were obtained with a three-cup anemometer, given their importance for outdoor thermal behavior and module cooling. The environmental channels were synchronized with the photovoltaic electrical

measurements to provide a common temporal reference for subsequent analysis.

Temporal synchronization was provided by a DS3231 real time clock (RTC) and sensor outputs were aggregated and the measurement sequence managed by an ESP32 microcontroller. Each measurement record had an associated synchronized timestamp, allowing electrical and environmental variables to be aligned in time. Data were then written to an SD card module via SPI to provide local storage and measurement redundancy. Thus, the resulting monitoring architecture combines photovoltaic electrical channels, environmental sensors, time synchronization, microcontroller-based data aggregation and local data logging. This integrated setup enabled the evaluation of voltage, current, operating power, irradiance, temperature, humidity, wind speed, and associated derived variables in a common temporal framework. The prototype was tested under natural outdoor conditions in Peshawar, Khyber Pakhtunkhwa, Pakistan. The site is a semi-arid outdoor environment with high solar exposure, seasonal

temperature and humidity variations, low precipitation and potential deposition of airborne particulate matter. No artificial manipulation of the surrounding weather conditions was imposed during the field campaign. This meant that the modules were exposed to the natural environmental variability associated with the transition from autumn to winter. The field exposure was thus designed to characterize the photovoltaic performance and environmental sensitivity under realistic operating conditions, as opposed to controlled laboratory illumination or thermal environments.

The overall matched analysis period was from 4 October 2025 to 25 January 2026. Both photovoltaic configurations shared the observation dates, so a direct comparison under the same external environmental conditions was possible. The month of January is only the observed period through 25 January, and so was treated explicitly in the data rather than extrapolated to represent the full calendar month. The period-specific environment structure for further analysis is shown in Table 2.

Table 2. Environmental observation structure used for the field analysis

Period	Daily records	Mean irradiance (mW cm ⁻²)	Mean temperature (°C)	Mean RH (%)	Mean sunshine duration (h d ⁻¹)
October 2025	28	53.12	30.85	31.28	11.21
November 2025	30	42.54	23.67	47.39	9.20
December 2025	31	33.53	13.35	65.43	8.94
January 2026	25	35.92	13.19	59.07	9.12

As summarized in

Table 2, the environmental operating envelope changed progressively over the field campaign, with irradiance and ambient temperature generally decreasing from autumn toward winter, accompanied by an increase in relative humidity.

January exhibited partial recovery in irradiance relative to December, while operating in a substantially colder and more humid environment than in October. These period-level changes were retained as measured rather than normalized to a complete calendar month.

To enable meaningful comparison between photovoltaic configurations of different active areas, operating power was normalized to the corresponding active photovoltaic area. Power density was calculated according to;

$$PD = \frac{P}{A} \quad (3)$$

where PD is power density (mW cm^{-2}), P is operating power (mW), and A is active photovoltaic area (cm^2). This normalization is particularly important for the present study because Module A and Module B have active areas of 300 cm^2 and 500 cm^2 , respectively. Absolute power alone therefore cannot fully represent the relative performance of the two configurations.

Daily energy yield was calculated from operating power and effective sunshine duration according to;

$$E = P t \quad (4)$$

where E is daily energy yield (mWh day^{-1}), P is operating power (mW), and t is effective sunshine duration (h). The calculation was applied to the measured operating power, thereby maintaining consistency with the fixed-load experimental configuration. The use of operating power rather than maximum-power-point power was retained throughout the analysis.

Operating conversion efficiency was calculated using;

$$\eta = \frac{P}{GA} \times 100 \quad (5)$$

where η is operating conversion efficiency (%), P is operating power (mW), G is incident irradiance (mW cm^{-2}), and A is active photovoltaic area (cm^2). The irradiance values used in Eq. 5 were obtained from the synchronized environmental dataset. This formulation provides an area-normalized measure of conversion performance under the actual electrical loading conditions imposed during the field experiment.

For system-level reporting, the energy outputs of the two modules were treated as additive because the modules were maintained as electrically independent generators:

$$E_{\text{sys}} = E_A + E_B \quad (6)$$

where E_{sys} is aggregate operating energy yield and E_A and E_B are the independently measured energy

yields of Modules A and B, respectively. An aggregate operating efficiency was similarly evaluated from the combined operating power and total active area:

$$\eta_{\text{sys}} = \frac{P_A + P_B}{G(A_A + A_B)} \times 100 \quad (7)$$

where P_A and P_B represent the operating powers of Modules A and B, and A_A and A_B represent their active areas. So, the total active area was 800 cm^2 . The result is a system level quantity of area normalized aggregate operating efficiency rather than the efficiency of a single electrically merged photovoltaic generator. The modules kept the voltage and current paths separate during the measurement process, and this separation is necessary.

Data processing comprised temporal matching, consistency checking, derived photovoltaic variable calculations, period wise aggregation and statistical analysis of the relationships between environmental and performance variables. The main analytical data set was the daily records kept rather than the analysis reconstructed from rounded period-level averages. The approach maintained within-period variability and decreased data loss from early aggregation. Derived quantities were calculated from the underlying synchronized measurements wherever the necessary variables were available.

Descriptive statistics (arithmetic mean and sample standard deviation) were calculated separately for each observation period. Minimum and maximum values were kept where needed to describe the environmental operating envelope. The January statistics were clearly seen as a summary of a partial period, since data was available only up to January 25. No extrapolation was carried out to convert the January observations into a full calendar month estimate.

The Pearson's product-moment correlation coefficient was used to quantify the environmental-performance coupling, assessing linear relationships between daily PV response variables and environmental parameters. Spearman's rank correlation was also considered as a complementary non-parametric measure to reduce sensitivity to non-normal distributions and

to identify monotonic relationships that may not be strictly linear. Correlation analysis was performed both over the total period of matched observations and within periods of observations to check whether any apparent environmental sensitivity was consistent as the outdoor operating environment changed.

Since the environmental predictors were not statistically independent, the computed correlation coefficients were interpreted as indicating associative rather than causal relationships. In particular, irradiance, ambient temperature and relative humidity showed substantial seasonal co-variation. Thus, correlations computed across the entire field campaign characterize the structure of the observed operating envelope, but cannot independently assess the causal contribution of an individual environmental variable. This limitation was intentionally maintained in the analytical framework instead of inferring causal effects based on the magnitude of correlations alone. More robust partitioning of the individual contributions of correlated environmental predictors would require longer duration, multi-season observations and multi-variable modeling. To examine the possible change of the environmental sensitivity over the field campaign, the daily records were also stratified by observation period. The relationships between environmental forcing and photovoltaic response were separately assessed for Module A, Module B and the aggregate BIPV response. This time-resolved approach allowed us to identify changes in response slope, correlation strength and response variability. This provided an empirical basis for the evaluation of possible shifts of the photovoltaic operating regime.

The operational regime was determined empirically from the combined environmental envelope and the corresponding photovoltaic response rather than from calendar dates alone. A regime transition was identified as the simultaneous occurrence of three conditions: (i) a sustained change in the environmental operating envelope, (ii) a corresponding change in photovoltaic response magnitude or variability,

and (iii) a change in the statistical relationship between the environmental forcing and photovoltaic response. This definition did not impose universal environmental thresholds on the dataset, but instead derived regime boundaries from the observed field response and co-located environmental measurements.

Four descriptive operating states were identified from the measured data set: a higher-irradiance/lower-humidity state, a transitional state, a lower-irradiance/higher-humidity state and a later lower-output state that showed partial irradiance recovery without corresponding photovoltaic recovery. These labels are purely analytical descriptors of the data set at hand and are not intended to be universal climatic classifications.

The analysis also distinguished environmental variability from evidence of evolution of module states. The electrical performance trends were compared with the measured environmental envelope. However, in the case of visual observation of discoloration, active-area non-uniformity and patch formation, the observations were considered as qualitative supporting evidence rather than being directly transformed to quantitative degradation variables. The experimental documentation revealed significant visual changes for Module A, and limited visual structural changes for Module B. These observations provide an independent physical reference for the measured electrical response, rather than assigning quantitative degradation rates based on visual inspection alone.

No other environmental measurements or synthetic values were included in the analysis. Where available, the more detailed daily records underlying the rounded values at the level of periods were used preferentially for statistical calculations. Also, the observation period in January was kept as recorded and not extrapolated to represent a full calendar month. This treatment preserves the separation between measured observations and derived quantities and preserves traceability between field measurements, calculated photovoltaic metrics, environmental statistics and subsequent interpretation.

The complete methodological sequence, from BIPV module configuration and outdoor exposure to synchronized acquisition of electrical and environmental data, data storage, calculations of photovoltaic performance, statistical evaluation and environmental regime identification, is summarized in Fig. 1. The resulting framework provides a consistent basis for assessing how differences in photovoltaic architecture and module state interact with the naturally varying outdoor environment, while maintaining a clear separation between measured operating performance, derived metrics, and qualitative physical observations.

3. Results and Discussion

The field measurements reveal a progressive evolution of the environmental operating envelope and a corresponding divergence in the electrical and energy-yield trajectories of the two perovskite BIPV configurations. Rather than exhibiting a stationary response to outdoor forcing, the modules underwent distinct changes in operating power, conversion efficiency, cumulative energy contribution, and environmental sensitivity as the field conditions transitioned from comparatively warm, dry autumn conditions toward cooler, more humid winter conditions. The results presented in this

section therefore integrate the measured environmental evolution, module-level electrical response, energy contribution, normalized performance retention, environmental correlations, and empirical operating-regime transitions to distinguish instantaneous environmental effects from changes associated with the evolving module state.

The environmental conditions changed substantially throughout the observation period. Fig. 2 presents the synchronized seasonal environmental envelope, showing the daily evolution of solar irradiance, ambient temperature, and relative humidity. Mean daily irradiance decreased from $53.12 \pm 3.78 \text{ mW cm}^{-2}$ in October to $42.54 \pm 0.75 \text{ mW cm}^{-2}$ in November and $33.53 \pm 0.72 \text{ mW cm}^{-2}$ in December, then partially recovered to $35.92 \pm 0.70 \text{ mW cm}^{-2}$ in January. Over the same period, mean ambient temperature declined from $30.85 \pm 0.63 \text{ }^{\circ}\text{C}$ in October to approximately $13.2\text{--}13.4 \text{ }^{\circ}\text{C}$ during December and January. In contrast, relative humidity increased from $31.28 \pm 3.51\%$ in October to $65.43 \pm 0.40\%$ in December, then decreased to $59.07 \pm 0.46\%$ in January. These changes define a progressively colder, more humid operating environment, accompanied by a substantial reduction in available solar resources.

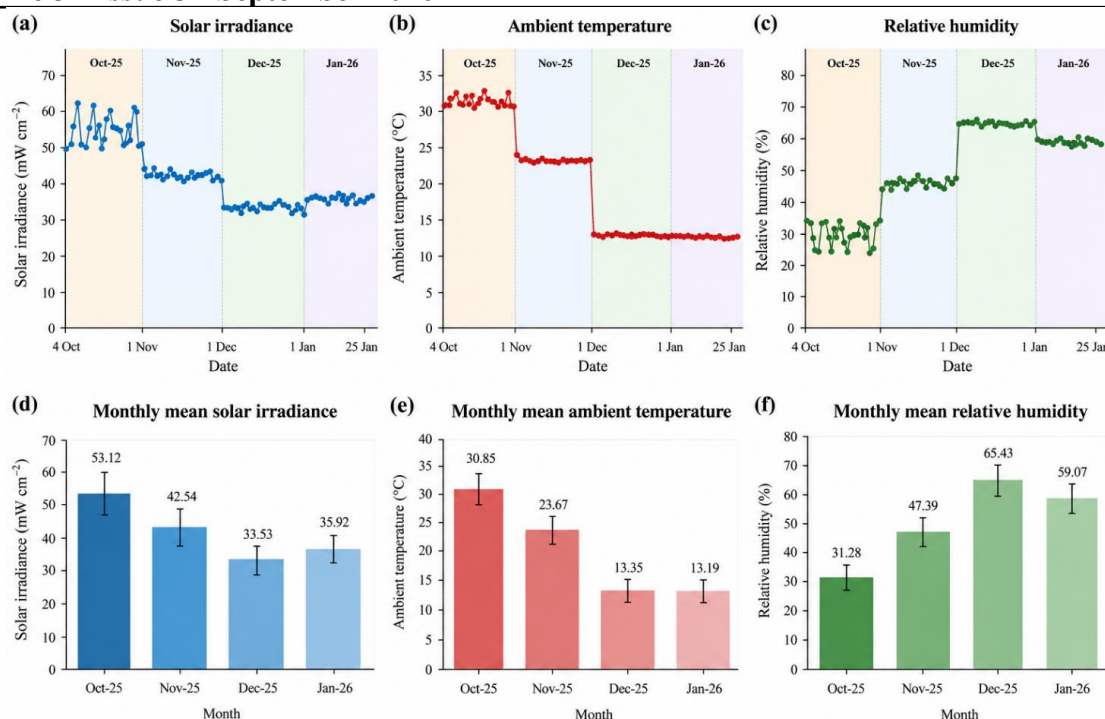


Fig. 2. Seasonal environmental envelope across the observation period: (a) daily solar irradiance, (b) ambient temperature, and (c) relative humidity

The period-level environmental statistics are summarized in Table 3. From October to December, mean irradiance declined by approximately 36.9%, relative humidity increased by approximately 109%, and ambient temperature decreased by approximately 56.7%, all relative to October. The combined environmental evolution therefore represents a transition from a comparatively high-irradiance, warm, and low-humidity state toward a lower-irradiance, cooler, and substantially more humid state. January

introduced a notable departure from the monotonic environmental trend: mean irradiance increased by approximately 7.1% relative to December, while relative humidity decreased by approximately 9.7%. However, this partial environmental recovery was not accompanied by an equivalent recovery in photovoltaic efficiency. The divergence between external solar-resource recovery and module-level electrical recovery is consequently important for interpreting the later operating response.

Table 3. Monthly environmental operating conditions derived from the matched daily dataset

Month	Irradiance (mW cm ⁻²)	Temperature (°C)	RH (%)	Sunshine (h d ⁻¹)
Oct-25	53.12	30.85	31.28	11.21
Nov-25	42.54	23.67	47.39	9.20
Dec-25	33.53	13.35	65.43	8.94
Jan-26	35.92	13.19	59.07	9.12

The electrical response under these common environmental conditions is presented in Fig. 3. Module A (INA219_1) operated predominantly within a lower-voltage regime of approximately 2–

4 V, whereas Module B (INA219_2) operated predominantly at approximately 17–20 V. This voltage separation is consistent with the fundamentally different electrical architectures of

the two generators: Module A comprised twelve 5×5 cm semi-transparent photovoltaic units arranged in a 3-series × 4-parallel configuration, whereas Module B consisted of a larger monolithic series-connected photovoltaic configuration. The

two modules therefore experienced the same outdoor forcing but converted that forcing through substantially different electrical architectures.

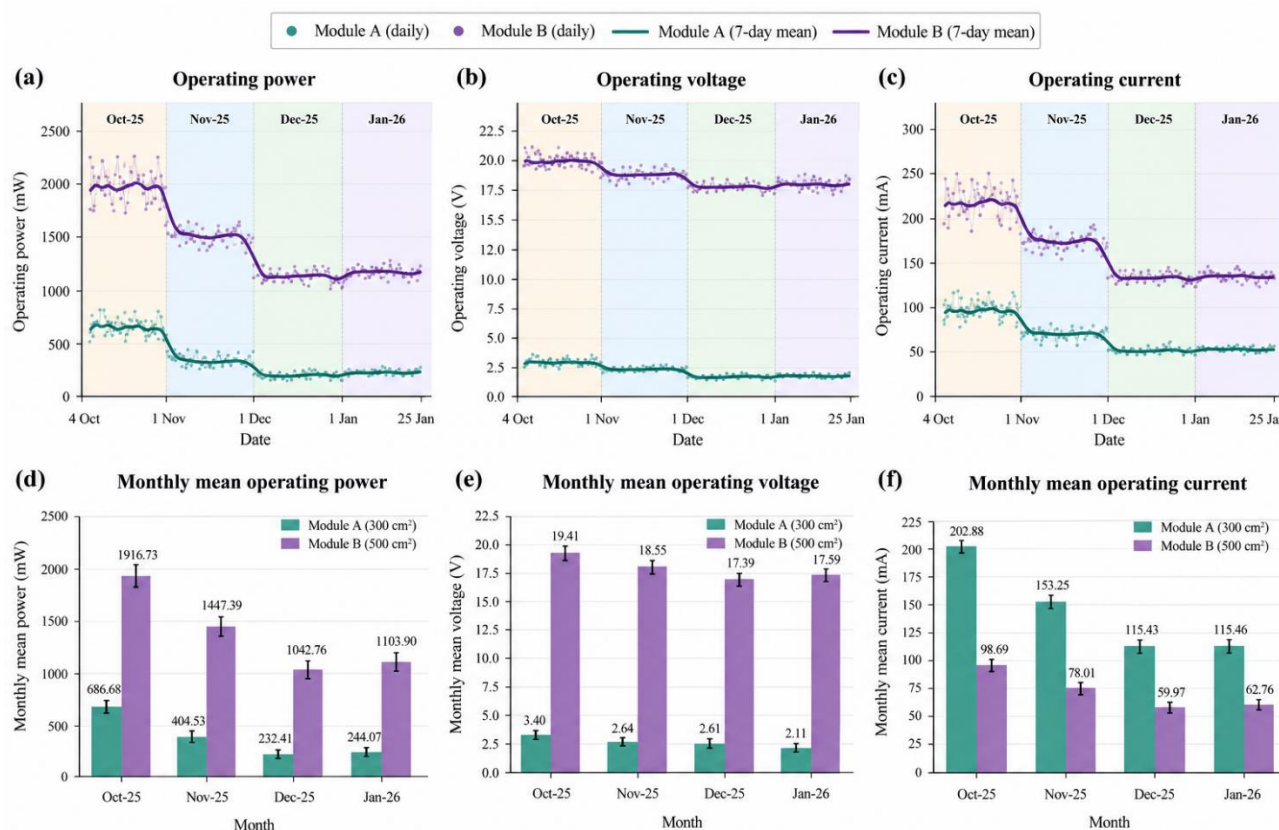


Fig. 3. Daily electrical performance under common environmental forcing: (a) operating power of Module A, Module B, and the combined output; (b) daily operating efficiency of the two modules; and (c) area-weighted system operating efficiency

The quantitative electrical-performance statistics are provided in Table 4. Module A exhibited a pronounced reduction in mean operating power from 686.7 mW in October to 404.5 mW in November and 232.4 mW in December, followed by only a limited recovery to 244.1 mW in January. Module B followed the same broad environmental

trajectory but retained substantially greater output, with mean operating power decreasing from 1916.7 mW in October to 1447.4 mW in November and 1042.8 mW in December, before increasing to 1103.9 mW in January. The peak observed operating power followed the same general pattern for both configurations.

Table 4. Monthly electrical operating performance of the two perovskite BIPV modules

Month	Module A mean operating	Module A peak observed	Module A	Module B mean operating	Module B peak observed	Module B	System efficiency (%)
Oct-25	686.68	1916.73	3.40	19.41	202.88	98.69	
Nov-25	404.53	1447.39	2.64	18.55	153.25	78.01	
Dec-25	232.41	1042.76	2.61	17.39	115.43	59.97	
Jan-26	244.07	1103.90	2.11	17.59	115.46	62.76	

	power (mW)	power (mW)	efficiency (%)	power (mW)	power (mW)	efficiency (%)	
Oct-25	686.7	858.1	4.29	1916.7	2186.8	7.21	6.12
Nov-25	404.5	443.9	3.17	1447.4	1511.4	6.80	5.44
Dec-25	232.4	249.2	2.31	1042.8	1090.3	6.22	4.75
Jan-26	244.1	264.3	2.26	1103.9	1139.8	6.15	4.69

The efficiency trajectories, shown in Fig. 3(b), reveal a larger difference between the two configurations than can be seen from the absolute operating power alone. Module A declined from 4.29% in October to 3.17% in November, 2.31% in December, and 2.26% in January. Module B showed a slower decline, starting at 7.21% in October and then declining to 6.80%, 6.22% and 6.15% in the following observation periods. As seen in Figure 3c, the area-weighted system efficiency decreased from 6.12% in October to 5.44% in November, 4.75% in December and 4.69% in January.

The contrast in Table 4 is especially important because both modules were exposed to essentially the same environmental forcing. The mean irradiance declined about 32.4% from October to January. Instead, the operational efficiency of module A dropped by ~47.2% and that of module

B only dropped by ~14.8%. So, the degradation of Module A was much more than just the change in solar resource availability. The difference suggests that the seasonal drop in irradiance cannot alone explain the different efficiency trajectories. Rather, the electrical response seems to have become more and more dependent on the module's particular state and architecture.

The cumulative energy response provides another view of this divergence. Fig. 4 shows the monthly energy yield and the relative contribution of each module to the total energy generation. The total measured energy yields for the months of October, November, December and January were 812.88, 511.29, 353.29 and 307.39 Wh, respectively, resulting in a total measured energy yield of 1984.85 Wh for the whole period of observation. Module A contributed 445.64 Wh, Module B contributed 1539.22 Wh.

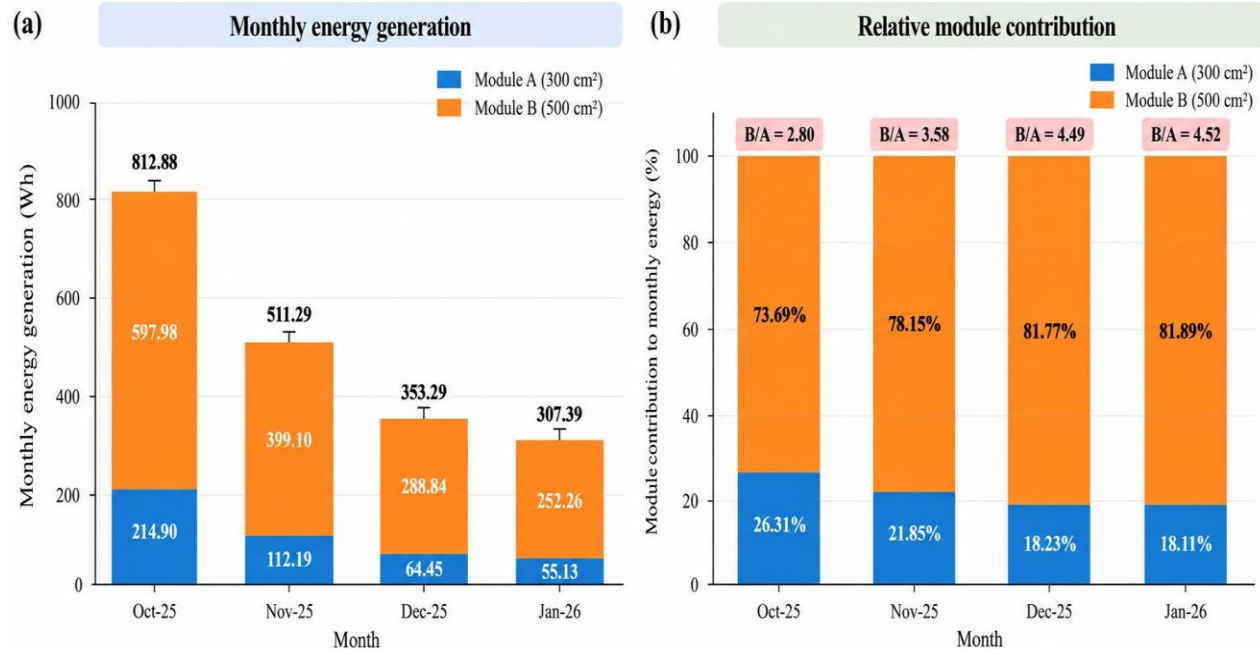


Fig. 4. Monthly energy yield and relative module contribution: (a) cumulative monthly energy generated by Module A, Module B, and the combined BIPV system; and (b) percentage contribution of each module to monthly energy generation

The monthly energy distribution is quantified in

Table 5. Module B occupied 62.5% of the combined active area but supplied 77.55% of the measured energy, whereas Module A occupied 37.5% of the active area but supplied only 22.45%. The contribution imbalance increased progressively through the observation period. Module A's contribution decreased from 26.31% in October to 21.85% in November, 18.23% in

December, and 18.11% in January, while Module B's contribution increased correspondingly from 73.69% to 81.89%. The B/A energy-yield ratio increased from 2.80 in October to 4.52 in January. The increasing contribution of Module B therefore cannot be explained solely by its larger active area; the relative operating response of the two configurations also changed during the field campaign.

Table 5. Energy yield and module contribution derived from the daily records

Month	Module A (Wh)	Module B (Wh)	Combined (Wh)	A share (%)	B share (%)	B/A ratio
Oct-25	213.87	599.02	812.88	26.31	73.69	2.80
Nov-25	111.71	399.58	511.29	21.85	78.15	3.58
Dec-25	64.40	288.89	353.29	18.23	81.77	4.49
Jan-26	55.67	251.73	307.39	18.11	81.89	4.52
Total	445.64	1539.22	1984.85	22.45	77.55	3.45

The normalized performance trajectories shown in Fig. 5 provide a clearer comparison because normalization removes the direct influence of the substantially different absolute output levels. Relative to the October baseline, Module A retained approximately 52.8% of its October

mean operating efficiency by January, whereas Module B retained approximately 85.2%. When peak observed operating power is used as the reference, Module A retained approximately 30.8% of its October value, and Module B retained approximately 52.1%.

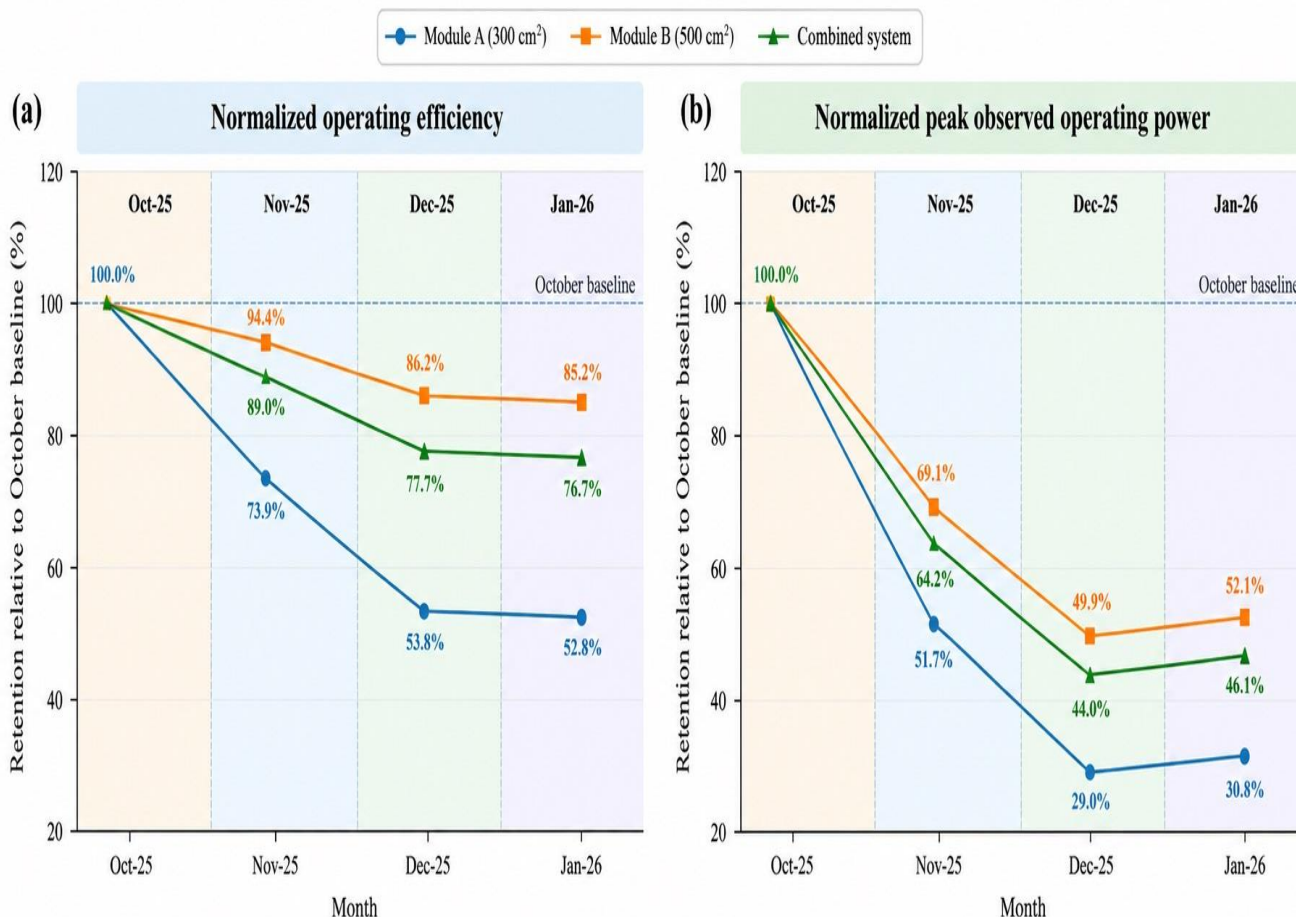


Fig. 5. Normalized performance retention referenced to the October baseline: (a) normalized mean daily operating efficiency and (b) normalized peak observed operating power for Modules A and B

The normalized trends in Fig. 5 provide evidence of progressively different performance retention between the two configurations. The difference is also consistent with the qualitative physical observations recorded during the experiment. Module A exhibited pronounced discoloration, non-uniform active-area appearance, and patch formation, whereas Module B showed comparatively limited visible structural change. The temporal concurrence between greater

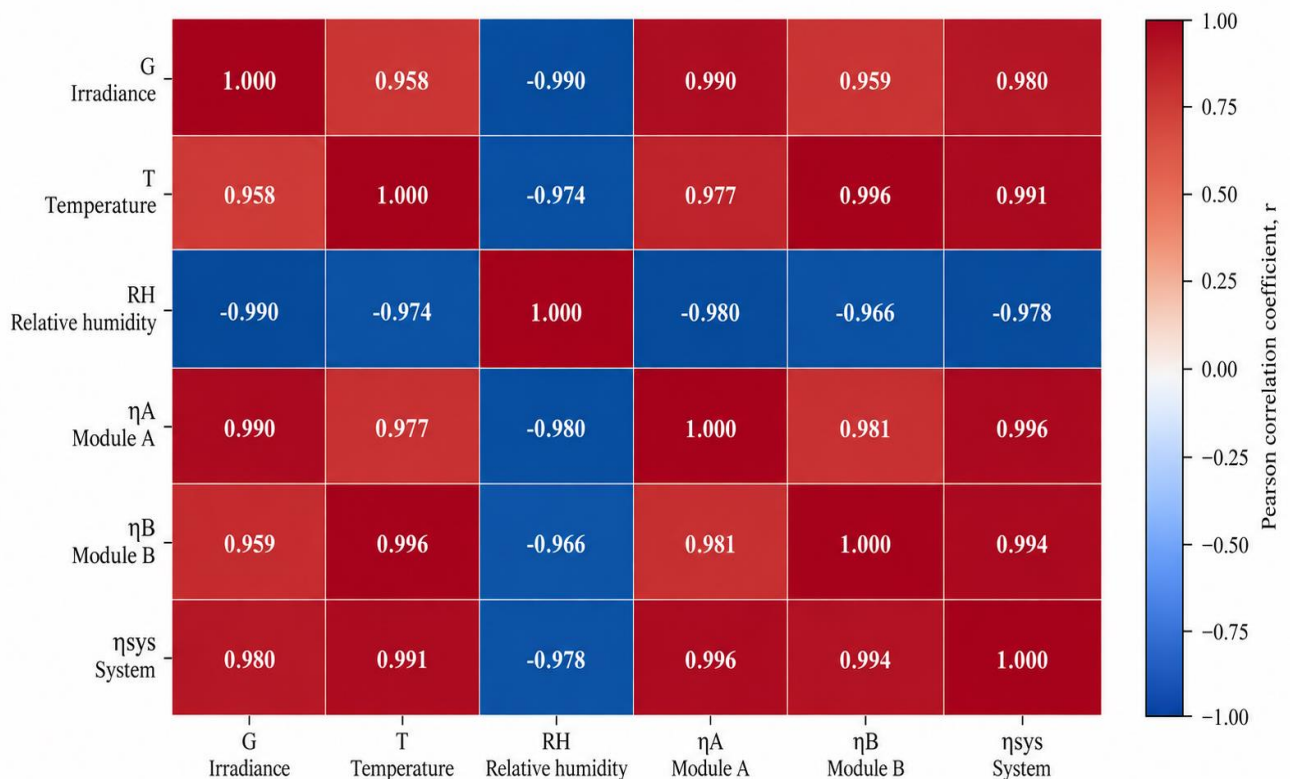
electrical deterioration and more pronounced visible changes in Module A provides supporting evidence that the observed divergence involved more than just a reduction in incident solar resource. However, because the experimental record lacks chemical, microscopic, or spectroscopic post-mortem characterization, the visual features cannot be uniquely assigned to a particular degradation mechanism. They are therefore treated as phenomenological evidence of

module-state evolution rather than direct identification of a specific material failure pathway.

The relationship between the environmental variables and operating efficiency is further examined using Pearson correlation analysis. Fig. 6 presents the correlation matrix, while the corresponding coefficients are reported quantitatively in Table 6. Operating efficiency exhibited strong positive associations with

irradiance and temperature and strong negative associations with relative humidity. For Module A, the Pearson coefficients were 0.990 for irradiance, 0.977 for temperature, and -0.980 for relative humidity. For Module B, the corresponding coefficients were 0.959, 0.996, and -0.966 , respectively. The area-weighted system response produced coefficients of 0.980, 0.991, and -0.978 , respectively.

Pearson correlation matrix of environmental and performance variables



Positive values indicate direct association; negative values indicate inverse association.

Pairwise correlations describe associations across the matched daily records and do not imply independent causal effects.

Fig. 6. Pearson correlation matrix of environmental variables and photovoltaic operating efficiency across the matched daily records.

Table 6. Pearson correlations between environmental variables and daily operating efficiency

Environmental variable	Module A, (r)	Module B, (r)	System, (r)
Irradiance	0.990	0.959	0.980
Temperature	0.977	0.996	0.991
Relative humidity	-0.980	-0.966	-0.978

The correlation structure shown in Fig. 6 and quantified in Table 6 demonstrates strong statistical coupling between the environmental variables and photovoltaic operating efficiency. Nevertheless, the magnitude of these coefficients should not be interpreted as evidence of independent causal effects. Irradiance, temperature, and relative humidity co-varied strongly over the observation period because the field campaign coincided with a pronounced seasonal transition. The strong positive temperature–efficiency association, for example, partly reflects the coincidence of warmer conditions with higher irradiance during October, whereas colder conditions occurred predominantly during the lower-irradiance, higher-humidity winter state. Similarly, the strong inverse relationship between humidity and efficiency is partly a consequence of the same seasonal environmental trajectory. Accordingly, the coefficients characterize the observed environmental–performance association within the field operating envelope rather than providing independent sensitivity coefficients for each environmental variable. This distinction is particularly important for outdoor photovoltaic studies because environmental predictors frequently exhibit substantial temporal covariance. Multivariable or controlled experiments would be required to isolate independent causal contributions.

The January observations provide an especially informative test of this interpretation. When Fig. 2, Fig. 3, and Fig. 6 are considered jointly, mean irradiance increased from 33.53 mW cm^{-2} in December to 35.92 mW cm^{-2} in January, while relative humidity decreased from 65.43% to 59.07%. Nevertheless, the efficiency of Module A decreased from 2.31% to 2.26%, and the efficiency of Module B decreased from 6.22% to 6.15%. Thus, partial recovery of the external solar resource was not accompanied by a corresponding recovery in photovoltaic efficiency. This behavior indicates that the later electrical response cannot be adequately described by instantaneous irradiance alone.

The combined environmental–performance interpretation is synthesized in Fig. 7. The figure integrates the environmental evolution shown in Fig. 2, the electrical response in Fig. 3, the normalized performance trajectories in Fig. 5, and the environmental associations presented in Fig. 6. It therefore provides a conceptual representation of the transition from the comparatively high-irradiance/low-humidity October state toward the lower-irradiance/high-humidity December state, followed by the January condition in which irradiance partially recovered while efficiency remained comparatively depressed.

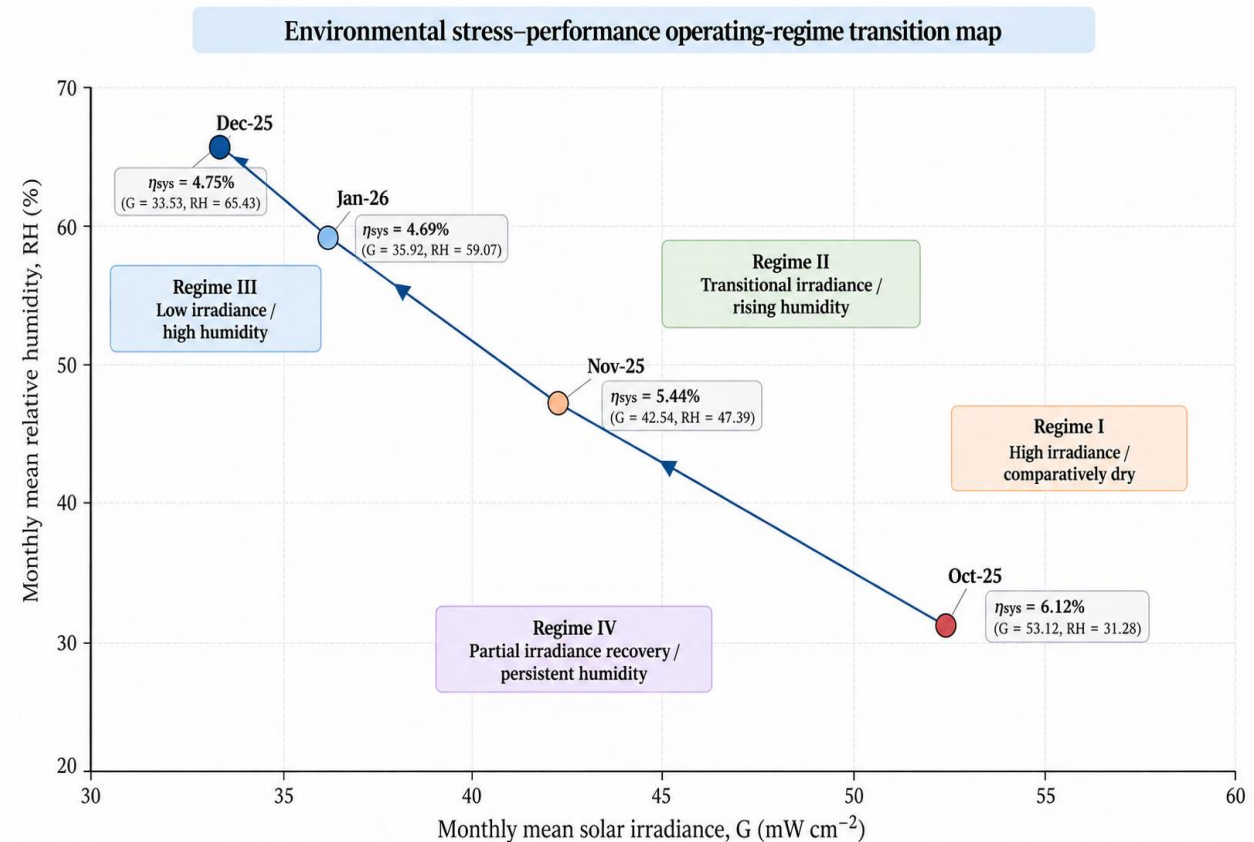


Fig. 7. Environmental stress–performance operating-regime transition map showing the progression from the high-irradiance/low-humidity state through transitional and low-irradiance/high-humidity conditions to the January partial-irradiance-recovery/low-efficiency state

The empirical operating regimes represented in Fig. 7. The first state corresponds to comparatively strong resource-responsive performance under higher irradiance, warmer temperature, and lower humidity. November represents a transitional environmental state characterized by reduced irradiance and increasing humidity. December constitutes the most distinct low-irradiance/high-humidity condition and coincides with pronounced divergence between the two photovoltaic configurations. January represents a later low-output state in which partial recovery of the external solar resource does not produce equivalent recovery in photovoltaic efficiency.

4. Conclusion

This field study shows that the outdoor performance of semi-transparent perovskite building-integrated photovoltaics (BIPV) under

semi-arid conditions is driven by the coupled evolution of environmental forcing and module state rather than by incident solar irradiance alone. The transition from comparatively warm, high-irradiance, low-humidity conditions to a cooler, lower-irradiance, higher-humidity environment during the observation period was associated with substantial changes in photovoltaic power and efficiency. However, the extent of these changes was significantly different between the two independently operated module configurations, indicating that environmental exposure and module architecture together affect field-level performance.

The two configurations showed clearly distinct performance trajectories. The greater deterioration in operating efficiency was shown by module A, which has an active area of 300 cm², declining from 4.29% in October to 2.26% in

January, corresponding to a reduction of approximately 47% relative to its October baseline. peak observed operating power went down from 858.1 to 264.3 mW. Module B, with an active area of 500 cm², showed superior absolute performance and better performance retention. Meanwhile, the operating efficiency dropped from 7.21% to 6.15% and the peak observed operating power dropped from 2186.8 to 1139.8 mW in the same period. Thus, although both modules experienced the same outdoor environmental forcing, their electrical responses evolved differently, indicating significant configuration-dependent behavior.

The cumulative energy results support this divergence further. The studied system produced about 1.985 kWh during the entire observation period, of which Module A contributed 445.64 Wh and Module B contributed 1539.22 Wh. Module B, though only 62.5% of the combined active photovoltaic area, supplied about 77.55% of the measured energy, while Module A, 37.5% of the active area, contributed only 22.45%. These results show that active area alone is not enough to describe BIPV energy contribution when modules differ in electrical architecture, operating stability, and retention of temporal performance.

The environmental–performance analysis revealed strong positive relations between operating efficiency and irradiance and temperature and strong negative relations with relative humidity. However, as the environmental variables were strongly co-varying seasonally, these relationships should be interpreted as associations within the observed environmental envelope, rather than as independent causal effects. The reaction in January in this respect furnishes particularly important evidence. Although the irradiance was partially recovered in comparison to December and the humidity was lower, no corresponding recovery of the operating efficiency was observed for either module. This decoupling of partial resource recovery from photovoltaic recovery suggests that the later electrical state was not simply a function of contemporaneous irradiance, but was increasingly driven by the evolving condition of the modules.

The observed electrical trends were related to contrasting physical appearances. For Module A, discoloration, non-uniform active regions and patch formation were shown. Module B showed relatively limited visible change. The agreement of stronger electrical deterioration and more pronounced visible changes in Module A is consistent with differential stability behavior between the configurations. However, these observations are phenomenological evidence and not definitive identification of a specific degradation mechanism, since post-mortem chemical, microscopic or spectroscopic characterization was not included in the present study.

The results are consistent with an environmental-performance regime interpretation specific to the studies in which photovoltaic operation proceeds from a relatively high-irradiance, warm and low-humidity state to lower-irradiance and higher-humidity states, followed by a partial recovery in irradiance without an accompanying proportional recovery in efficiency. The results thus suggest that the outdoor BIPV response is a dynamic state-dependent process, rather than a single stationary efficiency-irradiance relation. Such a distinction is particularly relevant for perovskite BIPV, where the measured operating state may be representative of both the current environmental conditions and the cumulative effects of previous exposure.

From an engineering perspective, the findings highlight the need to integrate synchronized environmental monitoring with module-level electrical measurements, normalized performance indicators, cumulative energy assessment and time-based performance-retention analysis. Field evaluation based on isolated efficiency measurements alone may obscure progressive divergence between neighboring photovoltaic elements. Therefore, for practical BIPV applications, the reliability of the whole photovoltaic architecture, including encapsulation, electrical interconnection, active-area configuration, and environmental exposure, should be evaluated in addition to the nominal conversion efficiency.

There are several limitations to be acknowledged. The field campaign spans a finite observation time and therefore does not establish long-term lifetime behavior. Moreover, the experimental set-up did not provide a full current-voltage characterization, nor a specific maximum power point tracking, so the results provided are representative of the performance at fixed electrical loads and not of the certified maximum power performance. The absence of post-mortem chemical and microscopic characterization also prevents the direct identification of the mechanisms behind the observed module divergence. Finally, the simultaneous variation of irradiance, temperature and relative humidity limits the extent to which each environmental variable can be separated from the others.

Future work should, therefore, extend the field campaign to multiple seasons and, ideally, multiple years and incorporate independent I-V characterization and maximum power point tracking. Direct module temperature measurements, spectral irradiance monitoring, and wind-dependent thermal characterization would further improve the interpretation of outdoor operating conditions. Continuous electrical monitoring combined with periodic diagnostics at the spectroscopic, microscopic, and materials levels would provide a stronger basis for distinguishing reversible environmental effects from irreversible degradation. Such integrated datasets would ultimately enable more reliable lifetime modeling, degradation-rate estimation and field-informed reliability assessment of perovskite BIPV systems under realistic outdoor conditions.

REFERENCES

M. I. Asghar, J. Zhang, H. Wang, and P. D. Lund, "Device stability of perovskite solar cells: A review," *Renew. Sustain. Energy Rev.*, vol. 77, pp. 131-146, 2017, doi: 10.1016/j.rser.2017.04.003.

- M. Babics *et al.*, "One-year outdoor operation of monolithic perovskite/silicon tandem solar cells," *Cell Rep. Phys. Sci.*, vol. 4, no. 2, p. 101280, 2023, doi: 10.1016/j.xcrp.2023.101280.
- E. Belloni *et al.*, "An overview on building-integrated photovoltaics: Technological solutions, modeling, and control," *Energy Build.*, vol. 324, p. 114867, 2024, doi: 10.1016/j.enbuild.2024.114867.
- L. Chen *et al.*, "A comprehensive review of a building-integrated photovoltaic system (BIPV)," *Int. Commun. Heat Mass Transf.*, vol. 159, p. 108056, 2024, doi: 10.1016/j.icheatmasstransfer.2024.108056.
- N. Gupta, "Exploration of benefits and performances of integration of semitransparent photovoltaics with buildings and infrastructure: A comprehensive review," *Environ. Prog. Sustain. Energy*, 2024, doi: 10.1002/ep.14464.
- IEA PVPS Task 15, "Building-Integrated Photovoltaics: A Technical Guidebook," International Energy Agency Photovoltaic Power Systems Programme, Paris, France, 2025.
- M. Jošt and others, "Perovskite solar cells go outdoors: Field testing and temperature effects on energy yield," *Adv. Energy Mater.*, 2020.
- A. D. Khan *et al.*, "Innovative designs for semitransparent carbon-based perovskite solar cells for building-integrated applications," *Sol. Energy*, vol. 282, p. 112951, 2024, doi: 10.1016/j.solener.2024.112951.
- S. Khatoon *et al.*, "Perovskite solar cell's efficiency, stability and scalability: A review," *Mater. Sci. Energy Technol.*, vol. 6, pp. 437-459, 2023, doi: 10.1016/j.mset.2023.04.007.

- M. V. Khenkin *et al.*, "Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures," *Nat. Energy*, vol. 5, pp. 35–49, 2020, doi: 10.1038/s41560-019-0529-5.
- B. P. Kore, M. Jamshidi, and J. M. Gardner, "The impact of moisture on the stability and degradation of perovskites in solar cells," *Mater. Adv.*, 2024, doi: 10.1039/D3MA00828B.
- S. M. S. Mazumdar, Y. Zhao, and X. Zhang, "Stability of perovskite solar cells: Degradation mechanisms and remedies," *Front. Electron.*, vol. 2, p. 712785, 2021, doi: 10.3389/felec.2021.712785.
- G. M. Meheretu, A. K. Worku, M. T. Yihunie, R. K. Koech, and G. A. Wubetu, "The recent advancement of outdoor performance of perovskite photovoltaic cells technology," *Heliyon*, vol. 10, no. 17, p. e36710, 2024, doi: 10.1016/j.heliyon.2024.e36710.
- S. G. Motti, J. B. Patel, R. D. J. Oliver, H. J. Snaith, M. B. Johnston, and L. M. Herz, "Phase segregation in mixed-halide perovskites affects charge-carrier dynamics while preserving mobility," *Nat. Commun.*, vol. 12, p. 6955, 2021, doi: 10.1038/s41467-021-26930-4.
- V. Paraskeva *et al.*, "Long-term outdoor testing of perovskite mini-modules: Effects of FACl additives," *Energies*, vol. 16, no. 6, p. 2608, 2023, doi: 10.3390/en16062608.
- V. Paraskeva *et al.*, "Diurnal changes and machine learning analysis of perovskite modules based on two years of outdoor monitoring," *ACS Energy Lett.*, vol. 9, no. 10, pp. 5081–5091, 2024, doi: 10.1021/acsenerylett.4c01943.
- H. Raza *et al.*, "Potential-induced degradation: A challenge in the commercialization of perovskite solar cells," *Energy Environ. Sci.*, vol. 17, pp. 1819–1853, 2024, doi: 10.1039/D3EE03317A.
- D. B. Ritzer *et al.*, "Translucent perovskite photovoltaics for building integration," *Energy Environ. Sci.*, vol. 16, pp. 2212–2225, 2023, doi: 10.1039/D2EE04137E.
- M. F. Sadaqat *et al.*, "Performance evaluation of a real-time BIPV system based on perovskite solar modules," *Results Eng.*, vol. 29, p. 109889, 2026, doi: 10.1016/j.rineng.2026.109889.
- A. R. Smith, M. Ghamari, S. Velusamy, and S. Sundaram, "Thin-film technologies for sustainable building-integrated photovoltaics," *Energies*, vol. 17, no. 24, p. 6363, 2024, doi: 10.3390/en17246363.
- K. S. Srivishnu, P. R. Markapudi, S. Sundaram, and L. Giribabu, "Semitransparent perovskite solar cells for building integrated photovoltaics: Recent advances," *Energies*, vol. 16, no. 2, p. 889, 2023.
- V. Stoichkov, N. Bristow, J. Troughton, F. De Rossi, T. M. Watson, and J. Kettle, "Outdoor performance monitoring of perovskite solar cell mini-modules: Diurnal performance, observance of reversible degradation and variation with climatic performance," *Sol. Energy*, vol. 170, pp. 549–556, 2018, doi: 10.1016/j.solener.2018.05.086.
- UET Peshawar, "BIPV Thesis Version 7: Experimental Methodology and Field-Study Dataset." 2026.
- C. Wang *et al.*, "Performance investigation of solution-processed semi-transparent perovskite solar cells in building sectors," *Energy Build.*, vol. 322, p. 114729, 2024, doi: 10.1016/j.enbuild.2024.114729.
- D. Wang, M. Wright, N. K. Elumalai, and A. Uddin, "Stability of perovskite solar cells," *Sol. Energy Mater. Sol. Cells*, vol. 147, pp. 255–275, 2016, doi: 10.1016/j.solmat.2015.12.025.
- Y. Wang and others, "Encapsulation and stability testing of perovskite solar cells for real life applications," *ACS Mater. Au*, vol. 2, no. 3, pp. 215–236, 2022, doi: 10.1021/acsmaterialsau.1c00045.

C. Yang *et al.*, "Achievements, challenges, and future prospects for industrialization of perovskite solar cells," *Light Sci. Appl.*, vol. 13, p. 227, 2024, doi: 10.1038/s41377-024-01461-x.

D. Zhang, D. Li, Y. Hu, A. Mei, and H. Han, "Degradation pathways in perovskite solar cells and how to meet international standards," *Commun. Mater.*, vol. 3, p. 58, 2022, doi: 10.1038/s43246-022-00281-z.

Y. Zhao, W. Zhou, Z. Han, D. Yu, and Q. Zhao, "Effects of ion migration and improvement strategies for the operational stability of perovskite solar cells," *Phys. Chem. Chem. Phys.*, vol. 23, no. 1, pp. 94–106, 2021, doi: 10.1039/D0CP04418K.

