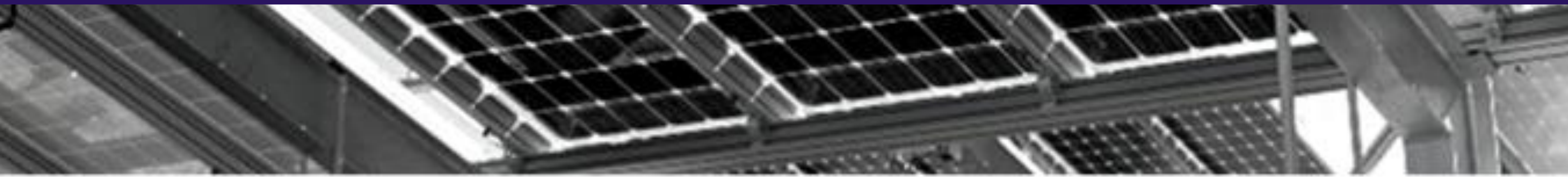
DELIVERABLE REPORT

NEXUS

Report on the outdoor performance of PVSK/Si minimodules in Ankara climate

Deliverable D4.6
October-2025

PREPARED BY
PARTNER NAME
COORDINATED BY
CEA



Grant Agreement n°101075330

NEXUS is a 3-year research and innovation project funded by the European Commission through the Horizon Europe Research and Innovation Action (RIA) grant N°101075330, responding to the call for a “*Sustainable, secure and competitive energy supply*” (HORIZON-CL5-2021-D3-02).

NEXUS aims to accelerate Europe’s energy transition by developing perovskite-silicon tandem photovoltaic technology, via a new European paradigm: an eco-design approach, based on efficiency, cost, sustainability, circularity and social aspects and using abundant materials. NEXUS aims to develop stable, 2-terminal perovskite-silicon tandem solar cells and modules with high power conversion efficiencies, using sustainable, coherent and competitive European PV production, to create a viable economic pathway for the European commercialisation of this technology.

NEXUS is formed of a multi-disciplinary consortium: 13 partners from 10 countries; 6 industrial partners & 7 RTOs, covering the whole value chain of innovation from research centres to technology providers, end-users and market and policies.

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Legal notice

NEXUS Consortium

Organization name	Short name	Country
COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	CEA	FR
ACCADEMIA EUROPEA DI BOLZANO	EURAC	IT
KARLSRUHER INSTITUT FUER TECHNOLOGIE	KIT	DE
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Abbreviations and acronyms list

Abbreviation	Meaning	Abbreviation	Meaning
PVSK	Perovskite	Si	Silicon
V_{oc}	Open-circuit voltage	I_{sc}	Short-circuit current
STC	Standard test conditions	PCE	Photovoltaic conversion efficiency

1. Executive Summary

1.1. Description of the deliverable content and purpose

This deliverable presents a comprehensive outdoor performance evaluation of perovskite/silicon (PVSK/Si) tandem minimodules tested in Ankara's semi-arid Mediterranean climate, as part of NEXUS project's WP4 activities. The study aims to correlate indoor and outdoor behaviors of two set of tandem modules; fabricated by different partners and laminated under controlled conditions, to evaluate stability, degradation patterns, and operational reliability under real environmental exposure. Measurements were carried out according to IEC 61724-1, with complementary thermographic inspections.

The deliverable provides a detailed description of the outdoor test infrastructure at GUNAM, including the 24-bed platform, electrical configuration, measurement intervals, and environmental monitoring. It details the setup and calibration procedures, the performance metrics of tested minimodules before and after lamination, and the long-term field results covering several months of exposure. Two distinct test series are analyzed: the first consisting of 5T-B, 5T-D, 4P-B, and 4P-D modules, and the second consisting of 4-cell and O1 modules. By integrating indoor reference data with outdoor performance evolution, the report aims to identify the tandem module performance under Ankara climate conditions along with the mechanisms driving possible efficiency (PCE) loss; such as temperature-induced degradation, encapsulation quality, and optical surface modifications, providing valuable input for the design of more durable tandem architectures.

This deliverable contributes directly to the NEXUS objective of establishing a validated outdoor testing methodology for PVSK/Si tandem devices and generating reliable degradation data that can inform life-cycle models, eco-design guidelines, and future upscaling of this technology. The deliverable will serve to predict and measure the performance of NEXUS tandem modules under real-world conditions in Ankara-Türkiye and assess their long term-stability.

1.2. Relation with other activities in the project

Deliverable D4.6 directly supports the objectives of WP4 (“Reliability, Energy Yield, and bankability”). In particular, O4.3: Develop a project-wide outdoor measurement infrastructure for performance and reliability characterization and O4.4: Characterize electrical performance and reliability under real-world outdoor operation conditions (performance stability). The data collected in Ankara’s high-irradiance and large temperature-variation environment complements outdoor evaluations conducted by other partners (CEA, KIT, EURAC, and UVEG), D4.6 reports real-world performance of tandem modules prepared in WP2; O2.4.

In summary, the activities reported in D4.6 form a critical experimental bridge between sustainable tandem integration of WP2 and the broader objectives of NEXUS to develop eco-designed and high-efficiency PVSK/Si tandem technologies measured under real-world conditions.

2. Outdoor Test at Ankara

2.1. Outdoor Test Infrastructure

2.1.1. Panel and minimodules Test beds

GUNAM Outdoor test facilities consist of 24 test beds capable of conducting long-term performance monitoring of photovoltaic (PV) panels. Each test bed is suitable for testing solar panels operating at different current and voltage levels. As shown in Figure 1, the test beds feature a flexible supporting infrastructure that allows panels of any size to be easily mounted and tested. Since the performance of PV panels is affected by outdoor conditions, environmental parameters are also measured throughout the test period. Table 1 shows the infrastructure details of the measurement system.

Figure 1. Outdoor testing platform

The PV Analyzer has independent electronic loads that draw the total generated power from the PV panels. To minimize losses during performance evaluation, the measurements are performed using the four-wire measurement method. Measurements are performed at 10-minute intervals, including I-V characteristics at MPP. .

Table 1. GUNAM outdoor testing infrastructure features

Features	Description
Number of test beds	24
Testbed's inclination angle	32˚
Testbed's azimuth angle	180˚
Measured parameters (PV modules)	V_{OC}, I_{SC}, V_{MPP}, I_{MPP}, I-V curve, T_{module}
Measured parameters (environment)	Irradiance (global horizontal, diffuse, direct beam, front and rear tilted surface), ambient temperature, relative humidity (RH), wind speed, UV index, and UV dose.
Climate information	According to the Köppen–Geiger climate classification, it is classified as Csb — a semi-arid Mediterranean climate.
Location	METU, Ankara / Türkiye (39.894248, 32.782075)

2.1.2. Thermographic imaging

Thermographic imaging is a method aimed at non-contact analysis of surface temperature distribution of PV panels under outdoor conditions. This technique enables monitoring of panel conditions by detecting temperature anomalies (hot spots) caused by factors such as cell damage, partial shading effects, bypass diode failures, or connection issues that negatively affect energy production. These inspections are conducted in accordance with the IEC-TS-62446-3 standard. The technical specifications of the FLIR T530 Series Thermal Camera used for thermographic imaging within GUNAM infrastructure are given in Table 2.

Figure 2. Thermal imaging device

Table 2. GUNAM thermal camera features

Parameter	Description
IR Resolution	320 x 240 pixel
Object Temperature Range	-20°C to +1500°C
Accuracy	± 2°C or %2 (when Ambient temperature is between 15-35°C)
Image Frequency	30 Hz

2.2. Assumptions, test protocol and calibration information

Data recording rate : 10 minutes

Connection to outdoor test stations : Measurements are performed using the four-wire method. For connection between the PV Analyzer and the panel under test, shielded and twisted-pair 20 AWG cables are used for voltage measurement, while 4 mm² solar cables are used for current measurement. MC4 connectors are attached to the ends of these two cables extending to the panel to establish the connection.

Cleaning during outdoor test : The glass surfaces of the panels are cleaned every week.

Thermal imaging rate : The panels are subjected to thermographic imaging once a month, starting from the beginning of the test process.

2.3. Outdoor measurement protocol

The PV panels to be tested are mounted onto the module test stations of the outdoor testing platform using suitable clamps. Electrical connections are made via the MC4 connectors available on the test stations, and the PV Analyzer is connected through T-type thermocouples. The temperature sensor is attached with transparent film to the center of the cell located in the middle of the panel. After this setup, configuration settings of the device connected to the load unit are completed. Measurements are taken every 10 minutes, with one I-V curve recorded per interval. Performance data are generated from the instantaneous measurements collected during each 10-minute period, while environmental conditions are simultaneously recorded at the same time intervals.

Table 3. Raw data outlier elimination criteria

Parameter	Unit	Quality control rule
Ambient temperature	°C	No
Ambient relative humidity	%	0 ≤ RH ≤ 100
Wind speed	m/s	No
Rain	mm	No
UV index	-	No
UV dose	-	No
Panel maximum power (P_{mpp})	W	No
Panel maximum voltage (V_{mpp})	V	No
Panel maximum current (I_{mpp})	A	No
Open-circuit voltage (V_{OC})	V	If $V_{oc}<V_{mpp}$, the relevant measurement data line is "nan"
Short circuit current (I_{SC})	A	If $I_{sc}<I_{mpp}$, the relevant measurement data line is "nan"
Fill Factor (FF)	%	Cannot be >100
Module temperature	°C	No
Irradiance on the panel front surface	W/m²	Outliers below 30 W/m² and those outside the ±3 range were filtered out by applying a Z-Score filter based on the 10-day moving average.
Irradiance on the panel rear surface	W/m²	Outliers outside the ±3 range were removed by applying a Z-Score filter based on the 10-day moving average.

The collected data are regularly downloaded during the first week of each month and transferred to Excel for analysis and reporting. Outliers in the downloaded raw data are filtered and recorded according to Table 3. The performance measurements and analyses of the PV panels are carried out in accordance with the IEC 61724-1 standard. Outdoor PCE values presented in this report were calculated using the equations defined by the standard.

Thermographic imaging is conducted monthly on days with at least 600 W/m² irradiance. If the irradiance is lower, the measurements are postponed to the following day. The captured images are analyzed for thermal anomalies based on the criteria presented in Table 4.

Table 4. Types of thermal anomalies

Category	Typical Appearance	Possible reasons
Hot spot	Single cell or partial area overheated	Microcracks, solder breakage, bypass diode failure
Edge heating	Heating along edge	Moisture ingress, delamination, strip breakage
String pattern	Regular temperature difference within specific array	String failure, incorrect polarity, contact loss
Uniform heating	Entire module hot but uniform	High current, inadequate ventilation
Cold area	Cold cell or group	Reverse connection, current flow obstruction

2.4. Tested module information

2.4.1. First set of Tandem minimodules tested in ANKARA

The data presented in Table 5 are for the modules provided by UOXF. The lamination was performed at CEA. The data shown were measured at CEA after lamination. A suitable supporting structure was fabricated using a 3D printer to ensure stable and proper mounting during outdoor testing.

Table 5. Measurement results and detailed information of the minimodules

Tandem cell batch	Cell ID | Top cell	Si front side morphology	Lamination date	I_{sc} (A)	V_{oc} (V)	FF (%)	V_{mpp} (V)	I_{mpp} (A)	PCE (%)	Area (cm²)
UOXF-oct2024	5T-B	Co-evaporated textured	12/5/2024	0.0049	1.388	56.8	1.01	0.0038	15.4	0.25
UOXF-oct2024	5T-D	Co-evaporated textured	12/5/2024	0.0211	1.214	49.6	0.84	0.0152	12.7	1
UOXF-oct2024	4P-B	Co-evaporated polished	11/13/2024	0.0044	1.629	60.7	1.233	0.0035	17.3	0.25
UOXF-oct2024	4P-D	Co-evaporated polished	11/13/2024	0.0173	1.542	54.2	1.153	0.0126	14.5	1

The samples presented in Table 5 arrived at GUNAM in the last week of December 2024. A customized junction box was designed and manufactured by the GUNAM team to allow testing of the minimodules in outdoor conditions. The modules were kept in a dark environment until they were mounted into the custom-designed junction box. Details of this design are shown in Figure 3.

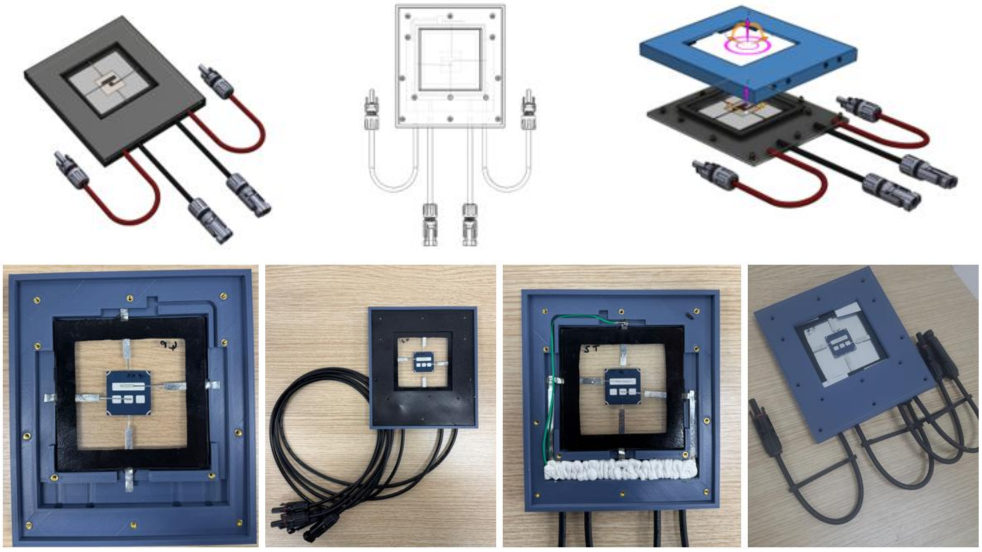

Figure 3. Custom-designed junction box and the minimodule holder

After completing all necessary preparations, the minimodules were mounted on the outdoor test stations on test beds, and the tests were initiated (Figure 4).

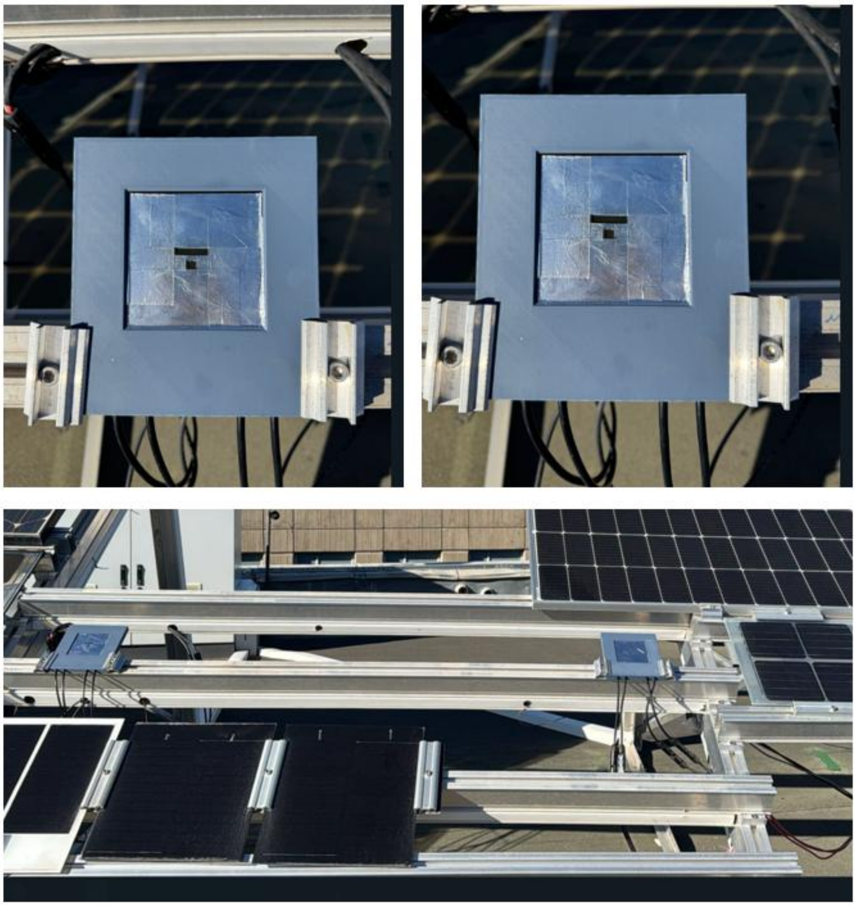

Figure 4. 5T and 4P modules at the outdoor testing station (Ankara, Türkiye)

2.4.2. Second set of Tandem minimodules tested in ANKARA

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Two modules: O1 tandem cell prepared by KIT and 4-cell tandem module prepared by UXOF. The lamination of both modules was performed at CEA. The corresponding performances are given in Table 6. The indoor results serve as a reference for evaluating the initial performance before outdoor exposure, ensuring that any observed changes in the subsequent outdoor tests can be accurately attributed to environmental effects rather than fabrication variations.

Table 6. Measurement results and detailed information of the modules at STC

Name	PCE (%)	V_{oc} (V)	J_{sc} (mA/cm2)	V_{mpp} (V)	I_{mpp} (mA)	FF (%)	Area (cm^2)
4-Cell (laminated)	18.94	6.98	18.35	5.31	65.96	59.13	4.62 x 4
O1 (Initial)	18.3	1.6628	18.2927	--	--	60.15	1
O1 (laminated)	16.61	1.77	14.22	1.412	11.18	66.09	

Figure 5. O1 and 4-cell minimodules at the outdoor test station (Ankara, Türkiye)

2.5. Results

2.5.1. Results of first set of Tandem minimodules

The minimodules presented in Table 5 were tested for a total duration of 206 days. The 5T-D module initially exhibited an outdoor PCE of 7.5% and maintained stable performance for approximately 150 days. However, it subsequently experienced a rapid degradation, with the average outdoor PCE dropping to around 2.5%.

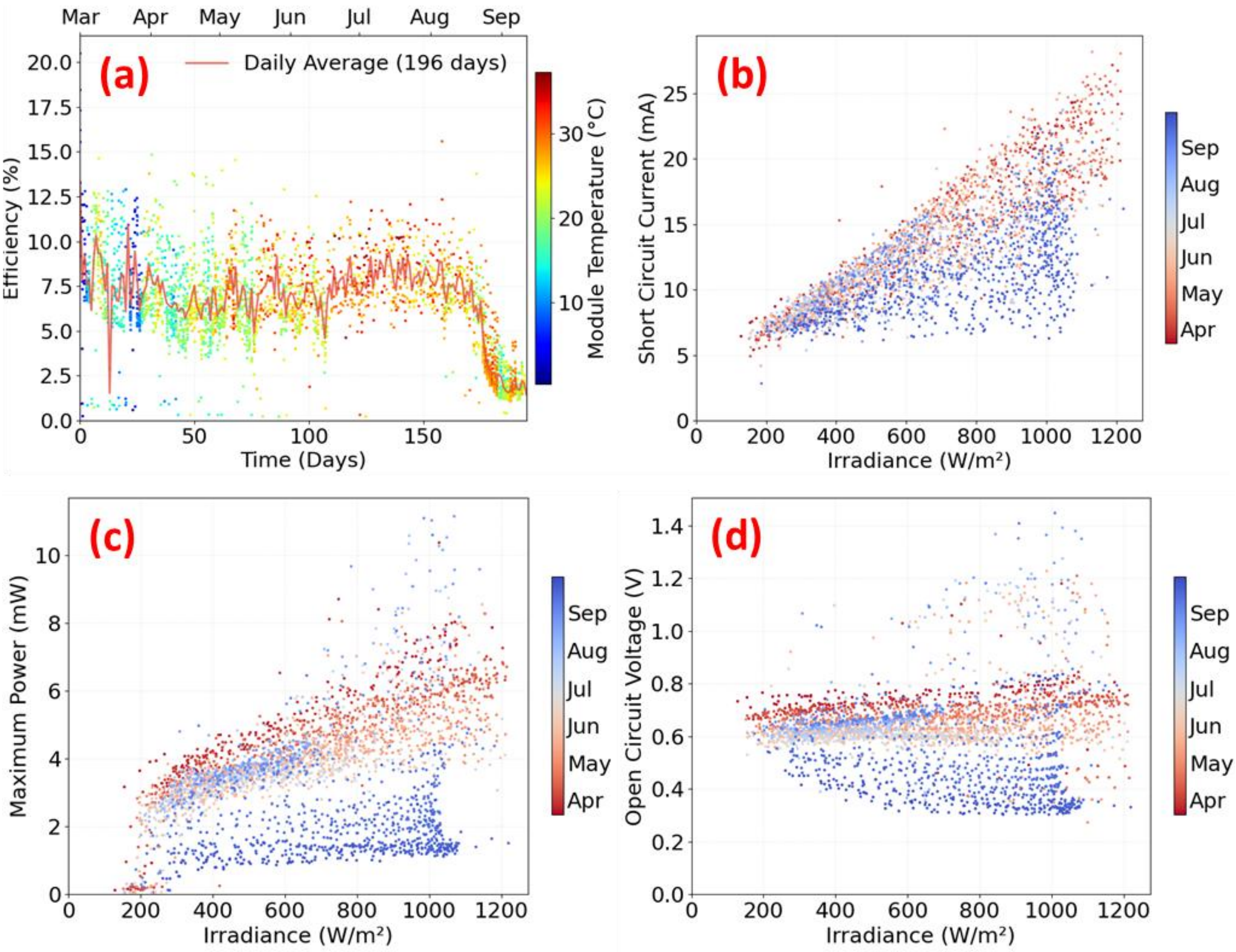

Figure 6. Outdoor test results of the 5T-D minimodule

A significant decrease in V_{oc} was particularly observed during the last two months (August and September). Figure 6 illustrates the variations in maximum power, short-circuit current (I_{sc}), V_{oc}, and irradiance. As shown in Figure 6b and Figure 6d, the drop in V_{oc} and I_{sc} indicates that the minimodule was no longer able to perform effective energy conversion under high irradiance conditions.

5T-B minimodule was tested for less than 100 days. The initial outdoor PCE is ~3.5% compared to 15.4% after lamination. The module experienced severe degradation down to 0% at day 70 (Figure 7).

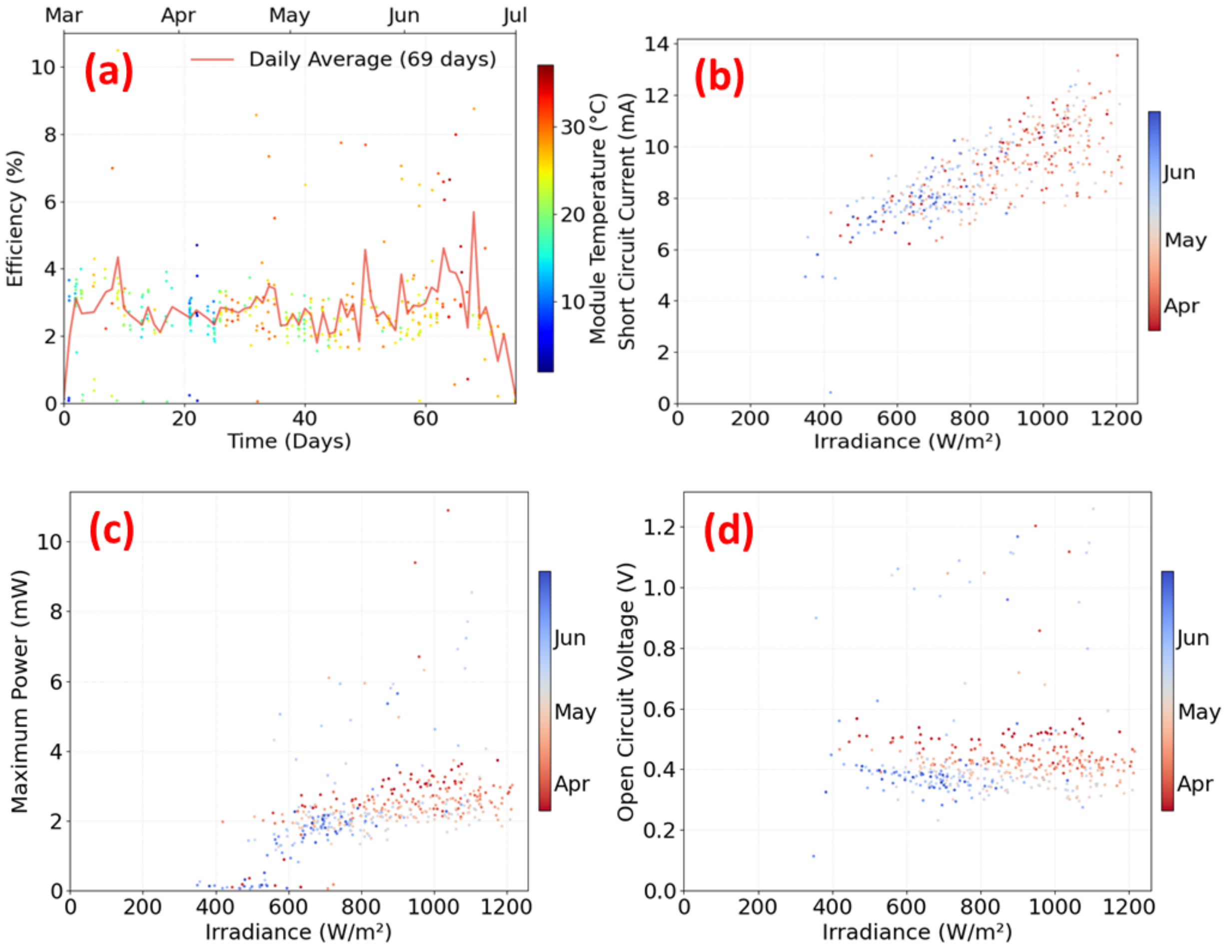

FIGURE 7. Outdoor test results of the 5T-B minimodule

Similarly, 4P-D and 4P-B showed much lower day 1 PCE of ~2.5% and ~7.5%, respectively, compared to the values measured after lamination (Table 5). Figure 8 and Figure 9 show the PV parameters of 4P-D and 4P-B, respectively. Within approximately 90 days, the PCE of 4P-D dropped below 1%. 4P-B module also experienced rapid performance degradation within ~100 days down to 0%.

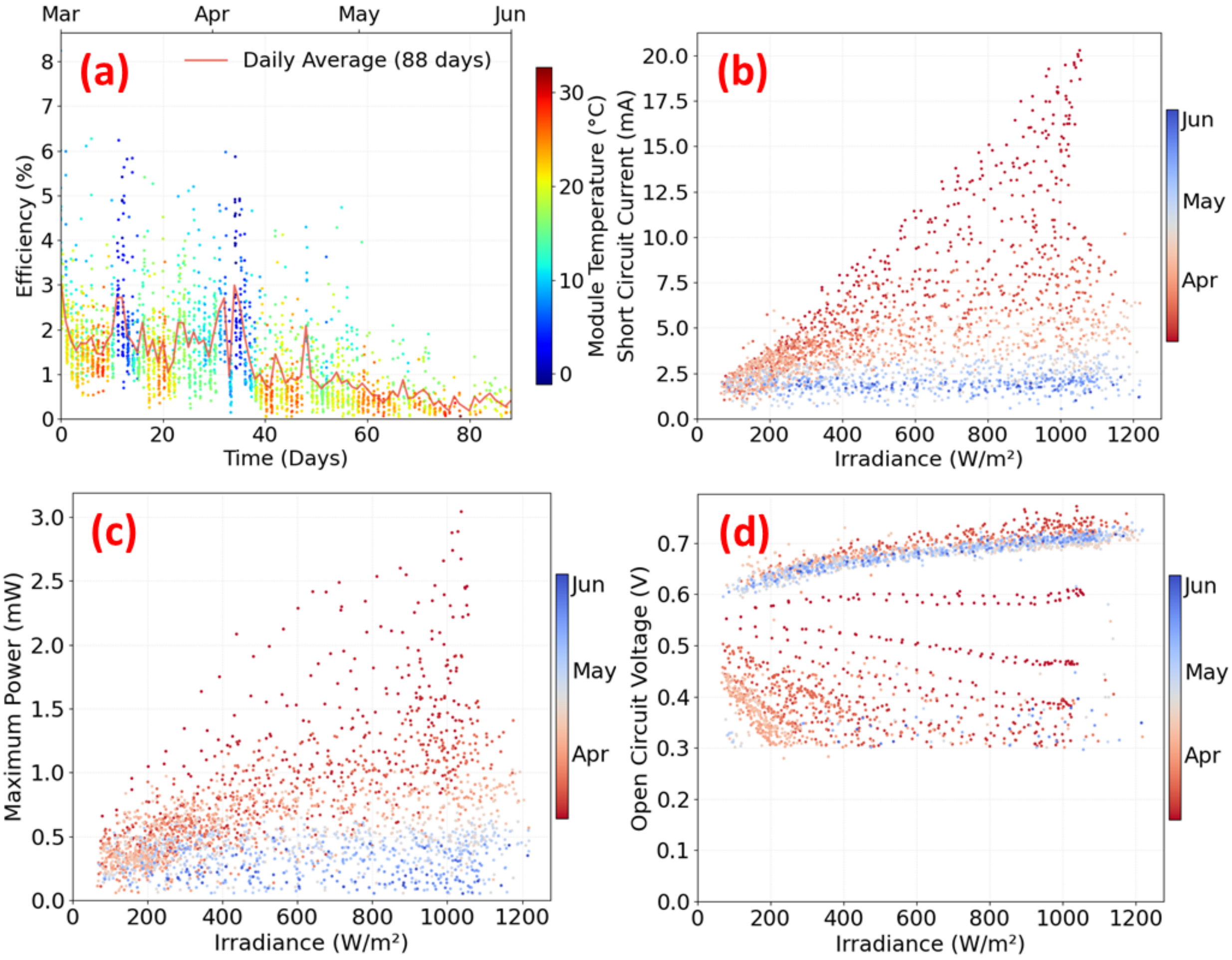

Figure 8 Outdoor test results of the 4P-D minimodule

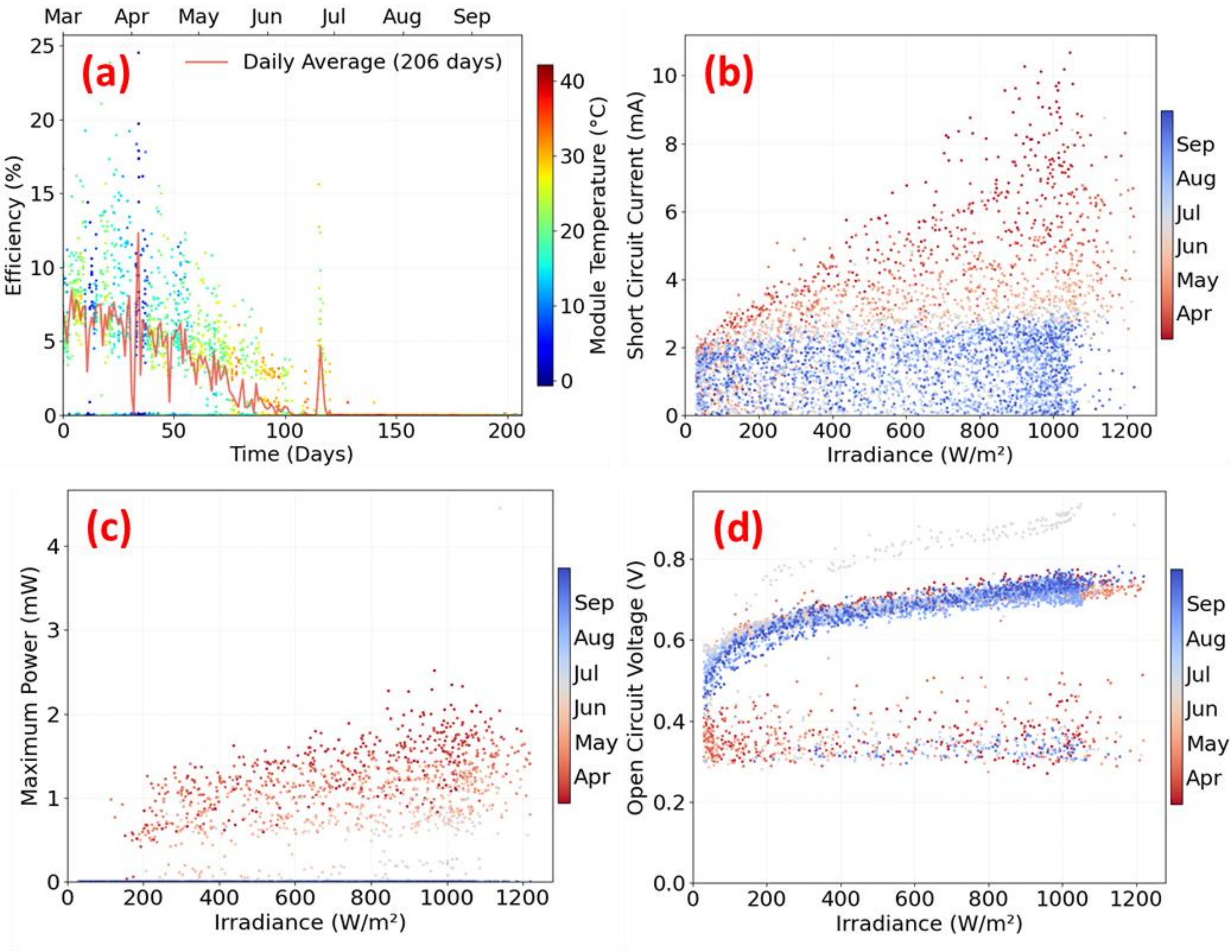

Figure 9. Outdoor test results of the 4P-B minimodule

A distinct behavior between those prepared on polished (4P-B and 4P-D) and textured (5T-B and 5T-D) silicon surface. 4P-B and 4P-D initially demonstrated higher V_{oc} and PCE, whereas 5T-B and 5T-D exhibited higher I_{sc} due to enhanced light absorption. However, during prolonged exposure, all modules experienced substantial PCE loss, primarily driven by reductions in V_{oc} for 5T-B and 5T-D and in I_{sc} for the 4P-B and 4P-D.

Table 7 summarizes the PCE values of the first set of minimodules after lamination, on the first day of outdoor monitoring, and on the final day of monitoring. A noticeable degradation in module performance was observed as early as the first day of outdoor exposure, which was later attributed to an unoptimized edge sealant used for the encapsulation. Due to the defective edge sealant, the devices were poorly protected against moisture ingress, resulting in rapid deterioration during field operation. Consequently, a definitive conclusion regarding the outdoor performance of the tandem solar cells could not be drawn based on this set of devices.

Table 7 . Measurement STC after lamination and during outdoor monitoring

Tandem cell batch	Cell ID | Top cell	Si front side morphology	Lamination date	PCE (after lamination) (%)	PCE (at day 1 of monitoring) (%)	PCE (at end of monitoring) (%)
UOXF-oct2024	5T-B	Co-evaporated textured	12/5/2024	15.4	~3.5	0 @day 70
UOXF-oct2024	5T-D	Co-evaporated textured	12/5/2024	12.7	~7.5	~2.5 @day 150
UOXF-oct2024	4P-B	Co-evaporated polished	11/13/2024	17.3	~7.5	0 @day 90
UOXF-oct2024	4P-D	Co-evaporated polished	11/13/2024	14.5	~2.5	<1 @day 90

Additionally, as shown in Figure 10, the 4P sample exhibited a distinct colour change between the images taken at the start of the test and those captured approximately 100 days later.

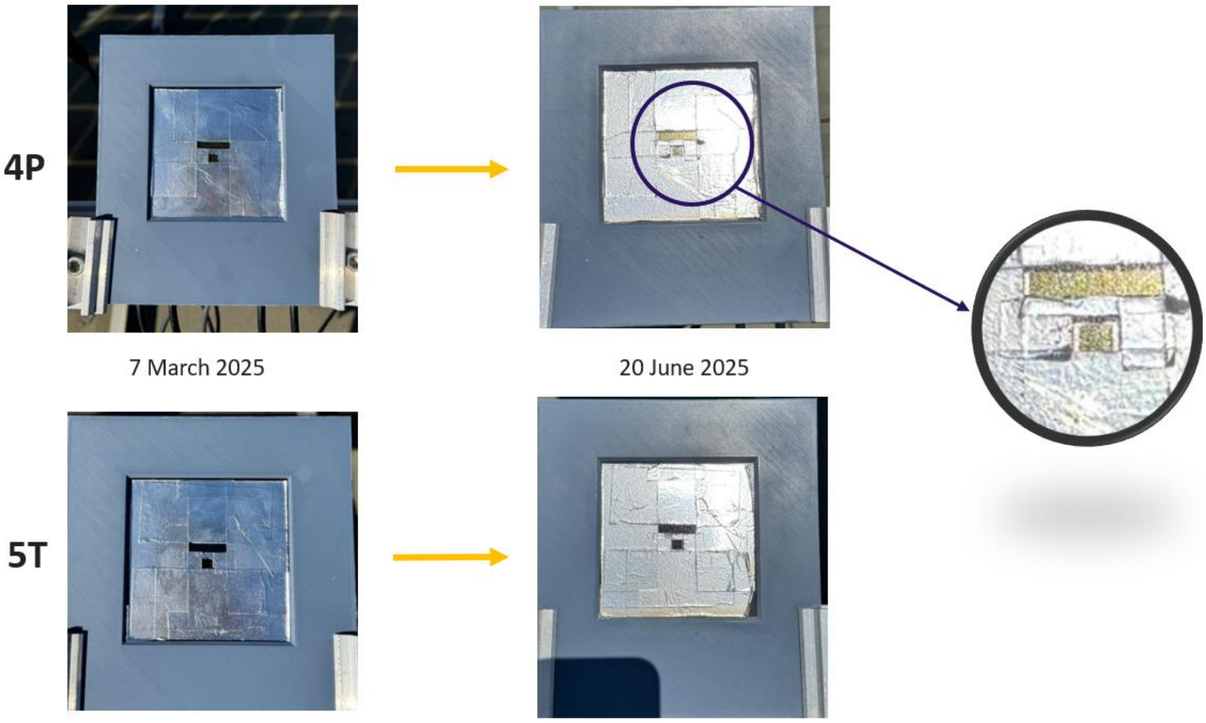

Figure 10. Images of the first batch of minimodules after 100 days of outdoor testing

2.5.2. Results of second set of minimodules

Two minimodules: one featuring a four-cell design and one single-cell laminate, as described in Table 6, were delivered to GUNAM on July 24, 2025. Appropriate connection interfaces were prepared to allow direct coupling of the minimodules with the outdoor test beds. The modules were installed on the outdoor test stations on August 1, 2025, and outdoor monitoring started (Figure 5). The active area was considered as 18.48 cm²; 4.62 cm² for each tandem cells. The outdoor performance data are given in Figure 11 (performed according to IEC 61724-1). It is to note that, *due to a technical reason, IV measurements could not be collected between 22.10.2025 and 28.10.2025.*

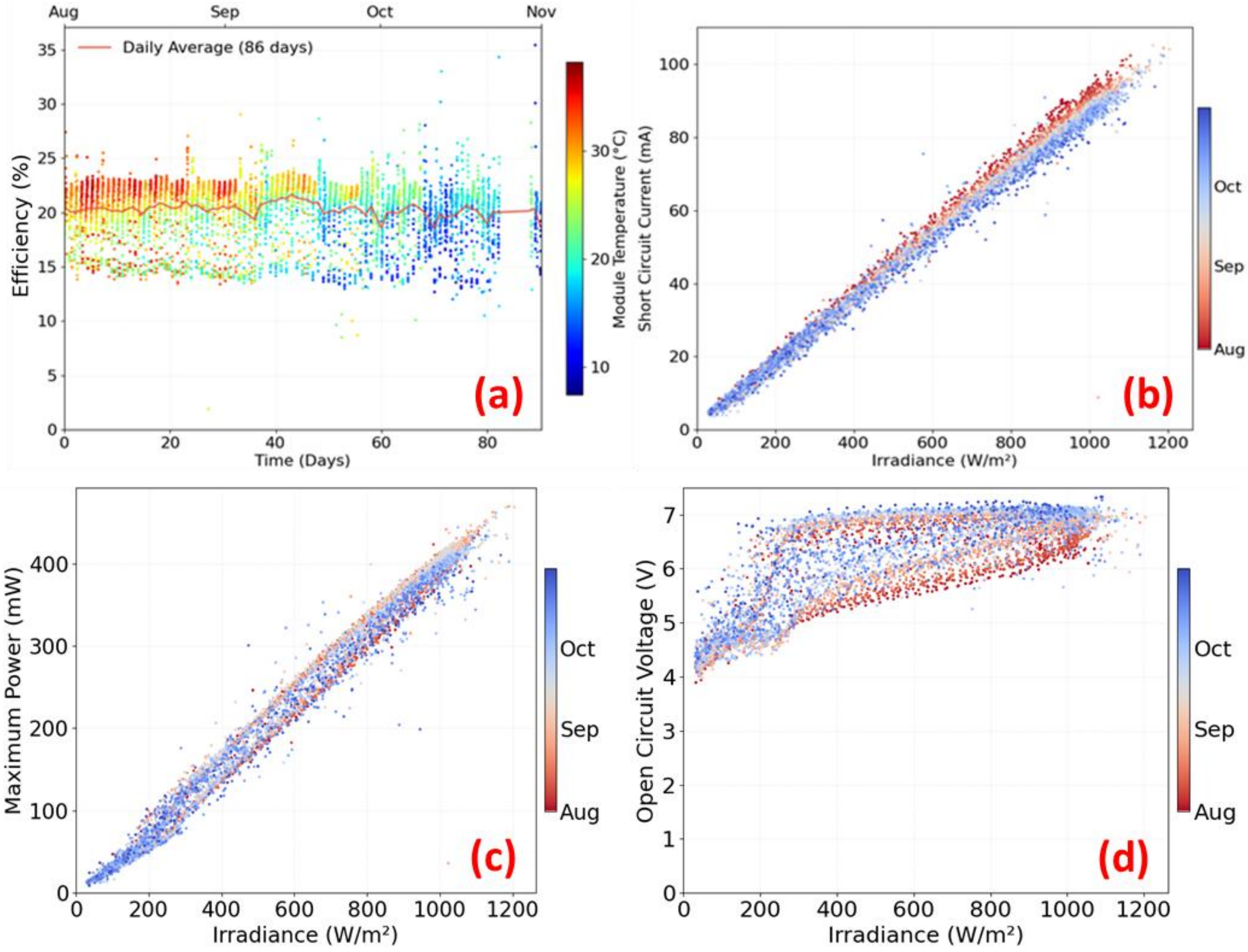

Figure 11. Outdoor test results of the 4-cell minimodule

As shown in Figure 11, the 4-cell minimodule demonstrated **remarkable stability**, maintaining an average daily outdoor PCE ~20% throughout the three-month testing period. This level of stability is particularly noteworthy given that the minimodule features 4 interconnected tandem cells, *indicating the promising reliability of the cells and the interconnection itself*. I_{sc} exhibited higher values in August, when environmental conditions were warmer compared to other months. Under an irradiance of 1000 W/m², P_{MPP} was measured to be ~420-450 mW.

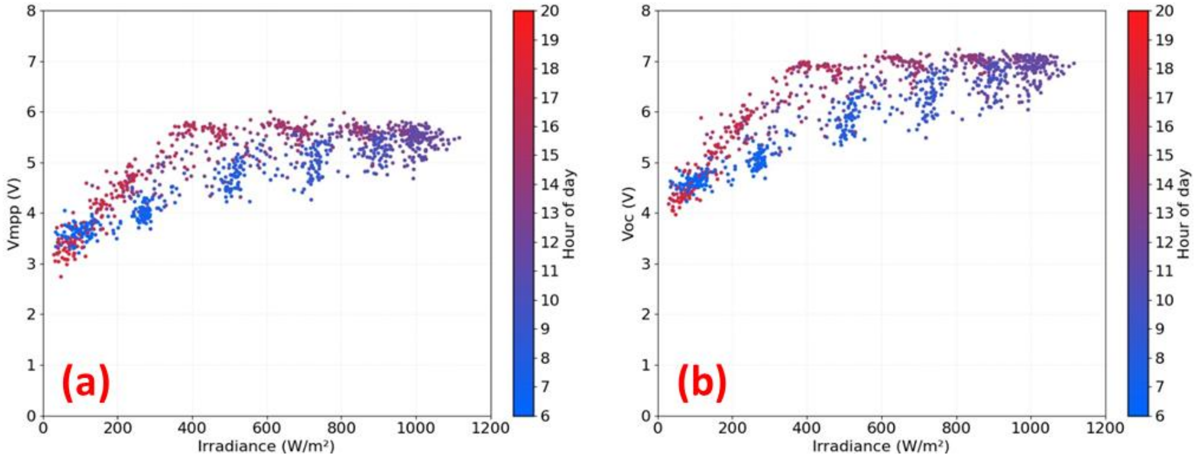

Figure 12. Change in (a) V_{Mpp} and (b) V_{oc} with irradiation at each hour of everyday for the 4-cell minimodule

V_{MPP} and V_{oc} at different hours of the day (indicated by colors) as a function of incident irradiance are given. The data presented in Figure 12 were obtained from the outdoor testing of the 4-cell mini-module, calculated on an hourly basis for each day in the ~90 days of monitoring. The voltage is low in the morning and increases in the afternoon (at ~400 and higher irradiance levels). This effect can be attributed to "light soaking" [1]. This effect is predominantly attributed to ionic motion and can cause perovskite cells to convert lower energy in the morning time, whereas as light soaking accumulates toward the afternoon, they operate at with higher V_{oc} and efficiency. In the afternoon, in the 400–1000 W/m² irradiance range, the change in the measured voltage values is minimal.

When the test data set was examined, the difference between the temperature of the 4-cell minimodule and the ambient temperature was observed to be approximately 0-3°C in the morning and evening hours ($G < 300$ W/m²), while around noon time ($G \approx 800$-1000 W/m²) → $\Delta T \approx 6$-8 °C. The thermographic images of the two minimodules are shown in Figure 13.

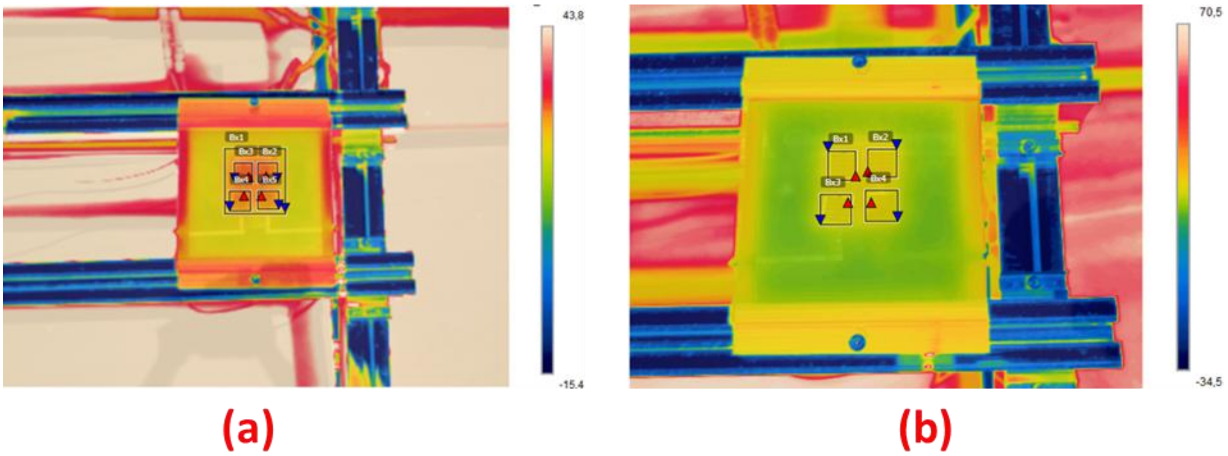

Figure 13. Thermographic images of 4-cell, left on 26.08.2025 @12:30, right on 23.09.2025 @12:40

The outdoor PCE of the single-cell minimodule (O1) is shown in Figure 14a. A decline in PCE is clearly observed over time. The PCE, which was ~15-17% at the beginning of August, decreased to the 10-12% by the end of October. The initial drop in PCE under high temperature and high irradiation conditions can be attributed to thermal effects. However, the continued downward trend observed until the end of October suggests possible degradation in the top cell of the tandem module. I_{sc} shows a quasi-linear correlation with irradiation (Figure 14b). The V_{oc}, shown in Figure 14d, fluctuated during the first period of testing but became focused from the second month onwards, and concentrated in the 1.4-1.6 V range.

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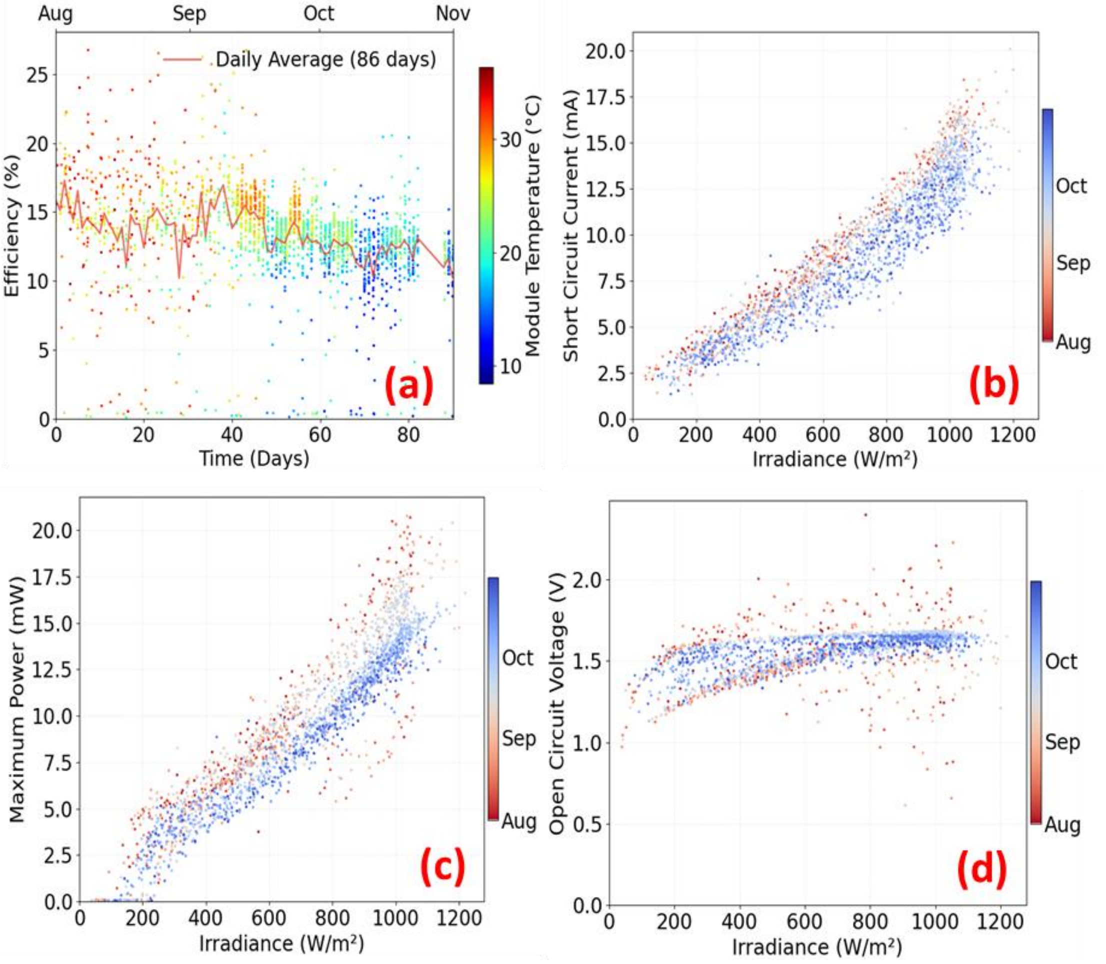

Figure 14. Outdoor test results of the O1 minimodule

The O1 minimodule, like the 4-cell minimodule, measured a temperature difference between the module temperature and the ambient temperature of 1-3 °C in the morning and evening, and 8-11 °C at midday. Following three months of monitoring, visual inspection of the 4-cell and O1 modules (Figure 15) showed no observable degradation in either sample.

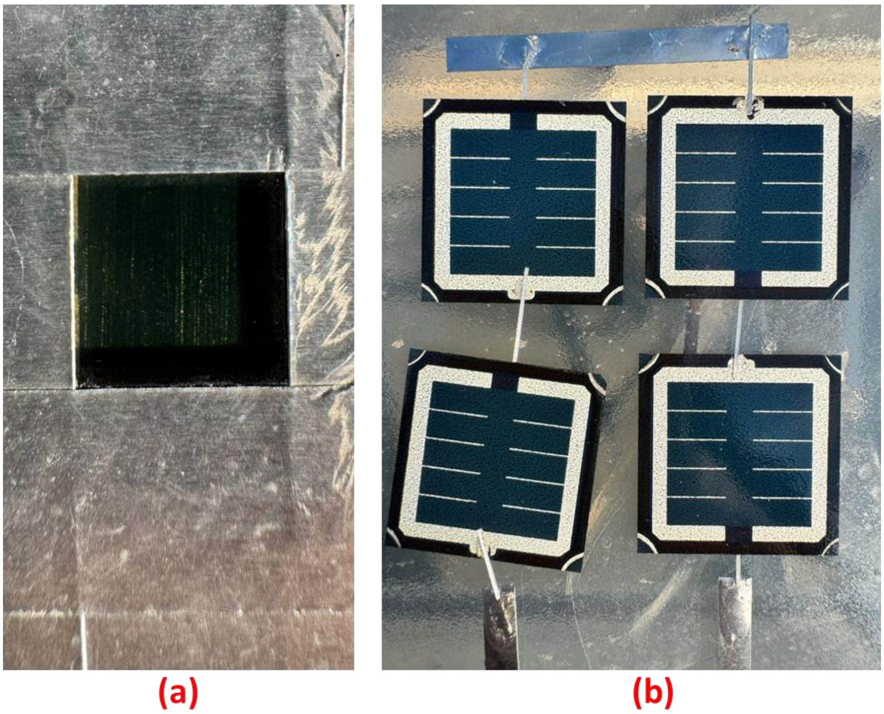

Figure 15. Images of (a) O1 and (b) 4-cell minimodules after 90 days of outdoor testing

3. Conclusions

For the first set of minimodules, decline in module performance became evident within the first day of outdoor testing compared to the values after laminations, most likely resulting from inadequately optimized edge-sealants. As a result, it was not possible to make a conclusive assessment of these tandem solar cells' behaviour under outdoor conditions. Color changes observed on the polished samples further confirms the severe degradation in the modules.

In contrast, the second set of modules (4-cell and O1) exhibited markedly more stable behaviour and a significantly slower degradation rate, retaining the majority of their initial PCE after approximately 90 days of outdoor exposure under Ankara's hot summer and early-to-mid autumn conditions (August-October). The 4-cell minimodule consistently achieved outdoor efficiencies of around 20%, whereas the O1 sample preserved approximately 80% of its initial performance. The measured temperature difference between the module surface and the ambient air was ΔT ≈ 6-8 °C at noon, and thermographic analysis confirmed uniform heating without any critical thermal anomalies. These findings demonstrate that the second set of modules; particularly the 4-cell, exhibited excellent stability and operational performance under Ankara's climatic conditions during the first 90 days of testing. At the time of writing this report, the modules are still in operation. Extended monitoring is being conducted to evaluate their long-term performance and identify any emerging degradation mechanisms.

Overall, the results indicate that module architecture, surface processing, and lamination quality critically influence the outdoor durability of tandem devices. The performance trends observed under Ankara’s high-irradiance and large temperature-swing conditions highlight the importance of thermal management, encapsulation optimization, and stability improvement of the PVSK top cell. The findings serve as a valuable dataset for validating degradation models and for guiding future activities on scalable, long-life PVSK/Si tandem module design.

References

[1] M. Remec *et al.*, “From Sunrise to Sunset: Unraveling Metastability in Perovskite Solar Cells by Coupled Outdoor Testing and Energy Yield Modelling,” *Adv Energy Mater*, vol. 14, no. 29, Aug. 2024, doi: 10.1002/aenm.202304452.

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