VIPERLAB

FULLY CONNECTED **VI**RTUAL AND **P**HYSICAL P**ER**OVSKITE PHOTOVOLTAICS **LAB**

D4.6 Final draft of harmonized test protocols and procedures for actual and most promising novel perovskite-based PV devices

DELIVERABLE REPORT

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FULLY CONNECTED VIRTUAL AND

PHYSICAL PEROVSKITE PHOTOVOLTAICS LAB

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DELIVERABLE

D4.6 FINAL DRAFT OF HARMONIZED TEST PROTOCOLS FOR ACTUAL AND MOST PROMISING NOVEL PEROVSKITE-BASED PV DEVICES

Project References

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1.3	Review	29/11/2024	AIT, HZB	S. Abermann. N. Maticiuc

DISCLAIMER

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ABBREVIATIONS

DTS: Draft Technical Specification

DUT: Device Under Test

EQE: External Quantum Efficiency

ESTI: European Solar Test Installation

IEC: International Electrotechnical Commission

Impp: Maximum Intensity Power Point

Isc: Short Circuit Current

ISOS: International Summit on Organic Photovoltaic Stability

MPPT: Maximum Power Point Tracking

NREL: National Renewable Energy Laboratory

PACT: Perovskite PV Accelerator for Commercializing Technologies

PCE: Power Conversion Efficiency

PSC: Perovskite Solar Cell

RR: Round Robin

TR: Test Report

TS: Technical Specification

Vmpp: Maximum Voltage Power Point

Voc: Open Circuit Voltage

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EXECUTIVE SUMMARY

VIPERLAB is an infrastructure project that aims to create a European environment where various infrastructures from 13 VIPERLAB partners can be accessed by different users from Europe and abroad. Moreover, VIPERLAB aims at boosting the development of this innovative environment of research infrastructures by a strongly interconnected set of supporting networking and joint research activities. VIPERLAB objective for this deliverable D4.6, which is part of WP4 "NA1-Harmonization and path towards standardization", is to define harmonized test protocols for perovskite PV technology development across the whole value chain from the materials to devices and applications.

In this report, several existing protocols for performance and aging, published by different entities (IEC, NREL, ESTI …) are reviewed, and are combined with the conclusions of the three VIPERLAB round robins (RR), executed within WP9 "JRA3-Characterization and standardization", on electrical performance measurements of the perovskite solar cells for the definition of harmonized test protocols.

Several topics are important in the phase of sample preparation:

- Exchange of properly packaged perovskite devices in order to minimize degradation effects due to ambient conditions present during storage and, transport. .
- Integrate a rear-side support designed to position the device precisely perpendicular to the primary light beam direction. This support should also feature thermal conductivity. so that temperature control systems can be effectively applied. The design of the rear side support should even include provisions to allocate a temperature sensor.
- The samples should include wirings to minimize differences due to contacting issues.
- A minimum sample size should be defined to avoid effects derived from different mask positioning.

Regarding the measuring system, all the laboratories should fulfil following minimum technical requirements:

- The spectral distribution of the light source should be as close as possible to AM1.5G spectrum. For single junction cells this effect can be minimized by using a spectral mismatch correction.
- Use of a reference cell spectrally matched with the device to be measured.
- For tandem cells a multi-lamp sun simulator is needed.
- For tandem cells, measurement of EQE is highly recommended for the adjustment of the spectral distribution.

Regarding the measurement protocols, it is considered a better option to report key values such as I_{sc}, V_{oc}, and PCE instead of providing the full I-V curve. Most of the reported protocols follow the same sequence of (a) performing a forward and reverse voltage sweep, respectively, (b) keeping the device under illumination at a voltage close to the V_{MPP} for several minutes, and (c) repeating the forward and reverse voltage sweeps.

A general conclusion from the **VIPERLAB Round Robins** is that these iterative inter-laboratory testing efforts successfully standardized measurement procedures across different laboratories.

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Using different organizational models (star-shaped, binomials or central-hub), the framework ensured consistent protocols distribution, identified discrepancies systematically, and refined methodologies to enhance reproducibility.

The review of **published protocols and standards** has provided key guidelines. IEC TR 63228:2019, PACT, ISOS, and emerging standards (e.g., IEC DTS 60904-1-4) emphasize preconditioning, metastability management, and stress-specific evaluations. These protocols address challenges like hysteresis, spectral sensitivities, and unique degradation mechanisms, facilitating harmonized performance assessments and long-term reliability tests for both single junction and tandem perovskite solar cells in lab and outdoor conditions.

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1. INTRODUCTION

The main objective of this deliverable is to compile different protocols currently used for testing and characterizing solar perovskite devices. Primary inputs for this deliverable come from *WP9-JRA3 "Characterization and standardization*", where different Round Robins (RR) on electrical performance have been carried out. Nevertheless, information derived from other work packages as well as published documentation on the subject have been considered.

VIPERLAB partners produce perovskite cells of different architectures and topologies and apply specific measurement procedures to check their performance. However, in order to achieve a sound development of the technology a common approach is required. In this document, first, a general overview on currently applied protocols is studied, and then, the analysis is focused on the results obtained in the WP9 Performance Round Robins. The following aspects on perovskite measurement and characterization methodologies have been evaluated:

- Samples description and preparation: packaging, shipment conditions, dimensions and contacting schemes.
- Requirements of equipment used: solar simulators, reference cell and temperature control.
- Ambient conditions: Inert or room atmosphere.
- I-V procedure: hysteresis, time at MPP, scan rates.
- Preconditioning: illuminance and thermal history of the device prior to the measurement.

2. INVENTORY OF AVAILABLE PROTOCOLS FOR PEROVSKITE ASSESSMENT

As the research community is developing new photovoltaic devices, existing general procedures for measuring mature photovoltaic technologies have been adapted to take into account their special behaviour.

Depending on its purpose, two different groups of protocols are established:

1. Performance characterization to determine the electrical behaviour of the device at specific test conditions
2. Long term stability to assess the device reliability under several environmental stress factors

Furthermore, when characterizing the electrical performance of PV devices two different strategies are commonly applied:

- Full I-V curve scanning
- Efficiency measurement, just around P_{max}

Among publicly available protocols addressing specific issues involved in perovskite characterization, either single junction or tandem, are:

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Reference	Performance	Stability
IEC TR 63228:2019: Measurement protocols for photovoltaic devices based on organic, dye-sensitized or perovskite materials	X	
Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures	X	X
IEC 60904-1:2020: Photovoltaic devices - Part 1: Measurement of photovoltaic current-voltage characteristics	X	
IEC 60904-1-1:2017: Photovoltaic devices - Part 1-1: Measurement of current-voltage characteristics of multi-junction PV devices	X	
IEC 60904-8:2014: Photovoltaic devices - Part 8: Measurement of spectral responsivity of a photovoltaic (PV) device	X	
IEC 60904-8-1:2017: Photovoltaic devices - Part 8-1: Measurement of spectral responsivity of multi-junction photovoltaic (PV) devices	X	
IEC TS 62876-2-1:2018: Nanotechnology - Reliability assessment - Part 2-1: Nano-enabled photovoltaic devices - Stability test		X
IEC TS 62607-7-2:2023 ED1: Nanomanufacturing - Key Control Characteristics - Part 7-2: Nano-enabled photovoltaics - Device evaluation method for indoor light	X	
IEC DTS 60904-1-4 Guidelines for I-V measurements of metastable PV devices	X	
NREL's steady-state efficiency measurement protocols	X	
IEC 61215-1:2021: Terrestrial PV modules - Design qualification and type approval - Part 1: Test requirements		X
IEC 61215-2:2021: Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 2: Test procedures		X
Consolidated protocols from CHEOPS project	X	X
PACT Module Protocols	X	X

A summary of each document is given below, taking into account only the testing requirements affecting perovskite technology.

2.1 IEC TR 63228:2019

This test report comprises measurement and characterization methods specific to emerging PV technologies employed at research institutes by the time of issuance (2019). The goal of this

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document is to pave the way to future standardization initiatives that will be carried out for these new PV technologies.

The review comprehends dye-sensitized, organic and perovskite solar cells. Different technical aspects covered by the report include preconditioning, I-V curve procedures, reference cell, spectral responsivity, samples preparation, temperature control and a final clause for tandem cells.

Regarding perovskite solar cells, these are the main recommendations derived from the document:

Preconditioning. Since perovskite absorbers/devices are sensitive to the exposure history of the device, it becomes necessary to apply a procedure to bring the cells to a representative and comparable state prior to measurements. In order to prevent degradation issues, it is not advisable to perform the preconditioning under light soaking. When the efficiency is measured via stabilized current measurements, holding the device at different voltage steps around maximum power point voltage, pre-conditioning may not be necessary as it inherently accounts for device stabilization during the measurement.

I-V curve measurement. The approach described in Figure 1 has been applied effectively for OPV and DSC devices and will likely be applicable to perovskite solar cells.

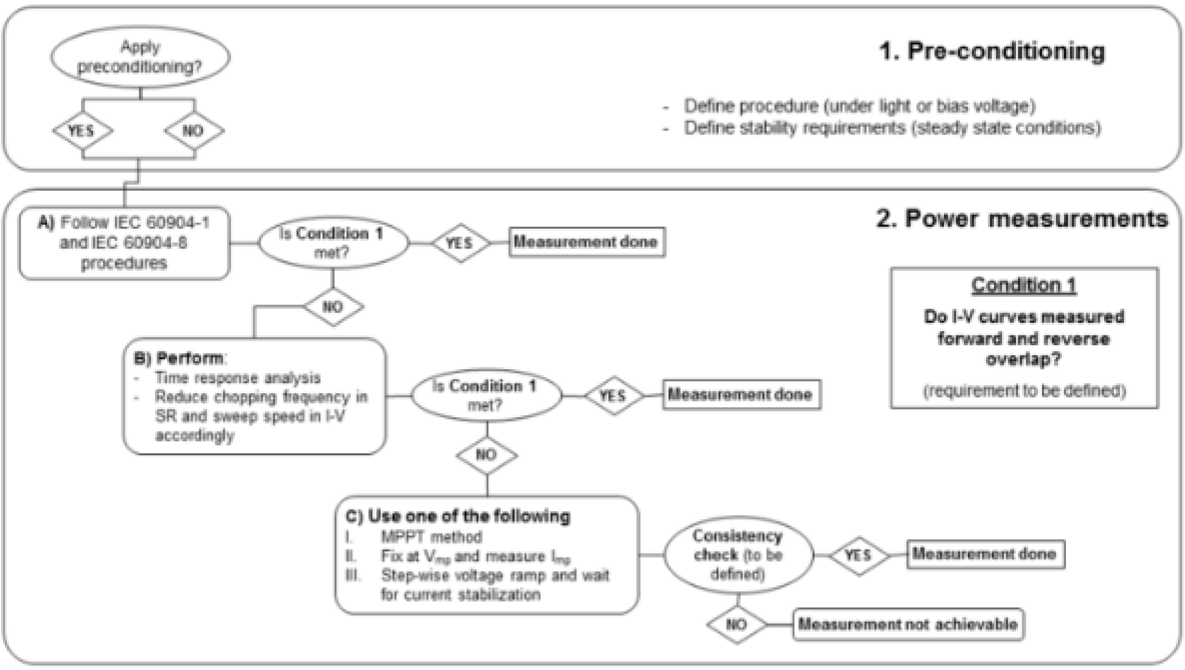

Figure 1. Flowchart for power measurement of emerging PV devices in IEC TR 63228:2019

As a summary, following aspects should be considered when measuring I-V curve of PV devices that exhibit transient effects:

1. The PV community should seek to reach consensus as to the meanings of the terms “steady-state”, “pre-conditioning” and “stabilization”,

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2. The use of a variable dwell time at each voltage step to specifically allow the current measurement to settle (dynamic I-V) should be the recommended practice.
3. It should be acknowledged that a lack of hysteresis at a single sweep rate does not guarantee the measurement is consistent with the device performance under steady state conditions.
4. Recommended practice should also include use of a reduced voltage sweep range, typically around the maximum power voltage, as a cross check against the full I-V curves - this includes measurements at a single voltage point and potentially maximum-power point tracking techniques.
5. It would also be valuable for any Technical Specification to confirm the prevailing consensus that reportable device efficiency measurements must represent the steady-state performance of the device.

Since taking full I-V curve of slow response devices can be time consuming, it is proposed, instead of full I-V scanning, to identify the bias voltage which gives maximum power, or which is close to P_{max} voltage. This could be carried out either by following methods:

- Maximum power point tracking (MPPT)

Measurement of steady-state photocurrent at several voltages around the presumed V_{mpp}

Reference solar cell. A pseudo reference cell having spectral responsivity similar to that of the cell being tested may be used when a stable reference solar cell of a test cell is unavailable.

Preparation of the samples: Recommendations on mask application and lead connections as well as temperature monitoring and rear side support of the Device Under Test (DUT) are proposed. The rear side support must allow consistent positioning of the device optimally perpendicular to light and be thermally conductive so that temperature control systems can be effectively applied. The design of the rear side support should even include provisions to allocate a temperature sensor. The samples should include wirings to minimize differences due to contacting issues.

A minimum sample size should be defined to avoid effects derived from different mask positioning.

Temperature control. Mounting the device on a cooled metallic plate equipped with a vacuum chuck is suggested.

2.2 ISOS protocols

The aim of these procedures is to unify testing protocols applied to perovskite cells when assessing the long-term stability of lab-scale devices. Although they are based on the International Summit on Organic Photovoltaic Stability (ISOS) protocols, additional procedures are proposed to account for properties and degradation modes specific to perovskites such as electrical bias and light–dark cycling.

In next table, the conditions described as per ISOS testing protocols are summarized:

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ISOS-protocol	Light condition	Temperature	Atmosphere	Load
ISOS-L-1	Constant	25 °C	nitrogen	MPPT
ISOS-L-2	Constant	65, 85 °C	nitrogen	MPPT
ISOS-LC-1	Cycled	25 °C	nitrogen	MPPT
ISOS-LC-2	Cycled	65, 85 °C	nitrogen	MPPT
ISOS-D-1	Off	25 °C	ambient	OC
ISOS-D-2	Off	65, 85 °C	ambient	OC
ISOS-D-1	Off	25 °C	nitrogen	OC
ISOS-D-2	Off	65, 85 °C	nitrogen	OC
ISOS-L-1	Constant	25 °C	ambient	MPPT
ISOS-L-2	Constant	65, 85 °C	ambient	MPPT
ISOS-T1	Off	cycled: RT to 65, 85 °C	nitrogen	OC
ISOS-T2	Off	cycled: RT to 65, 85 °C	nitrogen	OC
ISOS-T1	Off	cycled: RT to 65, 85 °C	ambient	OC
ISOS-T2	Off	cycled: RT to 65, 85 °C	ambient	OC
ISOS-LC-1	Cycled	25 °C	ambient	MPPT
ISOS-LC-2	Cycled	65, 85 °C	ambient	MPPT
ISOS-LT-1	Cycled	cycled: RT to 65 °C	ambient	MPPT

OC stands for open circuit, RT for room temperature.

These guidelines also include a comprehensive checklist for reporting results from perovskite stability studies more consistently.

2.3 IEC Standards and technical specifications

There are two technical committees at IEC level involved in standardization activities that must be observed when dealing with perovskite devices: TC82 *Solar photovoltaic energy systems* and TC113 *Nanotechnology for electrotechnical products and systems.*

Although it is only in test report IEC TR 63228 (from TC82) that perovskite technology is explicitly mentioned, the last editions of general specifications for PV devices laid in series IEC 60904 for characterization and in IEC 61215 for design qualification include some clauses related to metastable and tandem devices as perovskites are.

2.3.1 IEC 60904-1:2020 Photovoltaic devices - Part 1: Measurement of photovoltaic current-voltage characteristics

This standard describes procedures for the measurement of current-voltage characteristics (I-V curves) of photovoltaic (PV) devices in natural or simulated sunlight. These procedures are applicable to a single PV solar cell, a sub-assembly of PV solar cells, or a PV module.

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Regarding metastable devices their stabilization should be performed prior to any characterization (I-V and spectral responsivity measurements).

The I-V curve measurement should reflect as closely as possible the performance of the device under steady state conditions. In case of some thin film devices with complex response such as perovskite-based ones, see IEC TR63228.

2.3.2 IEC 60904-1-1:2017 Photovoltaic devices - Part 1-1: Measurement of current-voltage characteristics of multi-junction photovoltaic (PV) devices

It describes procedures for the measurement of the current-voltage characteristics of multi-junction photovoltaic devices in natural or simulated sunlight. It is applicable to multi-junction PV cells, sub-assemblies of such cells or entire PV modules.

2.3.3 IEC 60904-8:2014 Photovoltaic devices - Part 8: Measurement of spectral responsivity of a photovoltaic (PV) device

This standard specifies the requirements for the measurement of the spectral responsivity of both linear and non-linear photovoltaic devices.

2.3.4 IEC 60904-8-1:2017 Photovoltaic devices - Part 8-1: Measurement of spectral responsivity of multi-junction photovoltaic (PV) devices

The document gives guidance for the measurement of the spectral responsivity of multi-junction photovoltaic devices. The requisites of the apparatus and the procedure for the measurement using continuous or pulsed light source are explained.

2.3.5 IEC 61215: 2021 Terrestrial photovoltaic (PV) modules - Design qualification and type approval

This document lays down requirements for the design qualification of terrestrial photovoltaic modules suitable for long-term operation in open-air climates. This document is intended to apply to all terrestrial flat plate module materials such as crystalline silicon module types as well as thin-film modules. The subparts of IEC 61215-1 define technology variations which mainly affects the stabilization procedure (MQT19) described in clause 10.19 of the IEC 61215-2 standard.

2.3.6 IEC TS 62876-2-1:2018: Nanotechnology - Reliability assessment - Part 2-1: Nano-enabled photovoltaic devices - Stability test

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This technical specification proposes a reduced number of stability testing ISOS protocols where some parameters have been modified. Next table summarizes the stability testing conditions:

Test ID	ST1	ST2	ST3	ST4	ST5	ST6	ST7
Description	Dry heat	UV exposure	Damp heat	Light exposure	Outdoor exposure	Laboratory weathering	Thermal cycling
Light	None	UV	None	Daylight (600–1000) W m^{-2}	Ambient	Daylight (600–1000) W m^{-2}	None
Temperature	45 °C	65 °C	45 °C	45 °C	Ambient	38 °C	−40 to +85 °C
	65 °C		65 °C	**65 °C**			
	85 °C		**85 °C**	85 °C			
Humidity	Ambient	Ambient	85% rh	Ambient	Ambient	50% rh/water spray	Ambient
Environment	Oven	UV chamber	Climate chamber	Light soak chamber	Outdoor	Weathering instrument	Climate chamber
Load	None	None	None	Passive or active, M_{pp}	Passive or active, M_{pp}	Passive or active, M_{pp}	None

2.3.7 IEC TS 62607-7-2:2023 ED1: Nanomanufacturing - Key Control Characteristics - Part 7-2: Nano-enabled photovoltaics - Device evaluation method for indoor light

This Technical Specification specifies the efficiency testing of photovoltaic cells (excluding multi-junction cells) under indoor light. Although it is primarily intended for nano-enabled photovoltaic cells (organic thin-film, dye-sensitized solar cells (DSC), and Perovskite solar cells), it can also be applied to other types of photovoltaic cells, such as Si, CIGS, GaAs cells, and so on.

2.3.8 IEC DTS 60904-1-4 Guidelines for I-V measurements of metastable PV devices

This Draft of Technical Specification (DTS) will be part of the IEC 60904 series of standards. The forecast publication date is by the end of 2025. The document will provide guidance for measuring metastable PV devices, beyond what is provided in the IEC 60904 series. The content will be developed from a consensus of stakeholders including testing laboratories, companies, and research institutes. The intent will be to reduce the presently observed variability in results between different laboratories.

The document will primarily cater for the new perovskite-based PV devices; however, it is intended to be applicable to any new PV technologies that exhibit metastability. The methods in the document will apply to single-junction PV devices, however the project will consider that any defined procedure will eventually need to be consistent with the tandem PV device standards IEC 60904-1-1 and 60904-8-1, or otherwise those standards may need to be adjusted for consistency.

The document will focus on metastability-related issues that affect reproducibility of the measured I-V curve, hence it will record consensus and provide guidance on at least the following aspects:

1. Any mandatory or optional pre-conditioning, including how to demonstrate that the pre-conditioning has been sufficient.
2. How a dynamic I-V measurement should be performed (except where such documentation already exists in IEC 60904-1) e.g. how to demonstrate that sufficient settling has taken

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place at each voltage point, and how to deal with situations where such settling is not achieved.

3. How the individual measurements of the key I-V parameters should be performed, specifically Isc, Voc and Pmp (except where such documentation already exists in IEC 60904-1), e.g. how to demonstrate that sufficient settling has taken place, and how to deal with situations where settling is not achieved.

The document will not consider methods designed to produce long-term stabilisation in the device, e.g. technology-specific parameters for the Stabilisation procedure (MQT-19) in IEC 61215.

2.4 NREL's steady-state efficiency measurement protocols

The Asymptotic Pmax method used at the National Renewable Energy Laboratory (NREL) is based on time asymptotic current measurements for a set of constant voltages in the region of V_{mp}. To conduct an Asymptotic P_{MAX} scan, first, NREL performs a conventional fast IV scan to obtain approximately the voltage V_{MAX} corresponding to the maximum power point P_{MAX}. Then a set of voltages around V_{MAX} are selected and starts the Asymptotic IV scan by applying a constant voltage from this voltage set and monitoring the current of the device until it stabilizes. As the data are collected, fit the last 25% of collected data to a straight line. When the slope of this line reaches some acceptance threshold (changes less than 0.1%/minute for more than 30 s) then it records the average current for the last 30 s and move to the next voltage. Once the stabilized current for all voltage points has been obtained, the current vs. voltage is converted to power vs. voltage. Finally, a standard validated polynomial fitting algorithm is applied to obtain the P_{MAX} of the module.

2.5 Consolidated protocols from CHEOPS project

The partners of CHEOPS project agreed on following consolidated protocols in order to compare the results of different perovskite cells manufactured and exchanged within the frame of project consortium. The perovskite cells from 5 project partners with different architectures and topologies were assessed following the same instructions for performance and stability measurements.

All tests requiring irradiation of the solar cell must be performed in a steady-state sun simulator with the AM1.5 spectrum.

2.5.1 Cell performance measurements

The following steps were defined for the cell performance measurements:

1. Dark-IV scans in reverse (from V_{oc} to J_{sc}) and forward (from J_{sc} to V_{oc}) direction.
2. Light-IV scans at 1-sun illumination in reverse and forward direction.
3. MPP tracking for 5 minutes (at room temperature).
4. Light-IV scans at 1-sun illumination in reverse and forward direction.
5. External quantum efficiency measurement.

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2.5.2 Stability testing for encapsulated cells

The following tests were defined for stability testing:

- Test cells at 85 °C in the dark air.
- Thermal cycling between -40 °C and 85 °C for 200 cycles.
- Light soaking at 60 °C for 1000 h at the MPP if a suitable setup is available.
- Damp-heat test at 85% relative humidity and 85 °C for 1000 h**.**

2.6 PACT Protocols

The PACT Center (Perovskite PV Accelerator for Commercializing Technologies) was established in 2021 and is led by Sandia National Laboratories. The PACT Center aims to develop, validate, and document testing standards capable of accurate characterization of field performance and degradation prediction. To that end, they are working on the first versions of performance and reliability test protocols for perovskite PV technologies.

Regarding measurements, two protocols described below are available from the web: https://pvpact.sandia.gov/publications-and-protocols/

2.6.1 PACT Preconditioning Protocol Version 0.1 March 2022

The purpose of this protocol is to bring metal halide perovskite (MHP) modules to a repeatable and relevant state prior to making a performance measurement to quantify power degradation when the modules are being subjected to aging tests.

This initial protocol is designed to consider the metastability of the module across diurnal cycles, so the period of interest is defined to be 24 hours. Shorter or longer duration metastable behaviours may exist but are not considered here. This initial draft for perovskite modules only considers indoor preconditioning under well-controlled conditions.

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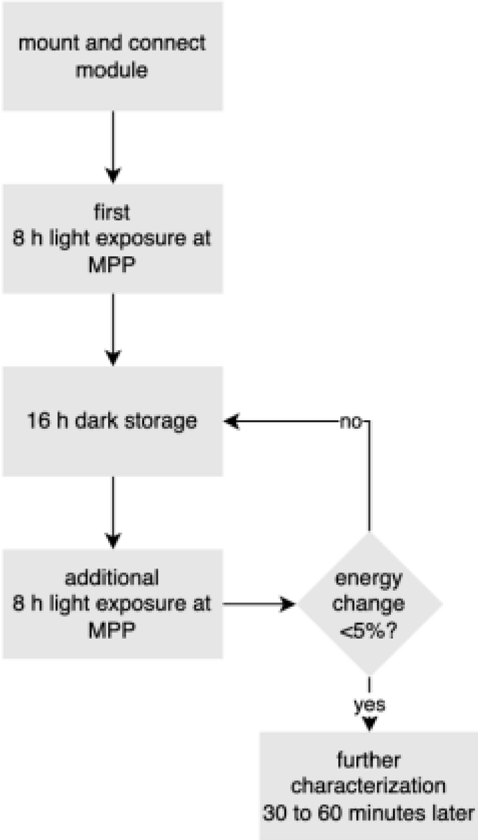

Figure 2. Test flow for preconditioning of perovskite modules.

This preconditioning protocol still needs to be validated before it can be adopted generally and may need to be adjusted as more experience is gained testing perovskite PV modules.

2.6.2 PACT Stress Testing Protocol Version 0.3 June 2024

The purpose of this protocol is to use accelerated stress testing to assess the durability of metal halide perovskite (MHP) photovoltaic (PV) modules. In its current form, the protocol aims to cover two aspects:

1. To apply field-relevant stressors to packaged MHP modules to identify early failure mechanisms which can be correlated to field-stressed modules of the same type.
2. Provide a minimum recommendation of the accelerated stress testing that may not be captured by existing standards such as IEC 61215.

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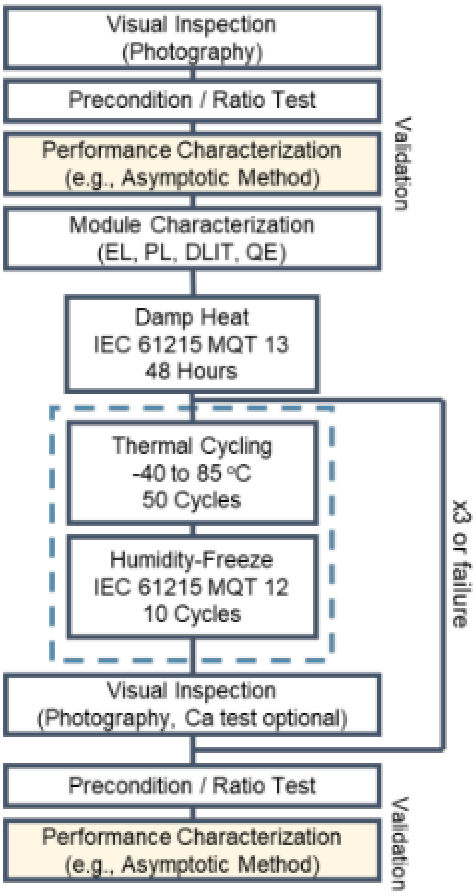

Figure 3. Test flow for examination of the package impermeability.

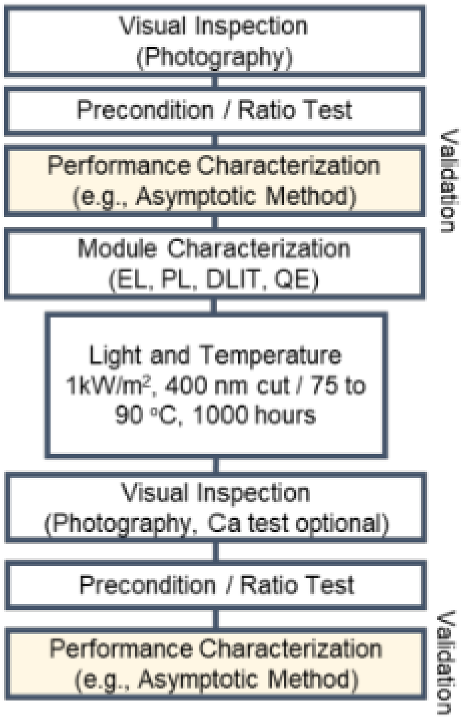

Figure 4.. Test flow for light and elevated temperature supplement stress test

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This protocol still needs to be validated before it can be adopted more generally and will likely be adjusted as more data is collected. All test parameters and durations will be optimized according to field data collected on sister modules. PACT anticipates updating this document and protocol bi-annually with supporting data and modified procedures.

2.6.3 PACT Perovskite PV Module Outdoor Test Protocol Version 0.1 May 2023

The purpose of this protocol is to define procedures and practices to be used by the PACT center for field testing of metal halide perovskite (MHP) photovoltaic (PV) modules. The protocol defines the physical, electrical, and analytical configuration of the tests and applies equally to mounting systems at a fixed orientation or sun tracking systems.

While standards exist for outdoor testing of conventional PV modules, these do not anticipate the unique electrical behaviour of perovskite cells. Furthermore, the existing standards are oriented toward mature, relatively stable products with lifetimes that can be measured on the scale of years to decades.

The state of the art for MHP modules is still immature with considerable sample to sample variation among nominally identical modules. Version 0.1 of this protocol does not define a minimum test duration, although the intent is for modules to be fielded for periods ranging from weeks to months. This protocol draws from relevant parts of existing standards, and where necessary includes modifications specific to the behaviour of perovskites.

2.7 ESTI Protocol

Based on the experience of European Solar Test Installation (ESTI), the following proposal for measuring I-V curve of perovskite devices is made:

1 Apply voltage bias prior to device illumination.

2 Avoid Isc, Voc and reverse bias scenarios.

3 Pre-condition the device near V_{MPP} under light (between 5 min and 60 min max) until:

- temperature is stable
- current is settled

4 Find actual V_{MPP} and wait until settling criteria is reached (0.2%/min)

5 Trace for 300 seconds

6 The average of the last 30 seconds is the first P_{MAX}

7 Measure reverse and forward IV curves with approximately 10 s duration. Voltage in between sweeps is kept at V_{MPP}.

8 Manually construct the I-V curve

9 Timeout per point is 10 min.

10 Ascertain settled V_{OC} and I_{sc} values

11 Re-measure P_{max} after V_{oc} and I_{sc}.

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2.8 Recent other activities

Various related protocols on I-V testing and power rating methods for metastable/ perovskite-based PV Devices are currently under development and have been presented recently, i.e. at the EU PVSEC 2024 in Vienna or at the "EERA PV BECOME PV workshop" on "Boosting the Exploitation and commercialisation of Emerging PV technologies", organized in November 2024 in Brussels. The VIPERLAB consortium was actively engaged in the organization of or participation at these and many other networking activities, respectively (see also deliverable D4.9), and was thus actively contributing to the discussion and further development of harmonized testing protocols for metastable/perovskite-based PV Devices.

3. FIRST VIPERLAB ROUND ROBIN ON ELECTRICAL PERFORMANCE

In the frame of *WP9 JRA3-Characterization and standardization*, several RRs have been conducted regarding performance and aging measurements.

In this part of the deliverable, main results derived from these intercomparisons are presented.

3.1 First Round Robin organization

Four different VIPERLAB partners offered samples for this RR1: CEA, Fraunhofer ISE, HZB and TNO. In order to reduce the time between measurements, the RR1 was organized in binomials. Each manufacturer measured its own devices, sent them to another partner and measured them again at their return to check their stability.

3.2 Samples description-First RR

Each of the 4 manufacturers providing perovskite samples for the RR has a different layout design. The samples exchanged for the *1st Electrical performance measurement of perovskite PV VIPERLAB Round Robin* are briefly described in the following table. The binomials formed by "manufacturer and measurer" were assigned considering the encapsulation condition and the architecture of the devices in order to better match the measurement requisites with the capabilities of the participating laboratories.

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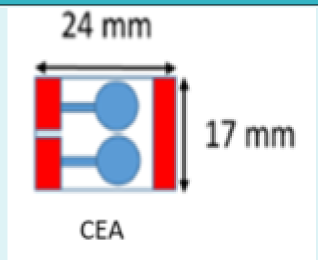
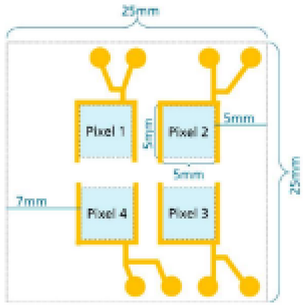
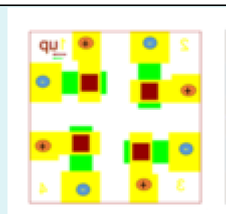
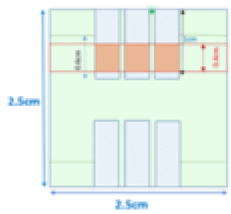
Manufacturer	Measurer	Structure	Design
CEA	CENER	Flex NIP, hot vacuum lamination	
Fraunhofer ISE	CEA	Tandem Si/NIP, 2T, box sealed in GB. Not encapsulated. Plus rigid PIN	
TNO	AIT	Rigid PIN, UV glue encapsulation	
HZB	Fraunhofer ISE	Rigid PIN, UV glue encapsulation. Slot-die coated perovskite layer	

3.3 Measurement protocols used by VIPERLAB partners in 1st RR

The participants of the VIPERLAB Round Robin shared their protocols currently used to determine the electrical performance of perovskite cells. Although minor differences were encountered among them, the final procedures were adjusted so that each binomial followed basically the same measuring steps.

Main measuring conditions are summarized in the next table:

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Table 1 – Status of the measurement protocols of the different groups and main conditions

	CEA (1st binomial)	CENER (1st binomial)	Fraunhofer (2nd Binomial)	CEA (2nd Binomial)	TNO (3rd binomial)	AIT (3rd binomial)	HZB (4th binomial)	Fraunhofer (4th binomial)
Cell type	SJ/flexible NIP		-Tandem Si/NIP - SJ Rigid PIN semi-transparent		SJ Rigid PIN semi-transparent		Rigid single junction (PIN)	
Encapsulated	YES		No		Yes, foil encpsulated		Yes	
Dimensions of cells tested	0,33 cm²		0,25 cm² (each tandem cell)		0,16 cm² (4mmx4mm)		0,40 cm² (10mmx 4mm)	
Solar simulator	Xe lamp	Xe lamp	Xe lamp (SJ) 2 lamps tandem	Xe lamp	dual source	Xe lamp	Wavelabs Sinus-70 LED	Xe lamp
JV regime	5*reverse 3*forward 120 sec. mini-scan forward 0,05V around MPP 1*reverse		2*reverse (or forward) 2*forward (or reverse) 60 msec fixed voltage tracking 1* reverse and forward	90 msec Continuous voltage sweep	2* (reverse - forward) *MPPT of the (best) pixel for 180s. Finally not applied.* 1* reverse and forward		2* (reverse - forward) 120 sec. mini-scan forward 0,05V around MPP 1* reverse and forward	3* (reverse - forward)
Connnectors	conductive tapes		All metallic rear size and dot contacts in the front		conductive tapes			
Scan rate			17mV/sec		200mV/sec	175mV/sec	20mV/sec	20mV/sec
Voltage span	-0.4 – 1.4 V		-0.1– 1.9 V		-0.2– 1.2 V		-0.1– 1.2 V	
Voltage step	50mV		10mV		20mV		10 mV	
Delay time	20ms						20ms	
Atmosphere JV performed	Air	Air	Air	Air	Air	Air	Air	Air
Temperature of JV	Ambient	table: 25ºC	table: 25ºC	Ambient	table: 25ºC	table: 25ºC	Ambient: 25 °C	table: 25 °C
Sun illumination intensity	1000W/m²		1000W/m²		1000W/m²		1000W/m²	
Reference cell	filtered Si	Si	filtered Si	filtered Si	Si	Si	KG3 filtered Si	WPVS filtered Si
Calibration of reference cell		Yes			Yes	Yes	Yes	Yes
Spectral mismatch calculation			YES			Yes	Yes	Yes
Are masks being used?	No		Yes		Yes		Yes	
Type of mask used	-		0,5mmx0,5mm		3mmx3mm		3mmx3mm	
No. of substrates circulated	3 of area (1,7x2,4)cm²		2 tandem and 1 SJ (2,5x2,5)cm²		3 of area (2,5x2,5)cm²		3 of area (2,5x2,5)cm²	
No. of pixels/substrate	2		4 (1 of them in SJ inactive)		4		6	
Total solar cells measured	6	2	8 tandem cells, 3 SJ cells		12		18	
Pre-condition	During measurement (light)		During measurement (light)		Not performed		During measurement (light)	
PCE variatons	(1-2)%		Up to 10% for tandem , <2% SJ		(1-2)%		<1%	

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4. SECOND VIPERLAB ROUND ROBIN ON ELECTRICAL PERFORMANCE

This section includes a summary about protocols used for the second Round Robin for the electrical performance assessment of perovskite photovoltaic (PV) technology for the VIPERLAB project.

4.1 Second Round Robin organization

All the samples used in the second Round Robin of performance measurement were **manufactured by the partner EPFL**.

The evaluation of perovskite solar cells follows a procedure known as **Star-shaped Round Robin** (RR). Initially, measurements are conducted at CENER. Subsequently, each participating laboratory independently assesses the solar cells, taking one substrate each. Following this distributed analysis, the evaluation cycle returns to CENER, where a final round of measurements is performed. This comprehensive approach, involving multiple participants and iterative measurements, ensures a robust and thorough assessment of perovskite solar cell performance, with **CENER acting as a central hub** in the evaluation process.

Apart from CENER acting as the central hub, the **participating partners in the intercomparison were AIT, CEA, ENEA, FRAUNHOFER ISE (FhG ISE) and Forschungszentrum JÜLICH.**

4.2 Samples description-Second RR

The design of perovskite solar cells supplied by EPFL is described below:

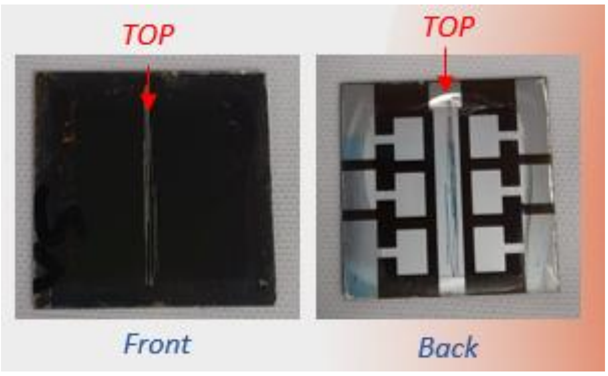

Figure 5. Front and rear view of perovskite solar cells supplied by EPFL.

The solar cells were supplied on glass substrates. Each substrate with a size of 2.5 cm x 2.5 cm contained 6 individual solar cells of pixel size 0.2 cm x 0.4 cm = 0.08 cm^2. Also, the cell electrodes were accessible through a central common (cathode) pad and small metal pads adjacent to each of the cells (anode).

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In addition to the cells, the manufacturer EPFL also supplied cables and substrate holders to facilitate making contacts with the cells. Finally, masks were also supplied which left only the pixels area open.

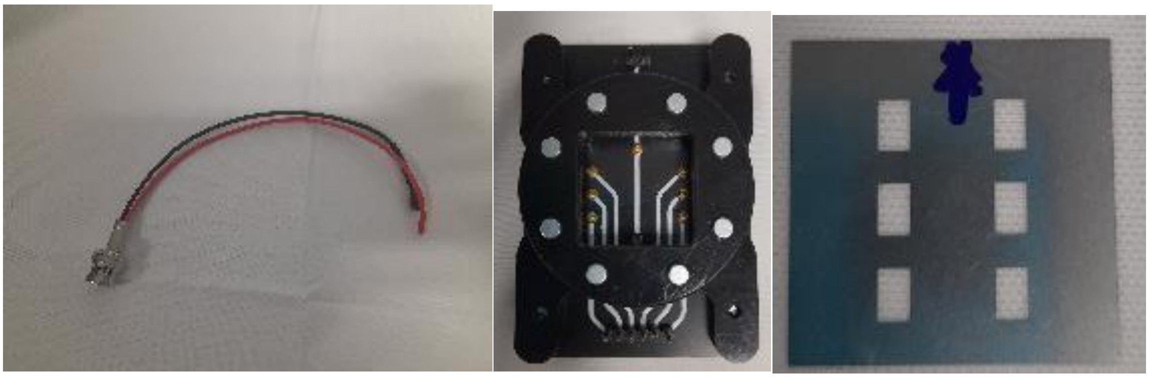

Figure 6. Cable (left), substrate holder (centre) and mask (right) supplied by EPFL.

4.3 Measurement protocols used by VIPERLAB partners in the 2nd RR

The protocol agreed by the partners to determine **the performance of the perovskite solar cells** (maximum power determination and IV curve) under study is summarised below:

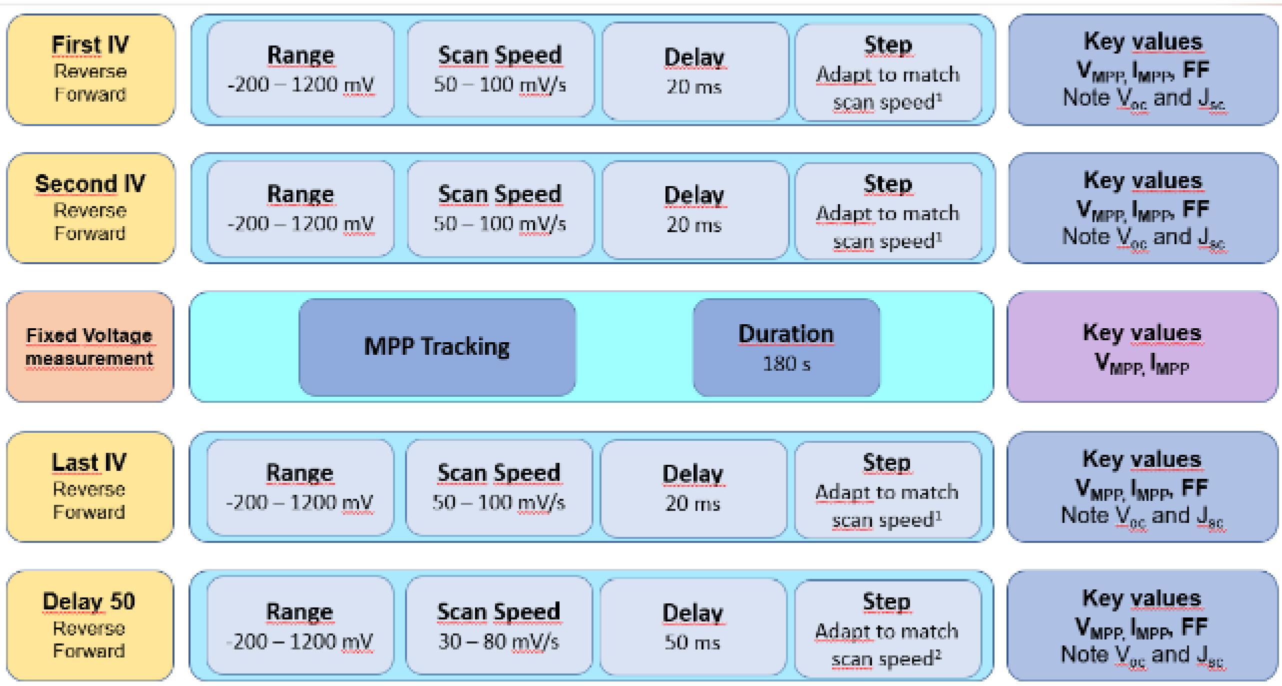

Figure 7. Protocol used to determine performance of single junction perovskite solar cells in 2nd RR.

The protocol consists, initially, of performing initial reverse and forward IV curves at a specific speed, twice in succession (First IV and Second IV). This is followed by a third step in which the cell is held at the maximum power point for 3 minutes. Finally, reverse and forward IV curves (Last IV) are performed while maintaining the sweep speed and the final IV curves (Delay 50) by increasing the delay time to 50 ms in order to find out the influence of this parameter on the results obtained.

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Concerning the measurement conditions of the IV curves, it is preferred to follow standard test conditions (1000 W/m^2, AM1.5G, 25 ºC). However, the labs were generally unable to follow the temperature directive due to the design of the solar cell and substrate holder, which made it difficult to actively control the temperature.

The protocol agreed by the partners to determine **the spectral response (SR) and external quantum efficiency (EQE) of the perovskite solar cells** under study is summarised below:

Figure 8. Protocol used to determine EQE of single junction perovskite solar cells for 2nd RR.

The main conclusions derived from the 2nd Performance RR conducted among VIPERLAB partners are reported in deliverable *"D9.7: Second Round Robin Report: Guidelines for Electrical Performance Measurement of Perovskite PV Technology".* Some relevant outcomes regarding measurement protocols followed are:

- The protocol used to determine performance consists of nine steps, including forward and reverse voltage sweeps and an exposure time at Maximum Power Point. A briefer protocol to determine performance could be sufficient to extract electrical parameters of perovskite solar cells.
- Increasing the delay time to 50 ms did not lead to a reduction in hysteresis, with the lowest hysteresis observed in the samples studied in the second sweeps.
- The normalized EQE vary by less than 3% in all cases and has been found to have good reproducibility.

5. THIRD VIPERLAB ROUND ROBIN ON ELECTRICAL PERFORMANCE

This section includes a summary about protocols used for the third Round Robin for the electrical performance assessment of perovskite photovoltaic (PV) technology for the VIPERLAB project.

5.1 Third Round Robin organization

All the samples used in the third Round Robin of performance measurement were **manufactured by the partner CEA**. Apart from **CEA acting as the central hub**, the p**articipating partners in the intercomparison were CENER, ENEA, FRAUNHOFER ISE and HZB.**

The evaluation of perovskite solar cells was initially conducted by CEA and then distributed to the rest of the partners as depicted in star-shaped round robin, see Figure 9.

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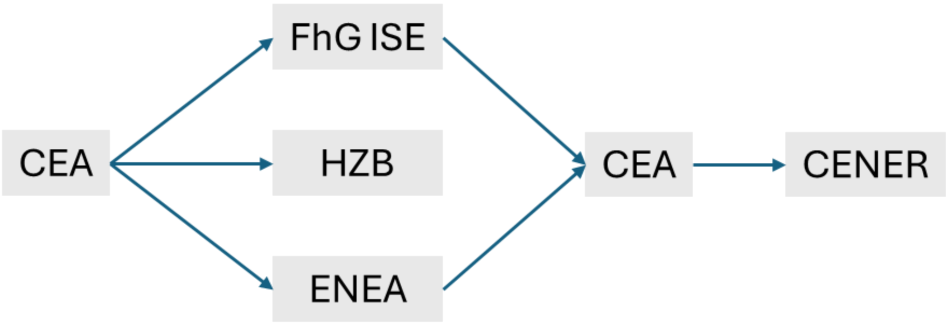

Figure 9. Organization of third performance round robin.

Some of the partners, Fhg ISE and ENEA, returned the samples back, so CEA could carry out a second measurement. CENER received their samples after the first measurement, and after measuring them they kept them to continue with ageing tests.

5.2 Samples description-Third RR

This round robin involved solely **perovskite – silicon tandem solar cells**. The design of the cells supplied by CEA is described below:

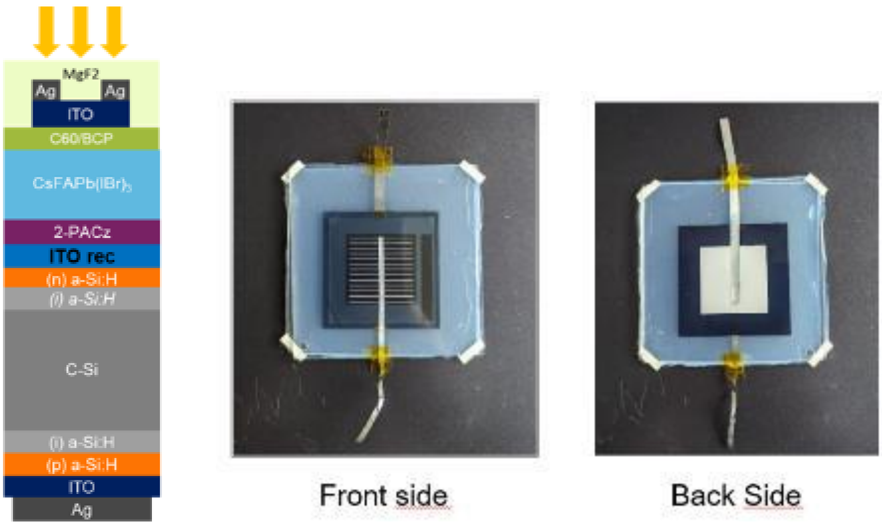

Figure 10 (Left) Scheme of perovskite-silicon tandem solar cell architecture and (right) front and rear view of tandem solar cells supplied by CEA.

The solar cells encompass a pin perovskite solar cell with a heterojunction silicon solar cell in **two terminals** configuration, having an **active area of 8.88 cm².** These solar cells feature a **glass/glass encapsulation** with dimensions of **80 x 80 mm**. For sealing, two types of encapsulation materials were used: **UV-polymerizable epoxy glue** and **TPO/ES** (Thermoplastic Polyolefin/Encapsulant Sheet). Finally, for electrical connectivity, the cells use **3M conductive tapes** as connectors.

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5.3 Measurement protocols used by VIPERLAB partners in 3rd RR

The protocols used to determine **the performance of the perovskite solar cells** (maximum power determination and IV curve) under study are summarised below:

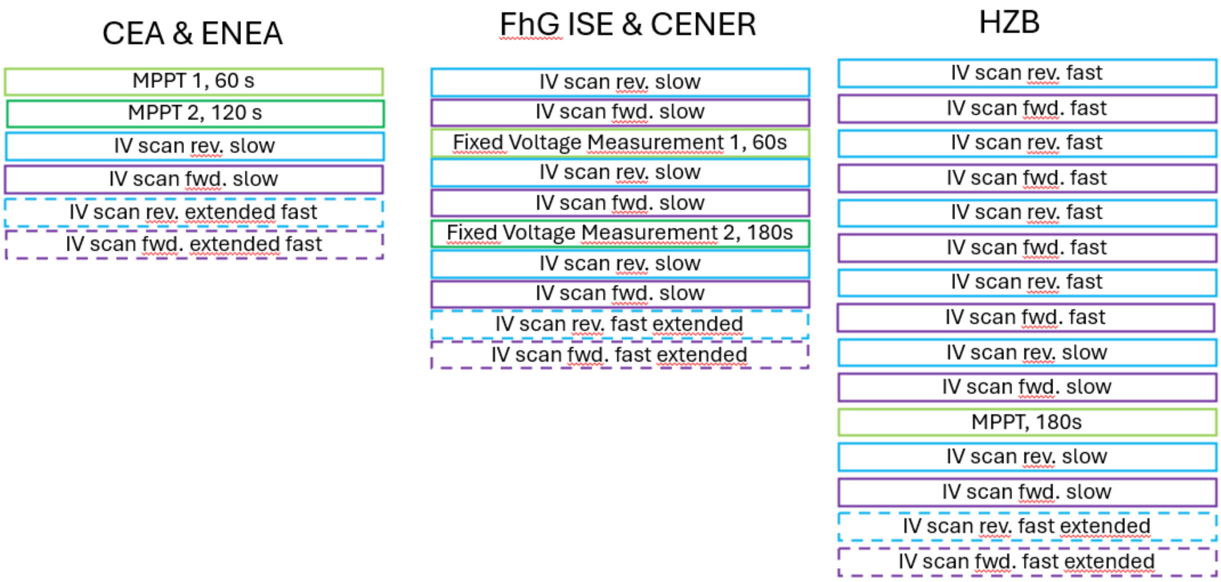

Figure 11 Protocols used to determine ***performance*** *of tandem perovskite-Si solar cells in RR3.*

These protocols are designed to evaluate the performance of tandem solar cells through a series of controlled tests under varying illumination spectrum conditions. The cells are initially tested under continuous 1 sun illumination with the AM1.5 solar spectrum, simulating standard sunlight exposure. This includes maximum power point tracking (MPPT) and fixed voltage measurements to track stability and efficiency over time and a range of IV scans performed in both forward and reverse directions. These IV scans are conducted at different speeds, categorized as slow and fast, to capture dynamic performance metrics. Additionally, extended IV scans are included to provide a more comprehensive view of the cell's response. The spectrum has been also adjusted under specific spectral conditions such as IR (infrared), Blue spectrum, and Dark (no light) environments. Under these conditions, further IV scans are conducted in both directions to assess the individual cells' behaviour across various spectral inputs.

Temperature control is also a crucial part of these protocols, as maintaining or varying temperature conditions during measurements causes differences in the results. Finally, the illumination equipment mostly used among the partners are LED-based solar simulators, except CENER, which uses a Xenon lamp with an additional 940 nm IR LED to reduce the mismatch factor and achieve a more accurate IV curve measurement for tandem cells. The maximum difference observed for Pmax during this third VIPERLAB RR for tandem cells was around 3%.

The standard *IEC 60904-8-1: Photovoltaic devices – Part 8-1: Measurement of spectral responsivity of multi-junction photovoltaic devices* and the publication of Meusel et al (2003) were taken as a basis to determine **the quantum efficiency (QE) of the perovskite tandem solar cells** under study.

More information about this RR can be found in *Deliverable 9.9 Guidelines for electrical performance measurement of perovskite PV technology – Main outcomes and final conclusions*.

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6. CONCLUSIONS

After the review of the different protocols used to measure perovskite devices, several recommendations related to sample preparation can be proposed to obtain reproducible results when comparing their behaviour by different groups, regardless of the device architecture:

- Exchange of properly packaged perovskite devices in order to minimize degradation effects due to ambient conditions present during storage and transport.
- Include a rear side support to position the device optimally perpendicular to the main/ central direction of the light beams, and which is thermally conductive so that temperature control systems can be effectively applied. The design of the rear side support should even include provisions to allocate a temperature sensor.
- Include wiring to minimize differences between samples due to contacting issues.
- Define a minimum sample size to avoid effects derived from different mask positioning.

Regarding the measuring system, all the laboratories should fulfil following minimum technical requirements:

- The spectral distribution of the light source should be as close as possible to AM1.5G spectrum. For single junction cells this effect can be minimized by using a spectral mismatch correction.
- For tandem cells a multi-lamp sun simulator is needed.
- A reference cell spectrally matched with the device should be always measured.
- For tandem cells, if possible, the EQE should be measured or three reference Si cells should be employed (one with short-pass filter, one with long-pass filter and one unfiltered) to adjust the total current and the balance between the two sub cells when using a two-lamp or LED cell tester.

Regarding the measurement protocols, it is considered a better option to report key values as I_{sc}, V_{oc}, and PCE instead of providing the full I-V curve. Most of the previously published protocols follow the same sequence of (a) performing a forward and reverse voltage sweep, respectively, (b) keeping the device under illumination and a voltage close to the V_{MPP} for several minutes, and (c) repeating the forward and reverse voltage sweeps. In general, it can be concluded that:

- Preconditioning is vital to ensure reproducible performance measurements due to the metastable nature of perovskite devices. Procedures like those proposed in IEC TR 63228:2019 and PACT protocols emphasize stabilization near operating conditions, avoiding degradation-prone methods such as prolonged light soaking.
- The consensus stresses the need for careful definition and validation of preconditioning steps to account for transient behaviours.
- Accurate I-V characterization involves strategies such as dynamic voltage sweeps with adjustable dwell times and focused measurements near the maximum power point (Pmax). This approach minimizes errors caused by hysteresis and metastable effects.
- The development of reduced sweep protocols, as noted in NREL's asymptotic Pmax method, allows efficient and precise determination of critical parameters while addressing challenges posed by slow device response.
- Long-term reliability assessments follow standards like ISOS and IEC protocols, which define stress conditions such as temperature, humidity, and illumination cycles. These standardized tests enable reproducible stability evaluations across different laboratories.

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- The incorporation of perovskite-specific stressors, such as light–dark cycling and electrical bias, ensures that unique degradation mechanisms are adequately captured.
- Efforts such as the CHEOPS project and PACT protocols underscore the importance of harmonized procedures to facilitate comparison of results among research and industrial groups. Consolidated guidelines provide a foundation for consistency in performance and durability assessments.
- Emerging standards like IEC DTS 60904-1-4 and adaptations in existing ones (e.g., IEC 61215) aim to address metastability-related issues unique to perovskite devices. These efforts are key to reducing variability and enhancing reproducibility.
- Collaborative development of guidelines for outdoor testing (PACT Outdoor Test Protocol) is critical as perovskites transition from laboratory to field applications, accounting for environmental and operational differences.
- Extended measurement steps, such as increasing delay times to assess hysteresis effects, did not significantly impact results, suggesting that simplified protocols might be adopted in routine evaluations.
- Tandem solar cells require specific protocols to address their unique behaviour under varying spectral conditions. These included adjustments for IR and blue-light spectra and careful Pmax tracking.
- The use of reference standards (e.g., IEC 60904-8-1) and tailored adjustments to match spectral and electrical responses for tandem cells highlights the importance of protocol customization for advanced architectures.
- The iterative nature of the Round Robin approach (e.g., initial measurements, inter-laboratory evaluations, and return measurements) provided a comprehensive validation framework. This ensured that potential discrepancies or device instabilities were identified and addressed systematically.
- The "star-shaped" organization, with a central hub laboratory (e.g., CENER or CEA), facilitated consistency in the distribution and evaluation of protocols. This structure is essential for managing complex inter-laboratory comparisons and ensuring uniformity in applied methodologies.

The combined use of IV curve analysis, spectral response (SR), and external quantum efficiency (EQE) measurements provided a holistic evaluation of cell performance. Including dynamic performance metrics, such as fast and slow scans, enhanced the understanding of cell behaviour under operational conditions

Finally, the VIPERLAB Round Robins successfully aligned measurement procedures across different laboratories, ensuring consistency. Adjustments to protocols during the rounds allowed for standardization, minimizing procedural differences.

In addition to this report and the executed Round Robins, the VIPERLAB consortium was actively engaged in the organization and cooperation of these and many other networking activities (see also deliverable D4.9) and was thus actively engaged in the discussion and further development of harmonized testing protocols for metastable/perovskite-based PV Devices.

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