VIPERLAB

D4.3

First draft of harmonized test protocols

DELIVERABLE REPORT

Version: 1
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FULLY CONNECTED VIRTUAL AND

PHYSICAL PEROVSKITE PHOTOVOLTAICS LAB

VIPERLAB

DELIVERABLE

D4.3 FIRST DRAFT OF HARMONIZED TEST PROTOCOLS

Project References

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Deliverable References

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1.2	Review	14-12-2022	HZB	N. Maticiuc

DISCLAIMER

'Fully connected virtual and physical perovskite photovoltaics lab' VIPERLAB is a Collaborative Project funded by the European Commission under Horizon 2020. Contract: 101006715, Start date of Contract: 01/06/2021; Duration: 42 months.

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ABBREVIATIONS

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

RR: Round Robin

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 D4.3, 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 first round robin (RR1) on electrical performance measurements of the perovskite solar cells for the definition of an harmonized test protocol. The RR1 was executed within WP9 "JRA3-Characterization and standardization" of the VIPERLAB project.

The final draft of the report (D4.6) planned for month 36 will also include the second round robin (RR2) on aging assessment of perovskite technology.

Several topics are important in the phase of sample preparation:

- Exchange of properly packaged perovskite devices in order to minimize degradation effects due to storage, transport and measuring ambient conditions.
- 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.
- 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.

Furthermore, the measuring system of different laboratories should fulfil 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.
- Use of a reference cell spectrally matched with the device to be measured.
- For tandem cells, measurement of EQE, if possible, otherwise apply a spectral mismatch correction using the data from the manufacturer.

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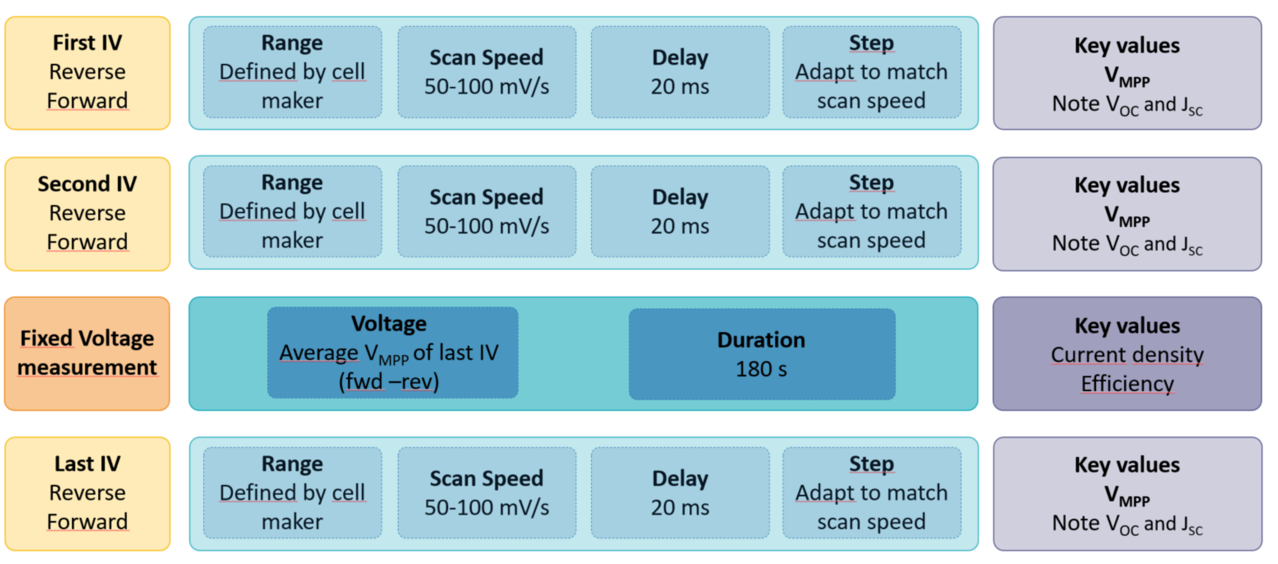
Regarding the measurement protocol itself, it is considered a better option to report key values as I_{sc}, V_{oc}, and PCE instead of providing the full I-V curve. With all the information compiled, the following measuring protocol has been proposed in the frame of VIPERLAB project:



The specific values proposed (voltage span, scan speed, delay, or duration of fixed voltage measurement) might be modified in case the manufacturer has performed enough tests to suggest values more adapted to the particular device.

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1. INTRODUCTION

The main objective of this deliverable is to propose a First draft protocol for testing and characterizing solar perovskite devices produced and measured by the partners of VIPERLAB project. Primary inputs for this deliverable come from *WP9-JRA3 "Characterization and standardization*" where the first Round Robin (RR1) on electrical performance were carried out. Nevertheless, information derived from other work packages as well as published documentation on the subject have been considered.

The final report on harmonized protocols (D4.6) planned for month 36 will also include the second round robin (RR2) on aging assessment of perovskite technology that is now in progress.

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 Robin. Following aspects on perovskite measurement and characterization methodologies have been evaluated:

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

A final proposal is made on the main parameters to be considered to get comparable performance indicators of the technology.

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 the special behaviour of these perovskite solar cells.

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

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

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

- 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:

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
Draft IEC TS 62607-7-2:xxx ED1: Nanomanufacturing - Key Control Characteristics - Part 7-2: Nano-	X	

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enabled photovoltaics - Device evaluation method for indoor light		
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 being issued (2019). The goal of this 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, mask the final result 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 PSC devices.

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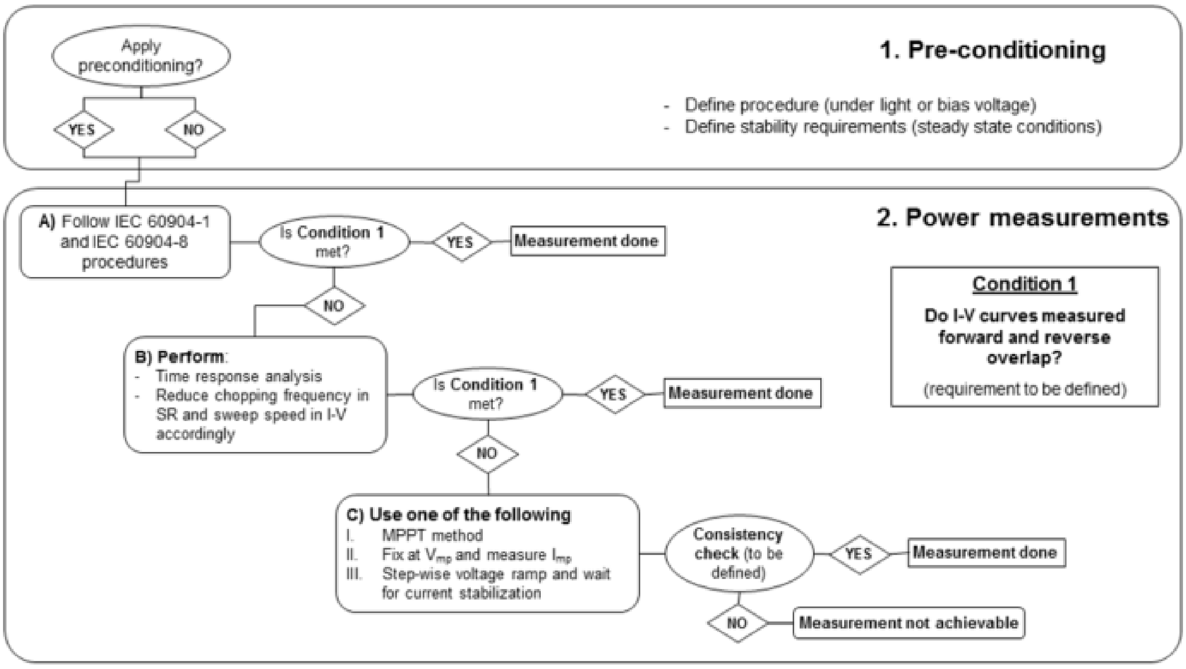

Figure 1. Flowchart for power measurement of emerging PV devices

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”;

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 also potentially maximum-power point tracking techniques;

5. It would also be valuable for any Technical Specification to confirm the majority view 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:

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- The maximum power point tracking (MPPT)
- Measurement of steady-state photocurrent at several voltages around the presumed V_{mp}

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 sucker 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:

ISOS-protocol	Light condition	Temperature	Atmosphere	Load
ISOS-L-1I	Constant	25 °C	nitrogen	MPPT
ISOS-L-2I	Constant	65, 85 °C	nitrogen	MPPT
ISOS-LC-1I	Cycled	25 °C	nitrogen	MPPT
ISOS-LC-2I	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-1I	Off	25 °C	nitrogen	OC
ISOS-D-2I	Off	65, 85 °C	nitrogen	OC

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ISOS-L-1	Constant	25 °C	ambient	MPPT
ISOS-L-2	Constant	65, 85 °C	ambient	MPPT
ISOS-T1I	Off	cycled: RT to 65, 85 °C	nitrogen	OC
ISOS-T2I	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

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 have to 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.

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.

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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 single 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

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

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2.3.7 Draft IEC TS 62607-7-2:xxxx 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.

The final draft version of this technical specification (113/710/DTS) has been circulated in October 2022 and it is expected to be published by the end of December 2022.

2.4 NREL's steady-state efficiency measurement protocols

The Asymptotic Pmax method used at the National Renewable Energy Laboratory (NREL)'s 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 of all 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 is recorded 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.

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5. External quantum efficiency measurement.

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 the 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

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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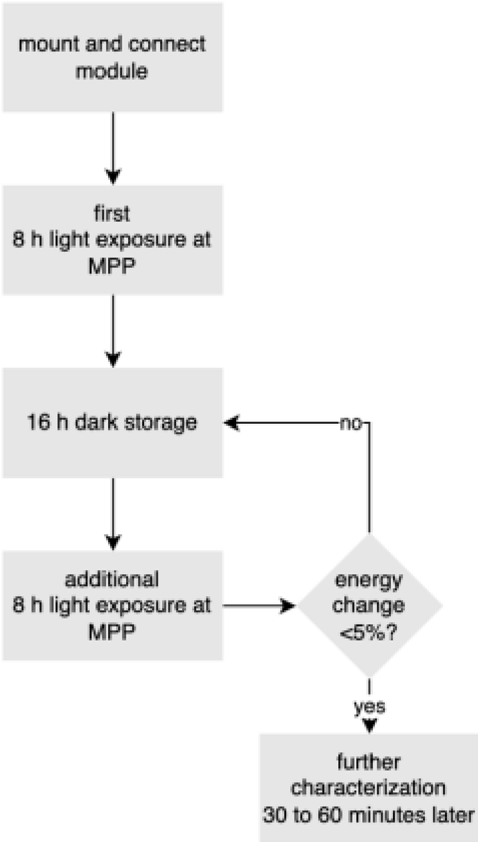

Figure 2. Test flow for preconditioning of perovskite modules

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

The purpose of this protocol is to use accelerated stress testing to assess the durability of metal halide perovskite (MHP) photovoltaic (PV) modules. The protocol aims to apply field relevant stressors to packaged MHP modules to screen for early failures that may be observed in the field. The current protocol has been designed for samples packaged within glass/glass-PIB (polyisobutylene) edge seal, without encapsulant. PACT anticipates adding additional testing sequences to evaluate additional stressors (e.g., PID, reverse bias) in the future.

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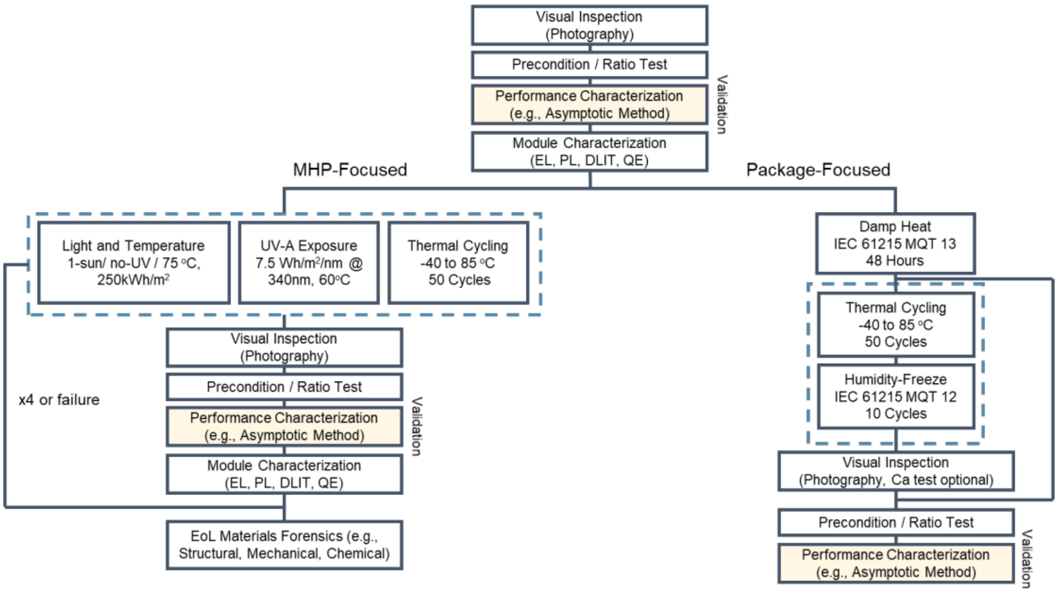

Figure 3. Test flow for stress testing MHP modules

The initial version of this protocol has not been tested or validated against field failures. The initial protocol has been designed with inputs from IEC61215:2021, the MHP ISOS protocols, and input from the community. This protocol will be revised and updated as PACT tests the approach and validates against field data.

2.7 ESTI Protocol

Based on experience of European Solar Test Installation (ESTI) following proposal for measuring perovskite devices is made:

a) One initial I–V sweep in each direction (forward and reverse, typically 10 s to 20 s each) holding the device under illumination for the shortest time possible. This serves as a rough estimate of the electrical response of the device and to extract an approximate V_{mp} value. I–V sweeps should not be repeated nor be made at slow sweep speeds, as the device might degrade under illumination.

b) Hold device (typically for several minutes) under steady-state illumination at voltage close to the approximate V_{mp} value determined in step (a); monitor the current and wait until a pre-defined stability criterion is met. After stabilization perform minor variations (order of ±2% typically) of the voltage to find real V_{mp}. This constitutes the first measurement of P_{max}.

c) Change voltage step-wise towards V = 0 V and wait for the current to stabilise at each step. Acquire a minimum of three measurements (depending on the sampling time) at each voltage step after stabilisation of the current. Continue until V = – (0.02 × V_{OC}) is reached;

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d) Move back to V = V_{mp} (in one step) and check (see below) if the current reaches the value obtained in (b) after pre-conditioning. They observed that for certain devices this requires to wait at this voltage for a few minutes. This constitutes the second measurement of P_{max};

e) Change voltage step-wise toward V = V_{OC} and wait for the current to stabilise at each step. Acquire at least three measurements (depending on the sampling time) at each voltage step after stabilisation of the current. Continue until V = 1.01 × V_{OC} is reached;

f) Move back to V = V_{mp} (in one step) and check (see below) if the current reaches the value obtained in (b) and (d) after pre-conditioning. They observed that for certain devices this requires to wait at this voltage for a few minutes. In some cases, holding the device intermediately for a period (10 s – 120 s) at V = 0 may accelerate this process. Once stabilisation of the current has occurred, hold the device at V = V_{mp} for at least 1 min. This constitutes the third measurement of P_{max};

g) Repeat the sequence (b) – (f) and acquire a second I – V curve for comparison;

h) Repeat (a) for comparison.

3. First VIPERLAB Round Robin on electrical performance

In the frame of *WP9 JRA3-Characterization and standardization*, several RRs are planned regarding performance and aging measurements. At this stage of the VIPERLAB project the RR1 on electrical performance measurements has been completed.

In this part of the deliverable main results derived from this intercomparison are analysed.

3.1 Round Robin organization

Four different VIPERLAB partners offered samples for this RR1: CEA, Fraunhofer, 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

Each of the 4 manufacturers providing perovskite samples for the RR has a different layout design. In the deliverable *D8.1 Standardization of substrate dimensions, device layout and best practices,* a generic design that could be easily adopted by VIPERLAB partners was proposed, however this report was released once the samples for this first RR had been already circulated. Nevertheless, for future editions of the RR the possibility of producing samples according to the generic design will be considered. In figure 4 below it is depicted the generic design of a substrate with six pixels and the photo mask. Also, the design for 4-pixels and 3-pixels is given:

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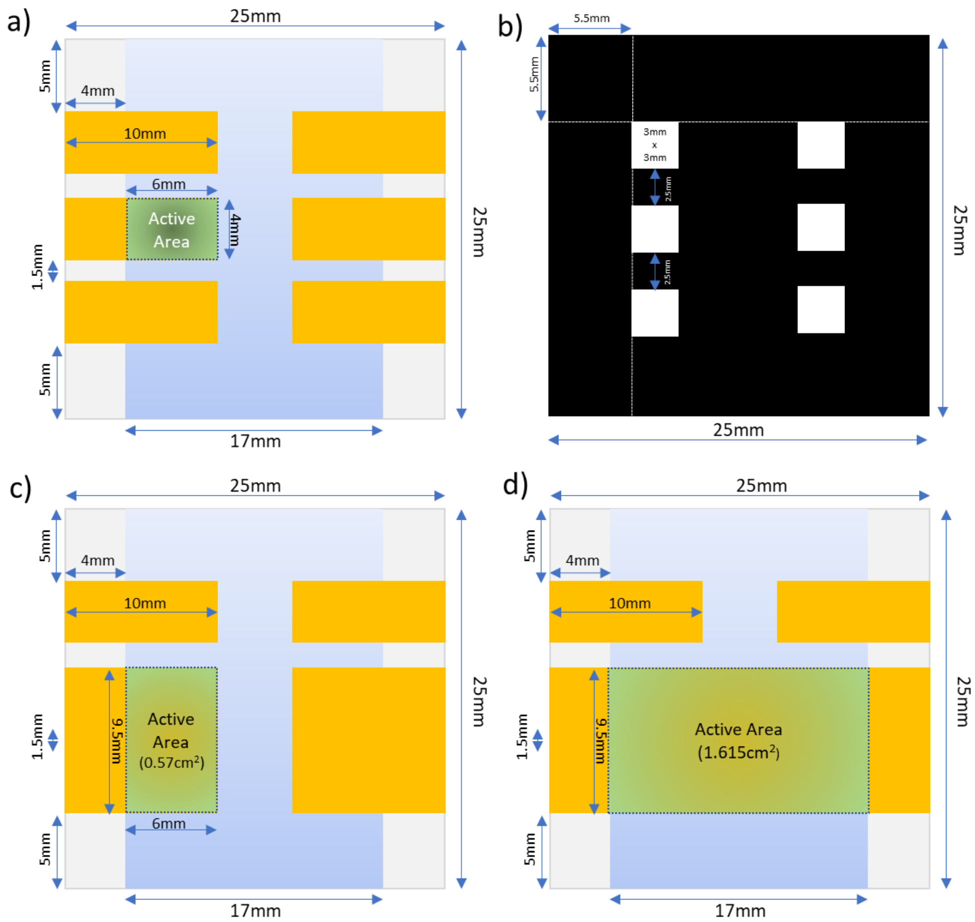

Figure 4.a) Proposed generic design with active area up to 0.25 cm^2. B) Photo mask for the generic design. C) 4-pixel design with active area up to 0.57cm^2. d) 3-pixel design with active area up to 1.6cm^2.

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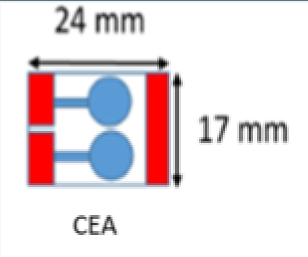
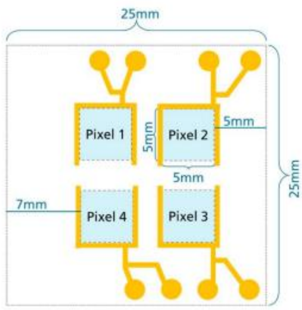
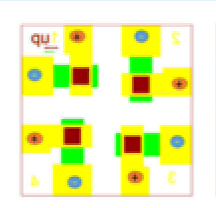
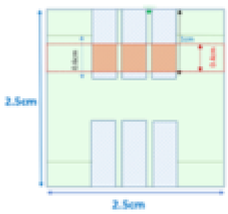
Manufacturer	Measurer	Structure	Design
CEA	CENER	Flex NIP, hot vacuum lamination	
Fraunhofer	CEA	Tandem Si/NIP, 2T, box sealed in GB. Not encapsulated. Plus rigid PIN	
TNO	AIT	Rigid PIN, UV glue encapsulation	
HZB	Fraunhofer	Rigid PIN, UV glue encapsulation. Slot-die coated perovskite layer	

3.3 Measurement protocols used by VIPERLAB partners

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	CENER	Fraunhofer	CEA	TNO	AIT	HZB	Fraunhofer
	1st binomial		2nd Binomial		3rd binomial		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 cm^2		0,25 cm^2 (each tandem cell)		0,16 cm^2 (4mmx4mm)		0,40 cm^2 (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		2*reverse (or forward) 2*forward (or reverse)		2* (reverse - forward)		2* (reverse - forward)	3* (reverse - forward)
			60 msec fixed voltage tracking	90 msec Continuous voltage sweep	*MPPT of the (best) pixel for 180s. Finally not applied.*			
	120 sec. mini-scan forward 0,05V around MPP 1*reverse		1* reverse and forward		1* reverse and forward		120 sec. mini-scan forward 0,05V around MPP 1* reverse and 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/m^2		1000W/m^2		1000W/m^2		1000W/m^2	
Reference cell	filtered Si	Si	filtered Si	filtered Si	Si	Si	KG3 filtered Si	VPVS 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)cm^2		2 tandem and 1 SJ (2,5x2,5)cm^2		3 of area (2,5x2,5)cm^2		3 of area (2,5x2,5)cm^2	
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. 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 storage, transport and measuring ambient conditions.
- 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.

Furthermore, the measuring system of different laboratories should fulfil 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, measurement of EQE should be performed if possible, otherwise a spectral mismatch correction using the data from the manufacturer should be applied.

Regarding the measurement protocol itself, 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. Similar approaches were applied by the four binomials in the RR1 on performance measurement. Taking all this information into account, the following measurement protocol has been proposed in the frame of VIPERLAB project:

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First IV Reverse Forward	**Range** Defined by cell maker	**Scan Speed** 50-100 mV/s	**Delay** 20 ms	**Step** Adapt to match scan speed	**Key values** V_{MPP} Note V_{OC} and J_{SC}
Second IV Reverse Forward	**Range** Defined by cell maker	**Scan Speed** 50-100 mV/s	**Delay** 20 ms	**Step** Adapt to match scan speed	**Key values** V_{MPP} Note V_{OC} and J_{SC}
Fixed Voltage measurement	**Voltage** Average V_{MPP} of last IV (fwd –rev)		**Duration** 180 s		**Key values** Current density Efficiency
Last IV Reverse Forward	**Range** Defined by cell maker	**Scan Speed** 50-100 mV/s	**Delay** 20 ms	**Step** Adapt to match scan speed	**Key values** V_{MPP} Note V_{OC} and J_{SC}

The specific values proposed (voltage span, scan speed, delay, or duration of fixed voltage measurement) might be modified in case the manufacturer has performed enough tests to suggest values more adapted to the particular device.

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