Accurate and reliable IV measurements of perovskite tandem devices

BCworkshop2025 - Amsterdam

December 9, 2025

PRESENTED BY

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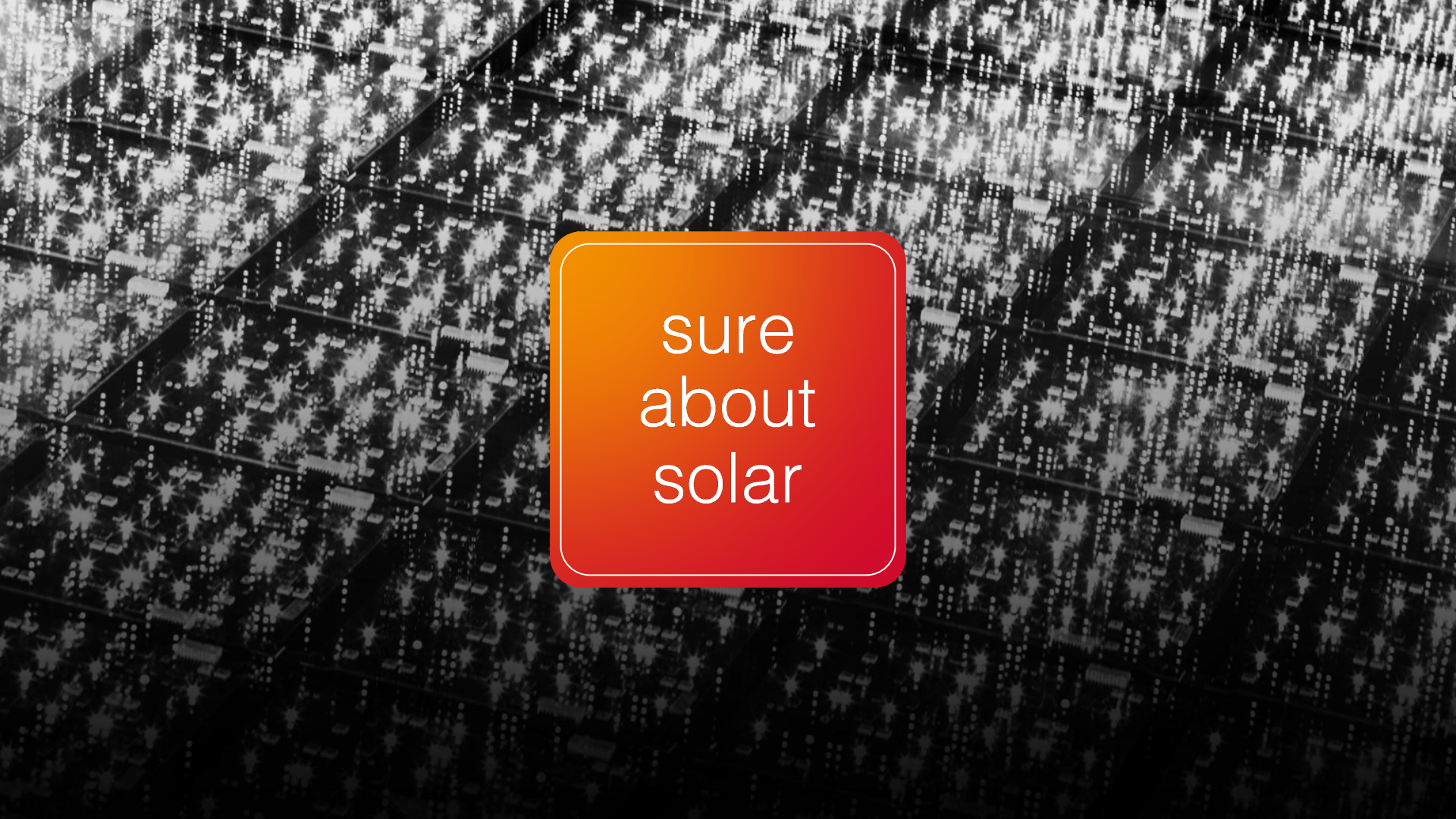

sure
about
solar

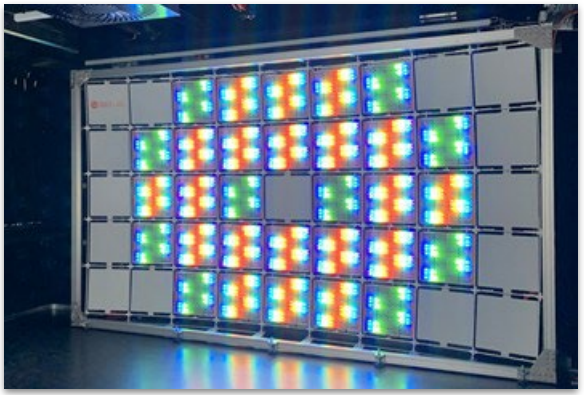
Our evolution

eternal**sun** | WAVELABS

Since 1980s
Inline & lab flashers
Originally Xenon, nowadays also LED

Since 2010s
Steady-state solar simulators
LED technology

Since 2025
Advanced metrology solutions
from R&D cells to commercial modules



From R&D cells to commercial modules

Our products

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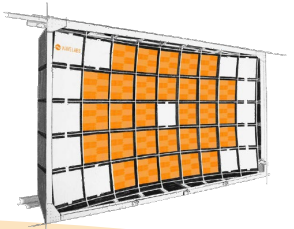


SINUS-3000 ADVANCED

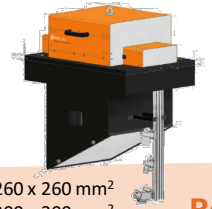
Advanced solutions for performance characterization

SINUS-70 ADVANCED

50 x 50 mm²

SINUS-360/430 ADVANCED

260 x 260 mm²



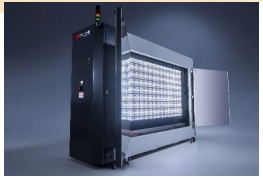
260 x 260 mm²
300 x 300 mm²

SINUS-360 PRO

SINUS-1000 ADVANCED

500 x 500 mm²

LED Light Soaker



Bifacial LED Flasher

Reliable solutions for production

Inline (bifacial) LED Flasher

300 x 300 mm²
450 x 450 mm²
600 x 600 mm²

Mini LLS

Flexible solutions for light soaking

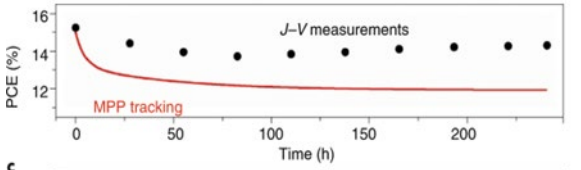
From R&D cells to commercial modules

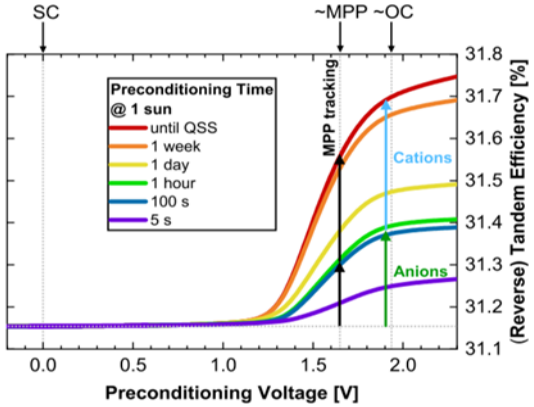
Characterization challenges

for perovskite (tandem) devices

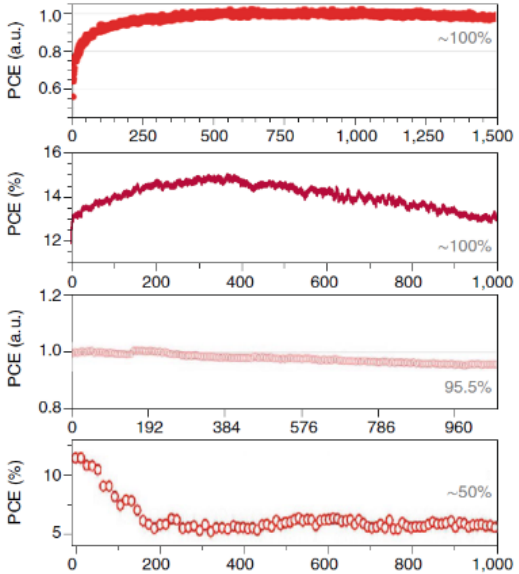
Perovskite PV devices show **metastability**

Stabilization & pre-conditioning dynamics:
device state depend strongly on history of light and bias state





Stabilization & degradation dynamics:
depend strongly on material stack



Source
Khenkin, M.V., Katz, E.A., Abate, A. *et al.*
Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures.
Nat Energy **5**, 35–49 (2020).
https://doi.org/10.1038/s41560-019-0529-5

Source
Christoph Messmer et al.
Toward more reliable measurement procedures of perovskite-silicon tandem solar cells: The role of transient device effects and measurement conditions
Prog Photovoltaic Res Appl. 2024;1-17.
https://doi.org/10.1002/pip.3782

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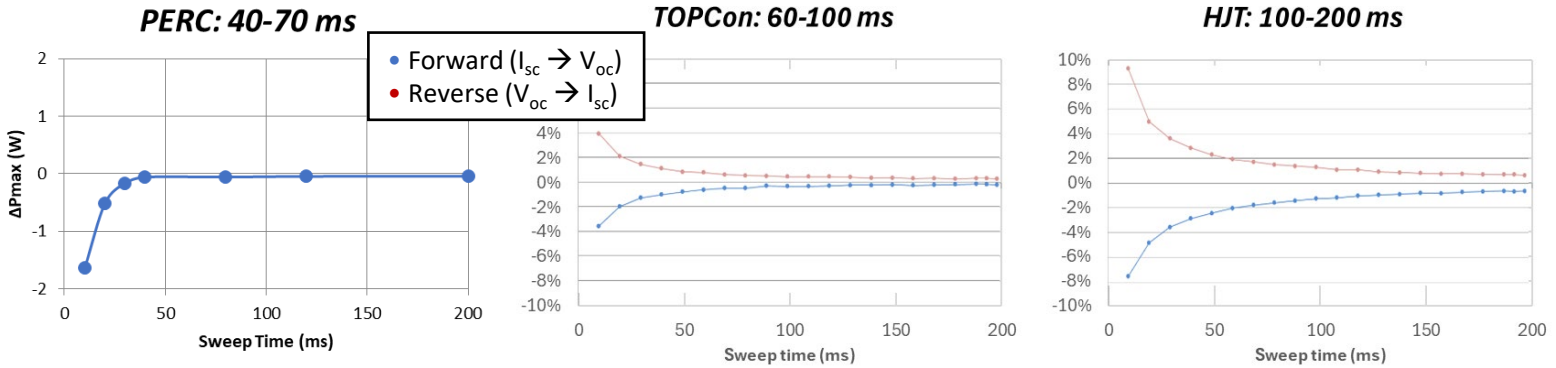
From IV measurements to MPP tracking

High efficiency cell technologies show **hysteresis**

High efficiency

- Passivation layers reduce recombination of carriers → higher V_{oc}
- Higher V_{oc} → increased charge build-up (capacitance) during the IV voltage sweep → lower measured P_{max}

Illustration[1]



Implication

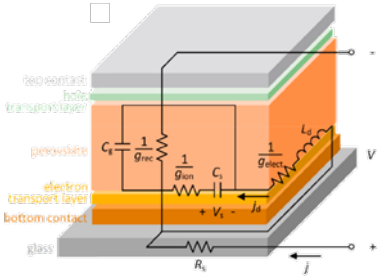
- Flash of 10 ms too short for P_{max} measurement due to higher capacitance
- For every cell V_{oc} increase of 18mV → ~2x increase carrier concentration → doubled sweep time effect [2]

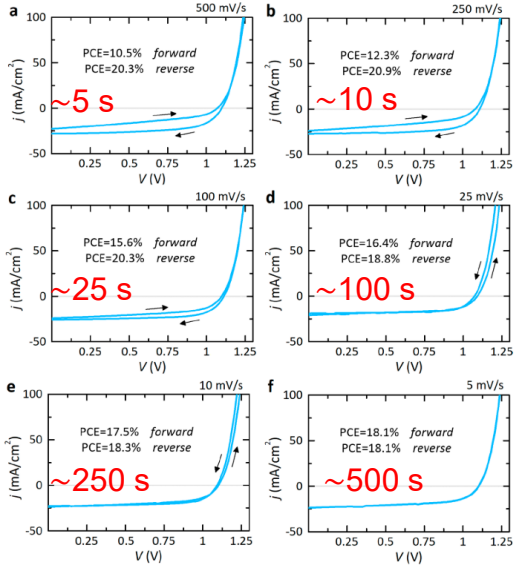
[1] Source: Based on 3500SLP sweep time sequence measurement of PERC module (2016); [2] Source: Smets et al., Solar Energy: the physics and engineering of photovoltaic conversion technologies and systems (2016)

Perovskite PV devices show **hysteresis**

- Hysteresis attributed to set of contributions:
  - Very fast geometric capacitance
  - Fast electronic-driven recombination
  - Slow ionic-driven recombination
  - Very slow interfacial capacitance
- Recommended to evaluate multiple timescales
- For steady-state IV measurements:

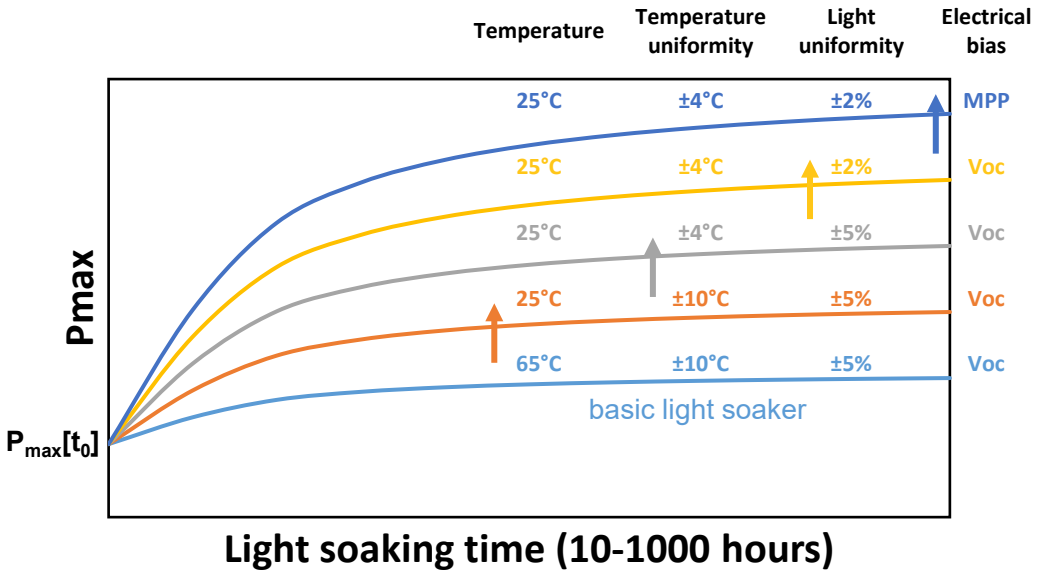
sweep times (~minutes)	>>	production cycle times (~15 seconds)





Source
Enrique H. Balaguera and Juan Bisquert
Accelerating the Assessment of Hysteresis in Perovskite Solar Cells
ACS Energy Letters **2024** *9* (2), 478-486
https://doi.org/10.1021/acsenergylett.3c02779

Measurement conditions influence device state



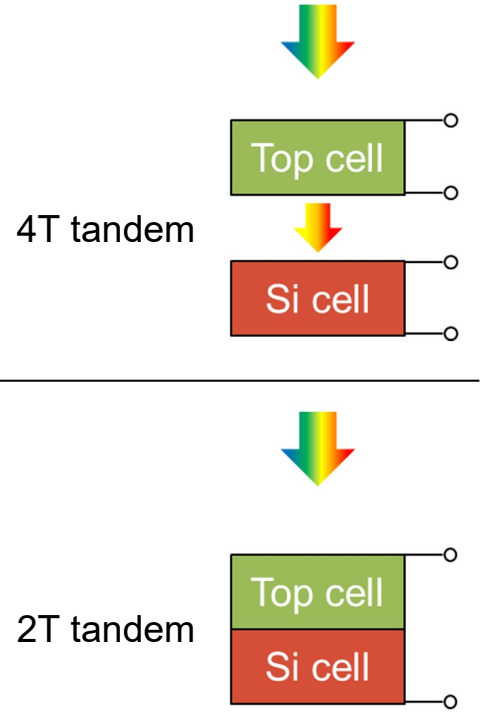
Test conditions are known to have an impact on settled power:

- **Module temperature**
- **Temperature uniformity on DUT**
- **Light uniformity**
- **Bias state** (between measurements)
- **Spectrum**

➢ More data is needed
for perovskite (tandem) PV modules

Tandem modules require additional care

- Four-terminal (4T) tandem modules have cells connected in parallel
  → cells can be measured separately
- Two-terminal (2T) tandem modules have cells connected in series
  → **tandem matching** required (according to IEC 60904-1-1) to prevent current limiting
- Bifacial 2T tandem modules can't be tested from the rear (no light on front cell)
  → testing with **double-sided illumination** required
- Perovskite-silicon tandem modules have cells with different **temperature coefficients**
  → stabilization/measurement at constant temperature (25°C or another agreed temp.)



Standardization of testing

for perovskite (tandem) devices

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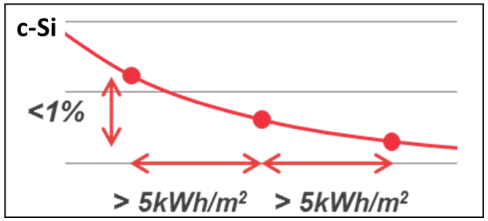
Performance testing of PV modules

Module performance testing:

- IEC 61215 Terrestrial photovoltaic (PV) modules – Design qualification and type approval
  - **Maximum power** determination (MQT 02) @ 20-50°C, 700-1100 W/m2
  - Performance at **STC** (MQT 06.1) @ 25±2°C, 1000±100 W/m2 (STC)
  - **Stabilization** (MQT 19) →



c-Si:	≥2x 5 kWh/m²
CdTe:	≥2x 20 kWh/m²
a-Si:	≥2x 43 kWh/m²
CIGS:	≥2x 10 kWh/m²

Perovskites (tandem) modules
→ IEC 61215-1-5 (tbd)

Has been used for first 2x1 m perovskite module IEC certification for GCL by TÜV Rheinland (October 2024) Source: GCL website

Module I-V characterization:

- IEC 60904 Photovoltaic devices series – Procedures for I-V characterization
- IEC 60891 Photovoltaic devices – Procedures for temperature and irradiance corrections

MPP tracking most common in industry

Stabilizing power by:

1. **MPP tracking** for minutes to hours
   - In continuous illumination
   - Using **Perturb & Observe** (P&O) method

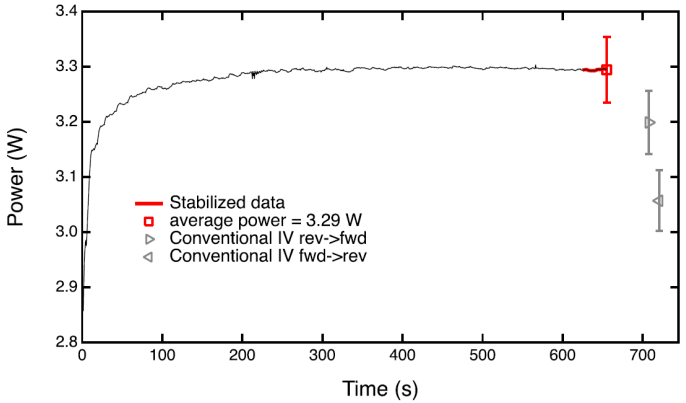
   → Stabilized Power Output (SPO)

Followed by:

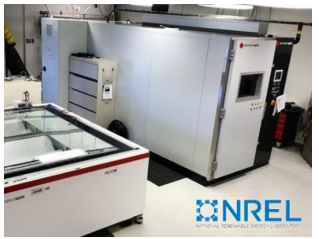
2. **Slow IV sweep** for sec. to min.

   → IV parameters (Isc, Voc, Rs, Rsh)

Mini-module measurement according this protocol by NREL:



→ Eternal Sun HPLS product



Source
Song, Ottoson, Gallon, Friedman and Kopidakis
Reliable Power Rating of Perovskite PV Modules
NREL/CP-5900-80309. 2021
https://www.nrel.gov/docs/fy21osti/80309.pdf

IEC CD 60904-1-4 (in development)

Rules for current-voltage measurements of perovskite-based PV devices

- IEC DTS 60904-1-4 standard for IV testing of perovskite devices in development
  → Committee draft recently completed by “metastable devices” project team in IEC TC82 WG2 (PV modules)
  → Further round robin testing of modules being planned

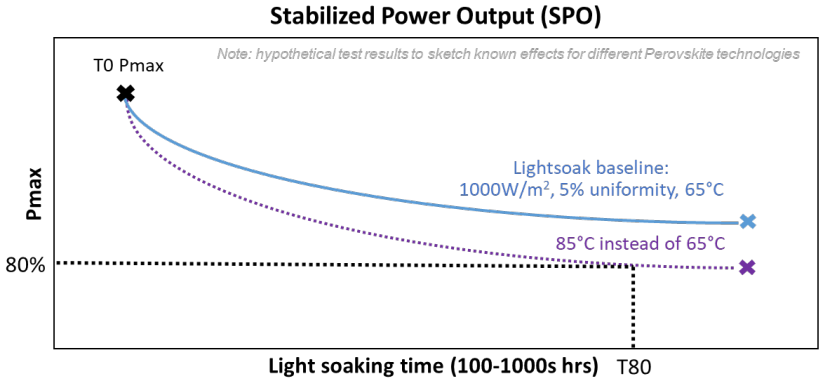
- Definitions in (draft) standard:
  o **Stabilization** (days) to address early life changes → IEC 61215 - MQT 19
  o **Pre-conditioning** (mins-hours) to improve measurement consistency → recommended, around Vmpp
  o **Settling** (mins) to determine settled values → settling criterion < 0.1%/min (or < 0.3%/min) over > 30s assessment window

- Main procedure to determined settled values for type approval:
  1. Measure reverse & forward IV curves
  2. Measure settled maximum power (Pmpp) → **MPP tracking** or (settled / non-settled) IV points around Vmpp
  3. Measure settled open-circuit voltage (Voc)
  4. Measure settled short-circuit current (Isc)
  5. Measure reverse & forward IV curves

Long-term stability testing

Long-term stability

time to 80% at 1 Sun & 85°C



Source
Tune, Kafedjiska, et. al. (66 authors)
Consensus statement regarding reliability testing of perovskite-based tandems
In preparation

For 30-year lifetime

- Average daily irradiance:
  3-7 kWh/m²
  → over 30 years:
  35.000-75.000 kWh/m²
- Acceleration factor ~ **3.5x**
  for 85°C vs 65°C (Ea=0.65eV)
- To demonstrate 30y in field:
  10.000-20.000h at 85°C
  (~1-2 years)

→ further acceleration needed once devices become more stable?

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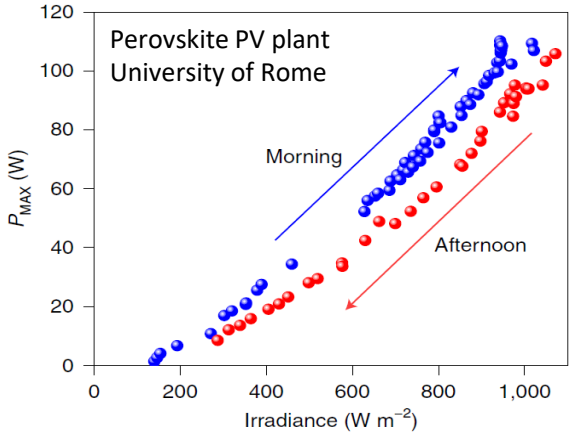
Including **outdoor effects**

Outdoor effects

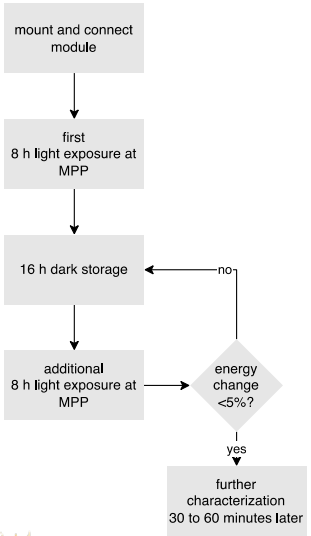
temperature, spectra, light soaking



Source
Pescetelli, S., Agresti, A., Viskadouros, G. et al. **Integration of two-dimensional materials-based perovskite solar panels into a stand-alone solar farm.** Nat Energy 7, 597–60 (2022) https://doi.org/10.1038/s41560-022-01035-4

Preconditioning

light-dark (day-night) cycles



PACT Perovskite PV Accelerator for Commercializing Technologies

Characterization solutions

for perovskite (tandem) devices

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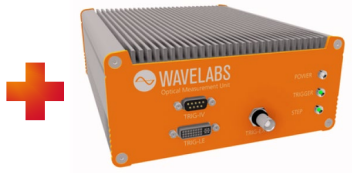
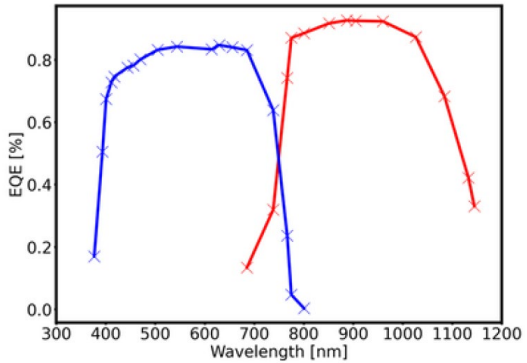
Solutions for perovskite PV testing

Reliable **tandem measurements**



Tandem EQE measurement

within 500ms

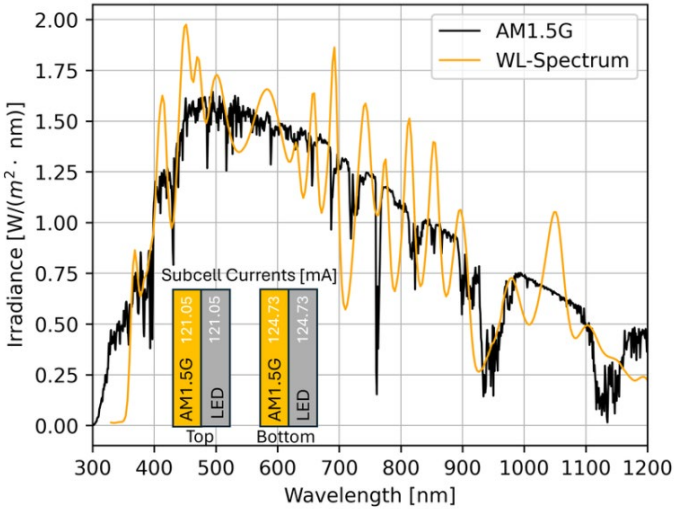


High accuracy Isc:
<0.3% mean deviation
vs monochromator reference

Fraunhofer ISE reference study:
Martin Schubert, 2CO.1.1, EU PVSEC 2025

Spectral balancing → Tandem autocalibration

IEC 60904-1-1 spectral mismatch correction

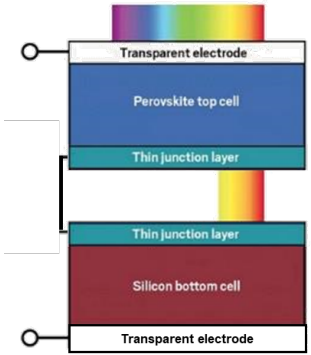


Matching Z-factor:
better than 1±0.005

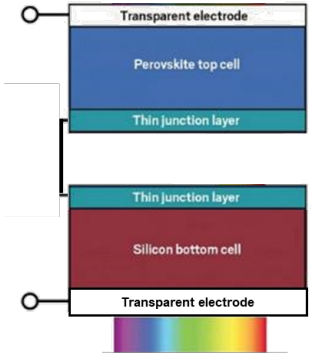
Measurement of **bifacial 2T tandem** modules

Testing bifacial 2T tandem modules requires double-sided illumination
→ with rear-side illumination only the bottom cell blocks the light
→ note: rear-side intensity will determine which junction is limiting

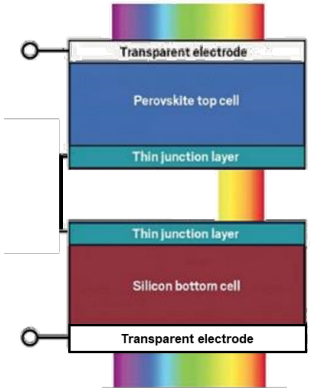
Front-side test:
Current match

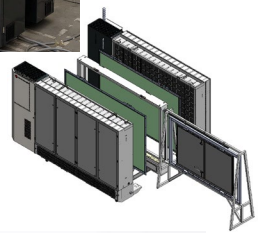


Rear-side test:
No current (match)

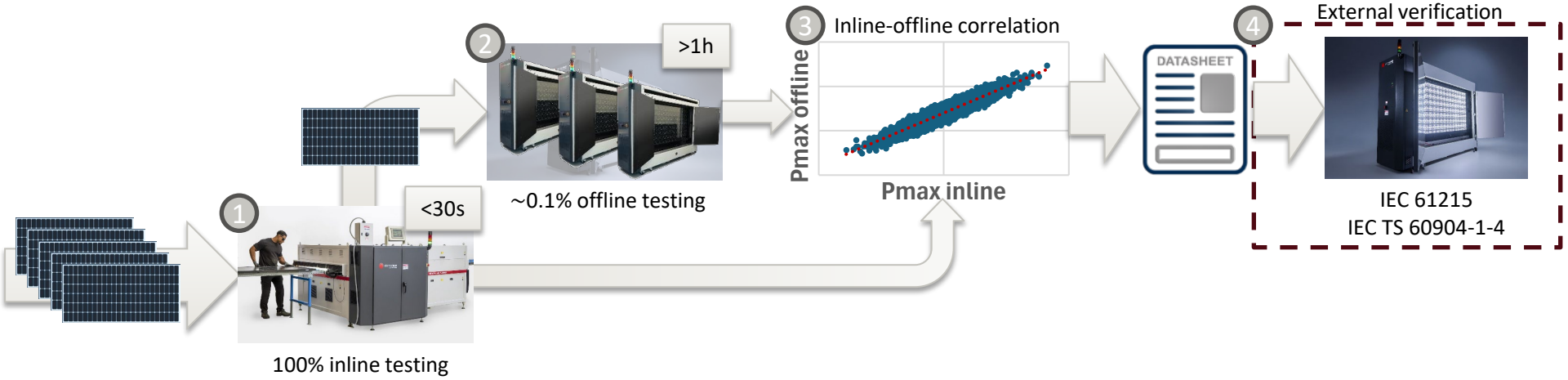


Double-sided test:
Bifacial current match





Method for **inline performance testing**



1)	100% inline testing within production cycle time (<30s)	→ initial power & quality control
2)	Offline stabilized testing (>1h) of production sample	→ stabilized power (& reliability testing)
3)	Correlation of inline and offline production data	→ nameplate power, uncertainty, binning
4)	External verification/certification of nameplate rating	→ product certification

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Statistical optimization needed for optimal test accuracy

Accurate and reliable IV measurements

of perovskite (tandem) devices

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Accurate and reliable IV measurements of perovskite tandem devices

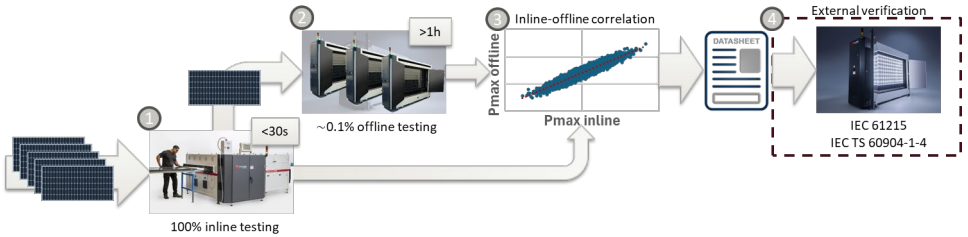
Perovskite-silicon tandem modules are progressing towards GW production and first commercial projects!
→ Inline cell & module characterization solutions needed for effective upscaling and commercialization

Challenges

- **Metastability** and **hysteresis** of perovskite (tandem) devices must be addressed
- **Tandem devices** require additional care
  → tandem matching for 2T tandems
  → double-sized illumination for bifacial 2T tandems
  → different temperature coefficients tandems
- **Measurements conditions** known to have impact on device state and (therefore) stabilized power

Solutions

- Standardization of methods for **stabilized power & stability**
  → IEC 60904-1-4 & more standards in development
- **Tandem autocalibration** method for spectral balancing
- **Double-sided test solutions** for bifacial 2T tandem modules
- Combination of **100% inline** with **offline sample testing**



Both our Leipzig and The Hague teams are ready to serve and support you!

Thank You!

Questions?

Ready for what's next?
Let's talk!

Name: Peter Pasmans
Business Developer Perovskites
Member of IEC TC82 WG2
Email: ppasmans@eternalsun.com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