Solar simulators
for high-efficiency and new PV technologies

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BCworkshop

December 4, 2024

Delft, The Netherlands

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sure about solar

Eternal Sun: sure about solar

Flashers:
IV characterization

LED & Xenon In-line flashers

Reliable workhorse of module manufacturers

BiFi and PVSK versions

Temperature Controlled Lab flashers

Accurate temperature coefficients and energy rating

Since 1980

Steady-State simulators:
stabilized power determination

Steady-State Simulator

R&D and certification labs

Climate chamber Simulator

Advanced reliability studies

Since 2010

A+ class LED Simulator

Power stability testing

Steady-state and pulsed

LeTID/LID tests

Company overview

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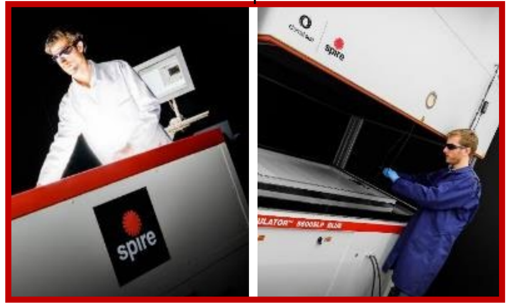
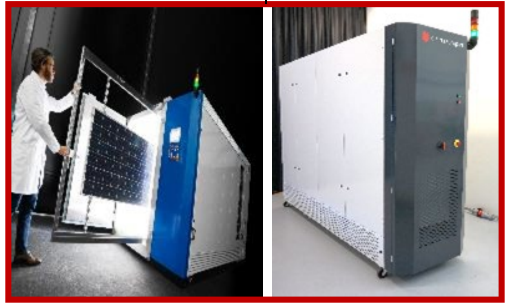
Assure the world of solar performance. Sure about Solar.

A — PV Testing Equipment



Flash Sun Simulators



Degradation lightsoakers

Tier 1 manufacturers
Certification labs
R&D Institutes

B — Quality Inspection Services

Import test labs QA

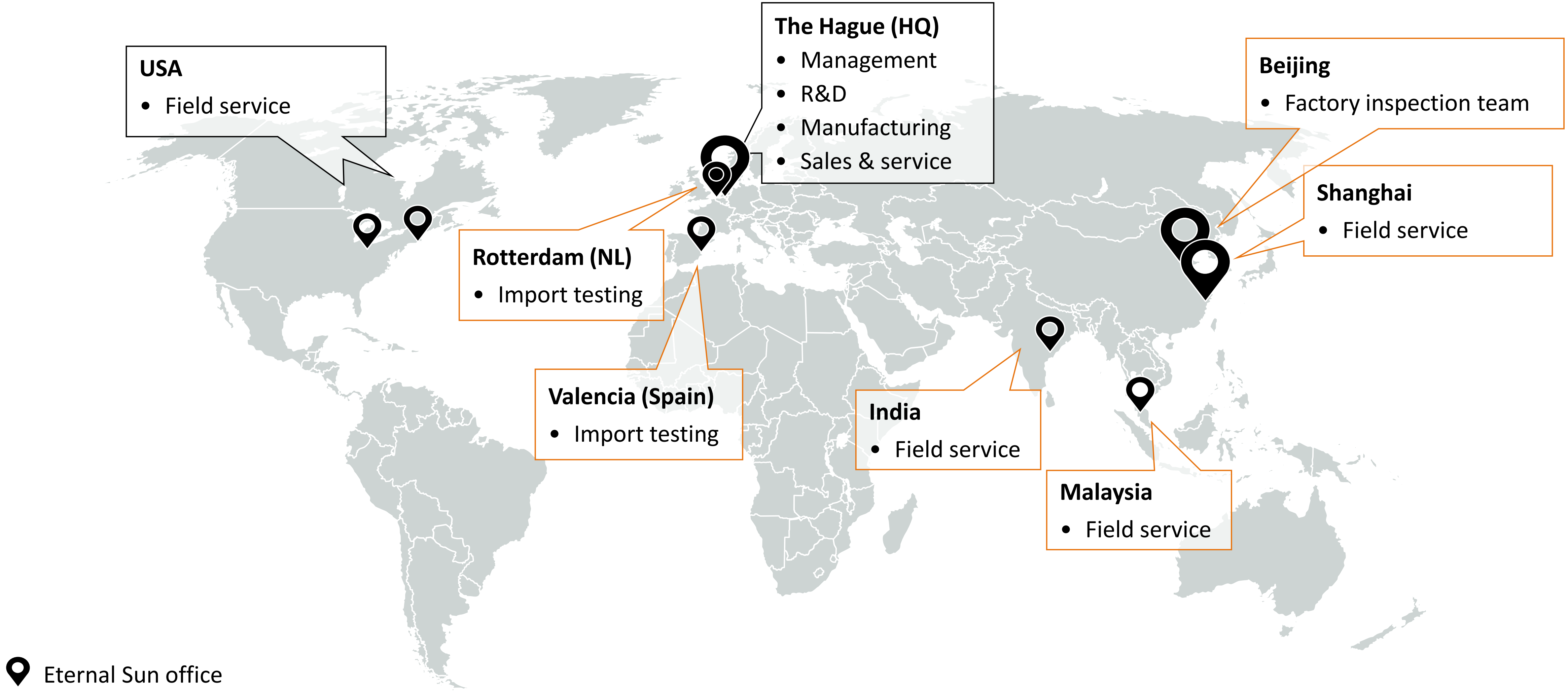
Factory inspection QA

Harbors of Rotterdam & Valencia

Engineering teams in Beijing, Shanghai

EPCs and PV plant owners Europe

Offices near our main customers



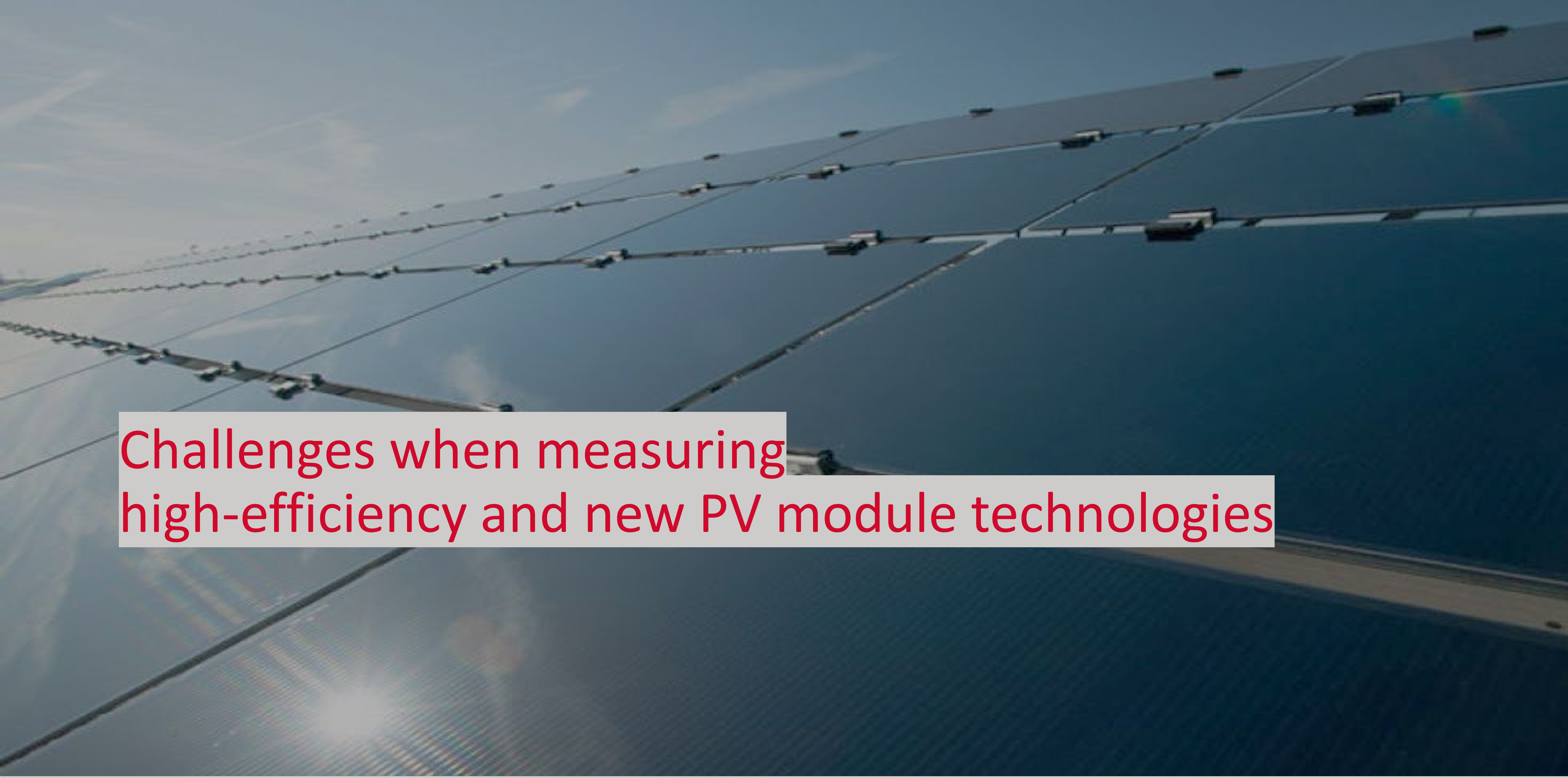
Scaling up from cell R&D to full module production

> 100
shipped

From Full cell / Mini-module RND

Scaling up device sizes and test volumes

To module production!



Challenges when measuring high-efficiency and new PV module technologies

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Solar simulators for high-efficiency and new PV technologies

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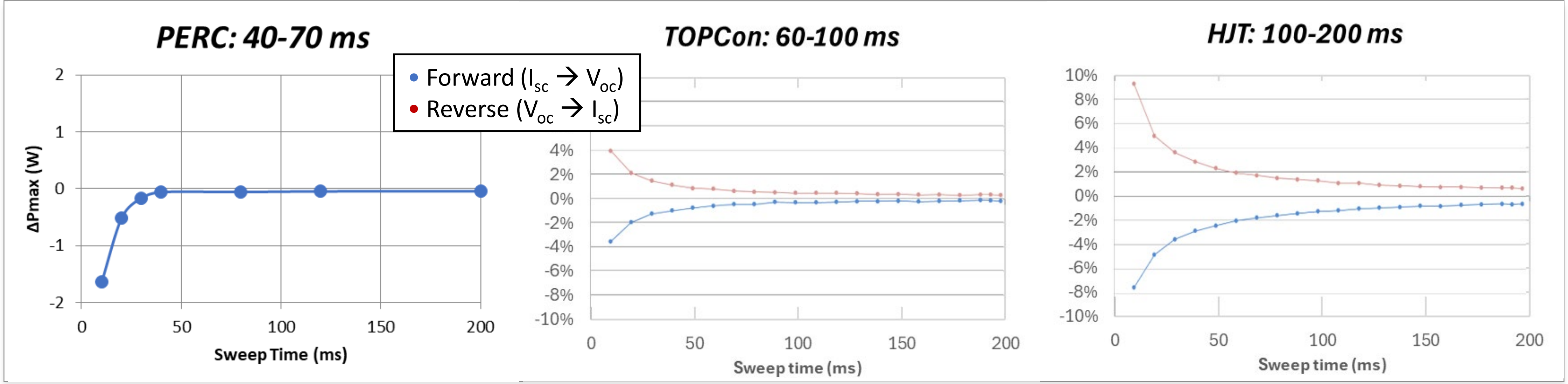
High efficiency cell technologies show increased charge built up (capacitance) during fast IV sweeps → also observed with back-contact PV modules

High efficiency modules effect

- *Layers such as passivation (PERC) reduce recombination of carriers → higher V_{oc}*
- *Higher V_{oc} → increased charge build-up (capacitance) during the IV voltage sweep → lower P_{max} measurement*

Illustration[1]



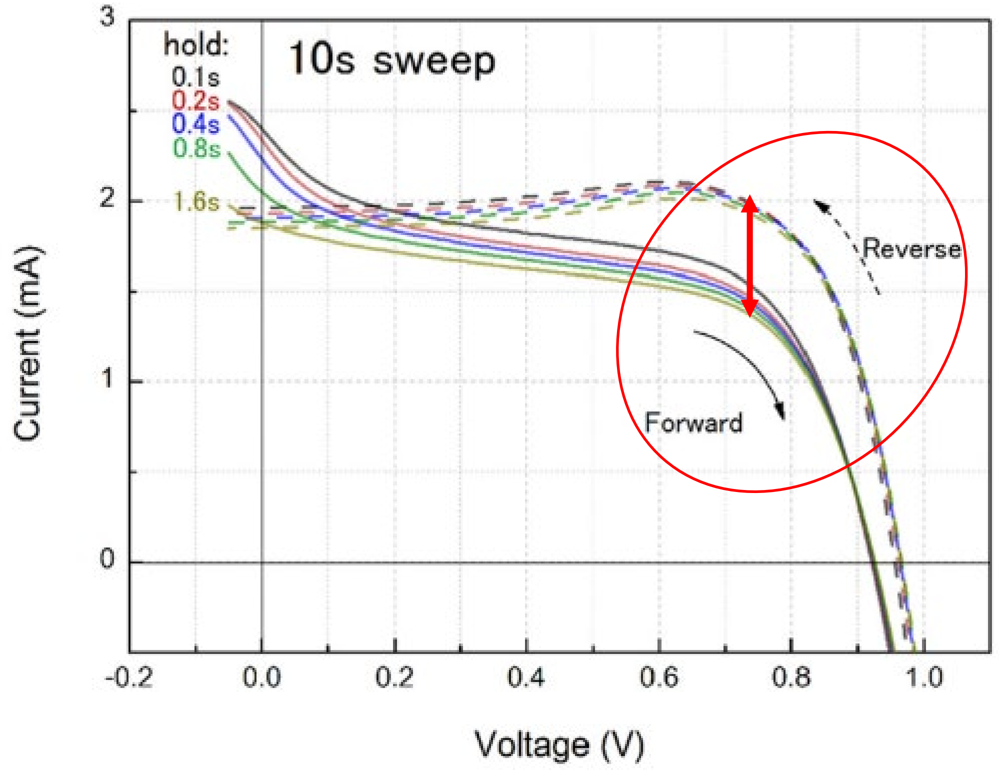
Implication

- *Commonly applied 10ms pulse too short for P_{max} measurement due to higher (junction and diffusion[2]) capacitance*
- *For every cell V_{oc} increase of 18mV → ~2x increase carrier concentration → doubled sweep time effect [3]*

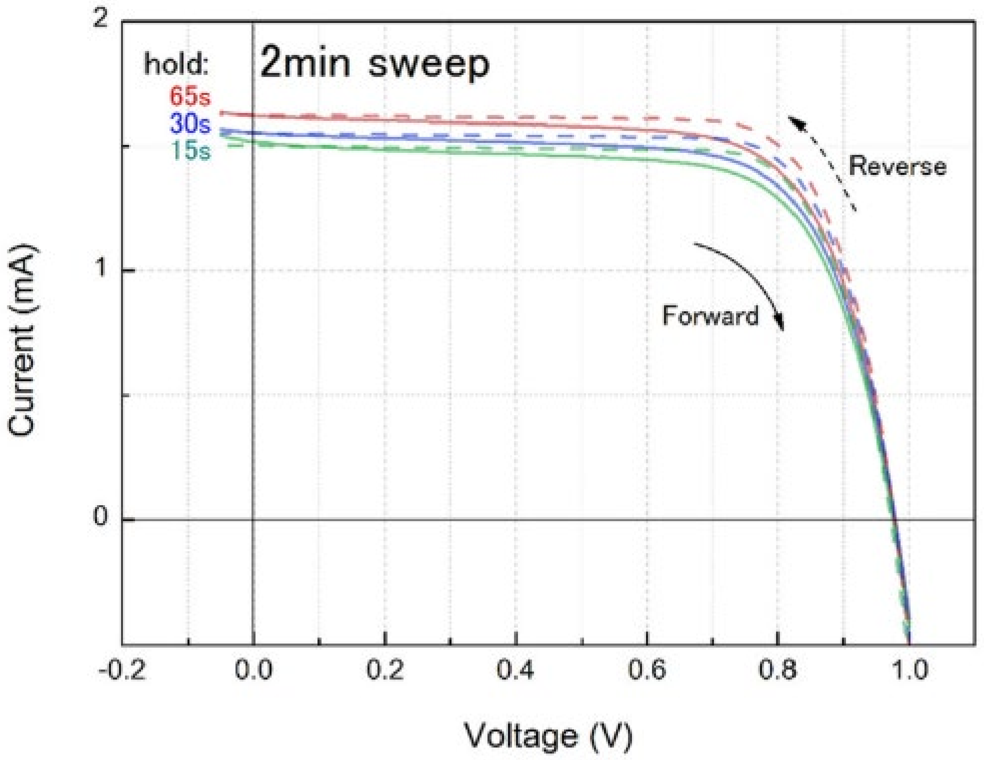
[1] Based on 3500SLP sweep time sequence measurement of PERC module (2016); [2] Source: Herman et al. Optimal I-V Curve Scan Time of Solar Cells and Modules in Light of Irradiance Level; [3] Source: Smets et al., Solar Energy (2016)

Strong hysteresis in perovskite PV: sweep times > production cycle times

10 seconds: large hysteresis



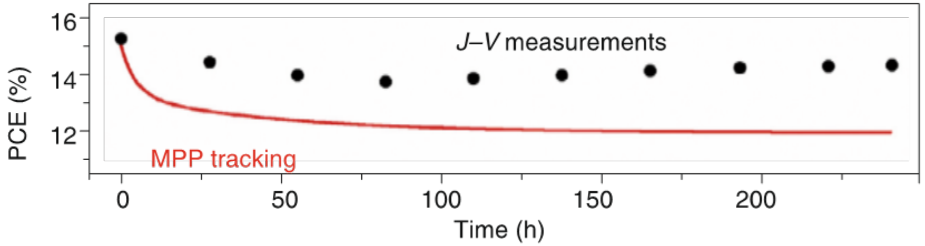
2 minutes: curves overlap



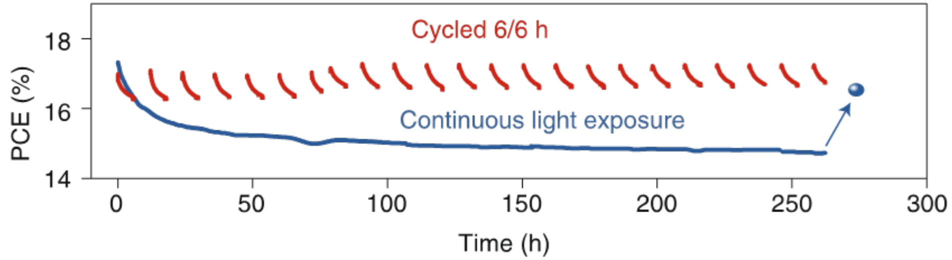
[4] Hishikawa et al. (AIST) / Current Applied Physics 16 (2016) 894 - 904

Perovskite PV devices show metastability under illumination

Impact of MPP tracking during light soak

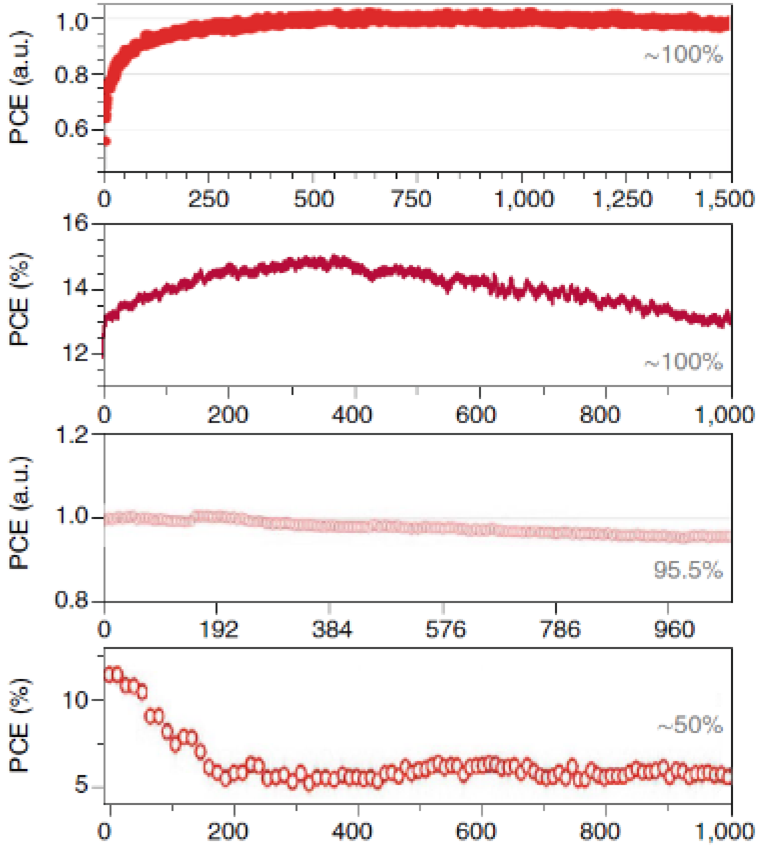


Impact of light cycles vs continuous light soak



[5] 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)

Stabilization & degradation depend strongly on material stack



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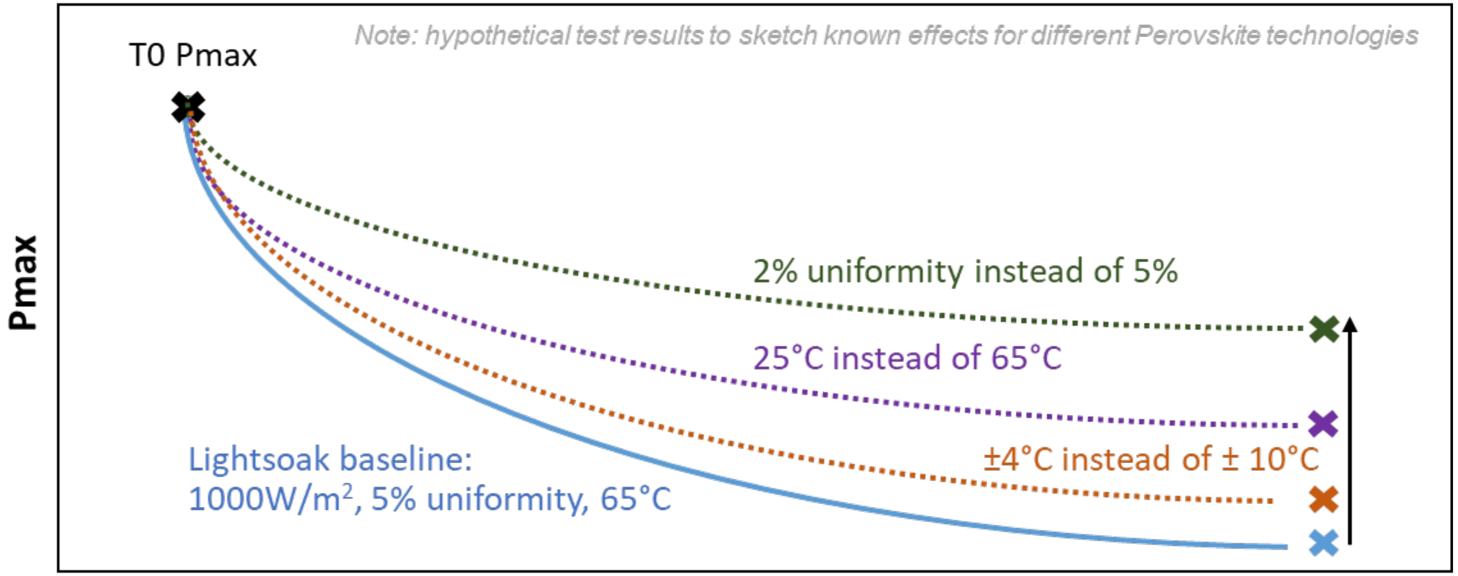
Test conditions influence stabilized Pmax values after 100-1000 hours

- **ISOS** long term stabilization protocols [3] **at different temperatures 25, 65 & 85°C**
- When scaling up to modules, **IEC PVQAT TG8** emphasizes impact of [4]
  1. **Light uniformity**
  2. **Temperature uniformity on DUT**

Stabilized Power Output (SPO)



Light soaking time (100-1000s hrs)

[6] Khenkin, Katz, Abate, A. et al. Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures, Nat Energy 5, 35–49 (2020)
[7] IEC PVQAT TG 8

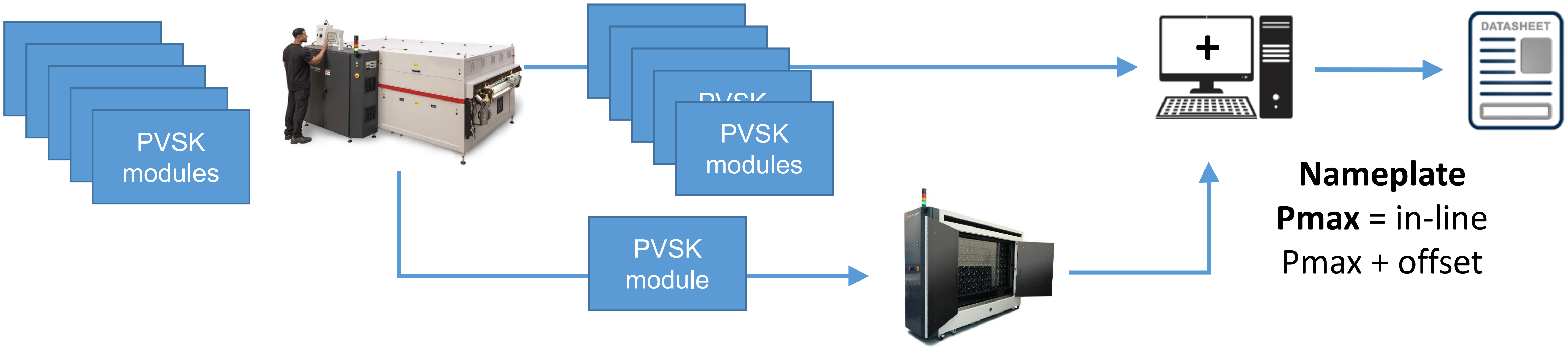
New IEC 60904-1-4: "Metastable devices" IV characterization norm

- New IEC 60904-1-4 standard in development:
  "Guidelines for current-voltage measurements of perovskite-based PV modules"
  - IEC TC82 (Solar PV) WG2 (modules) project team has started
  - Focus on performing power ratings at STC

- Find consensus on pre-conditioning:
  - Allowed exposure history of modules defined in draft standard
  - Temperature dependency of metastability → stabilize module at 25°C (STC)?
  - Stabilized Power Output (SPO) should not include degradation (type approval)

Inline test methods for manufacturing of perovskite PV modules

- Inline testing doesn't allow minute long sweeps or MPP tracking (typical 15 sec cycle time)
- The industry is still developing these short cycle time test methods (no convergence to one solution yet), Eternal Sun is working with its customers on methods for different material stacks
- In similar style to current **IEC 61215 for thin film technologies**, a combination of 100% inline testing with **offline (lab) stabilization sample testing** to determine a **controlled offset** will probably be the outcome



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Tandem characterization procedures have additional challenges

1. Tandem matched spectrum (recap)

For current matched or two terminal tandems:
junctions are series connected so they run at the same current

➔One of two junctions can limit the current of the other, negatively impacting Pmax

➔Tandem matching is required:
calibrating the light source spectrum for the two junctions separately

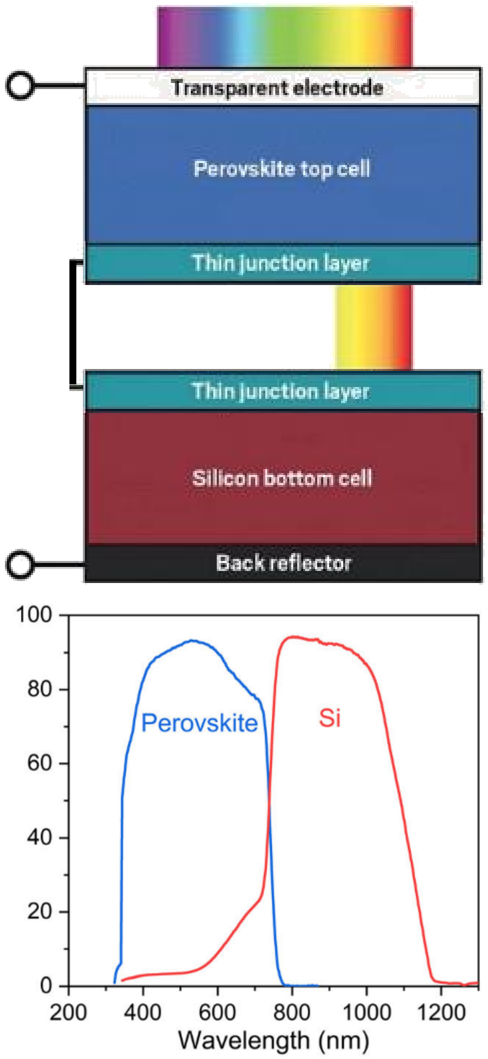
This is standardized in IEC 60904-1-1 Multi junction (tandem) devices

Four terminal tandems can be calibrated and measured separately

2. Temperature coefficients

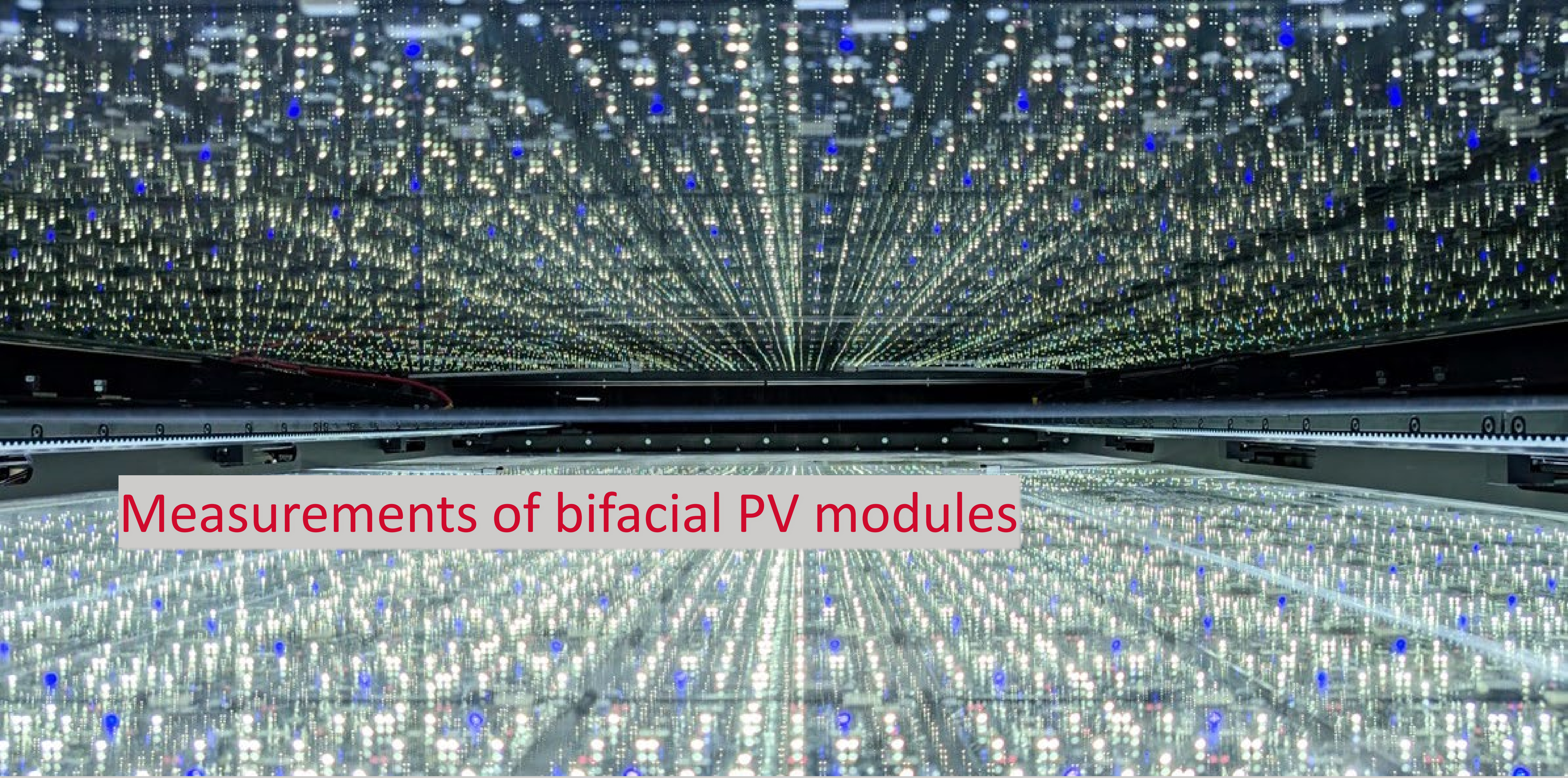
Because of different temperature coefficients for the C-Si & PVSK junctions

Pmax stabilization can also be done at 25°C STC



[8] Source: Song et al. How Should Researchers Measure Perovskite-Based Monolithic Multijunction Solar Cells' Performance? A Calibration Lab's Perspective (2022)

Measurements of bifacial PV modules

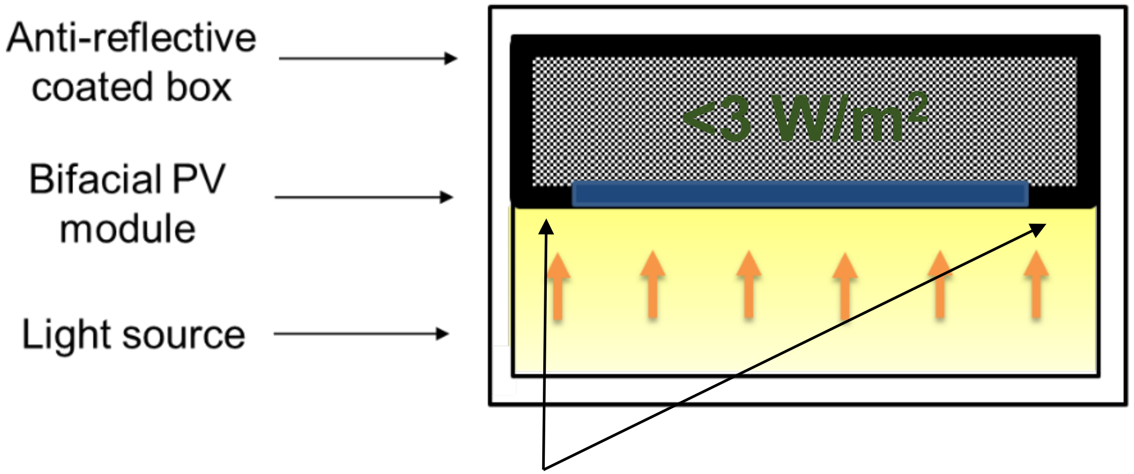


Measurements of Bifacial Modules: Flip method

"Do I need a double-sided flasher to measure bifacial modules?" → Not necessarily!

Single side method

(Flip the module to test front and rear side)



Close the gaps!

IEC 60904-1-2

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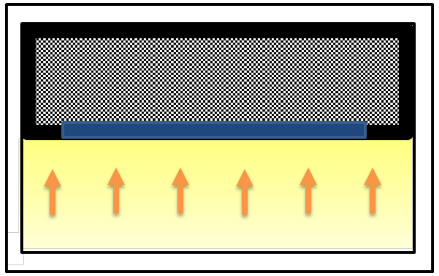
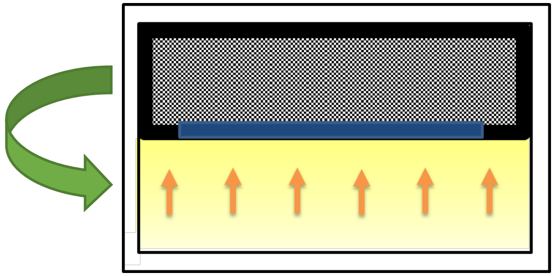
How to make a reference bifacial PV module using the flip method?

Step 1. Flash the front side at 1000 W/m2



Example = 300 W

Step 2. Flash the rear side at 1000 W/m2



Example = 240 W

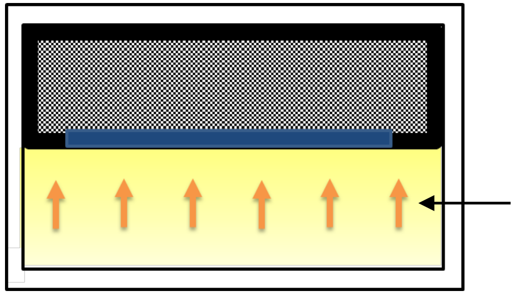
Step 3. Calculate φ by dividing Pmax rear/Pmax front

φ [-]
Example 240W/300W = 0.80

Step 4. Calculate three equivalent irradiances with the formula: $G_E = G_F + \varphi_{Pmax,STC} * G_R$

Standard conditions			
Bifacility φ [-]	Front side irradiance G_F [W/m²]	Rear side irradianceG_R [W/m²]	Equivalent irradiance G_E [W/m²]
0.80	1000	0	1000
0.80	1000	135 (BNPI)	1108
0.80	1000	300 (BSI)	1240

Step 5. Measure the bifacial module at the three equivalent irradiances

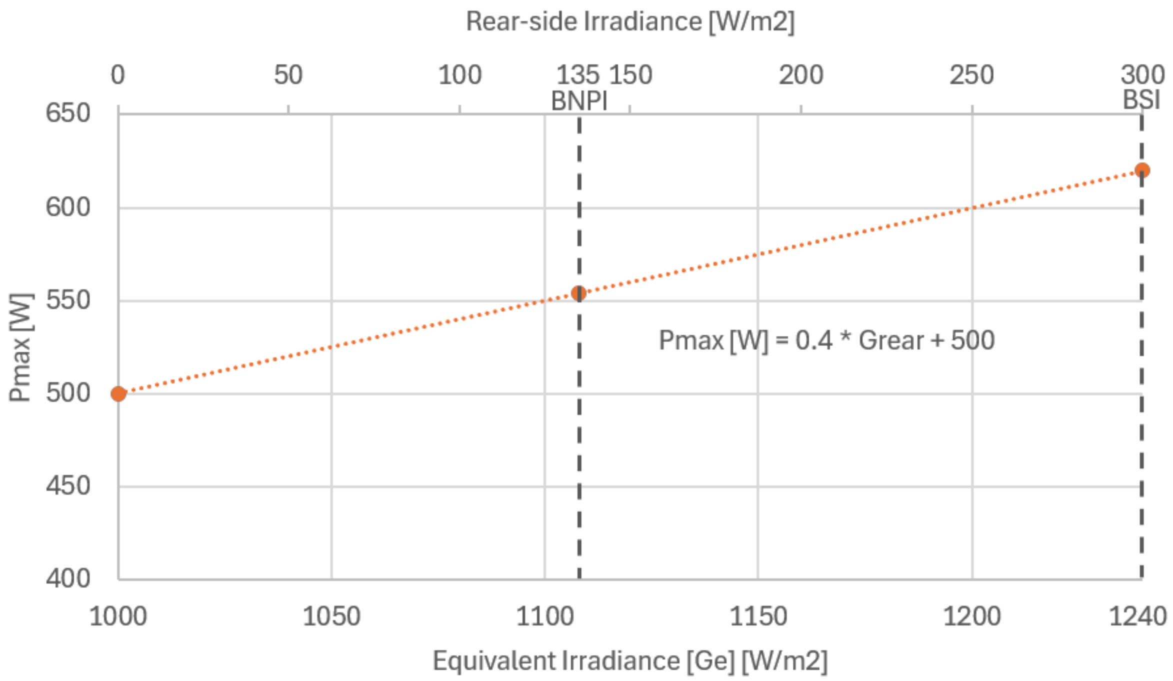


G_E Equivalent irradiance

Why equivalent irradiance on the front: module is running the same currents as in bifacial mode, which affects Rseries

How to make a reference bifacial PV module? → Determine the BiFi slope

Step 6. Plot everything



Step 7. Calculate the BiFi slope (see graph)

Step 8. Report everything → Bi-facial reference module measurement complete

φ [-]	G_R [W/m²]	G_E [W/m²]	P_{max} [W]	$Bifi,ref$ [W/(Wm⁻²)]	$Pmax,bifi,$ *DUT* [W]
80%	0	1000	500	0.4	500
	135	1108	-		554 (BNPI)
	300	1240	-		620 (BSI)

How to measure bifacial PV modules in a production line?

1. **Calibrate** the simulator to the reference bifacial PV module **of the same type** at 1000 W/m2 front side, no need to cover rear side -> because if both reference are in-line and not covered, rear irradiance effect cancels out
2. **Measure** in-line bifacial PV module with 1000 W/m2 front side (no need to cover rear side if rear irradiance condition is the same, it cancels out). Extrapolate BSI and BNPI power ratings with the Bifi slope from the reference module or batch sample tests

Sampling from production batches:

1. **Measure** in-line bifacial PV module with 1000 W/m2 front side and with the equivalent irradiances (Ge) of 1000 + 135 W/m2 (BNPI) and 1000 + 300 W/m2 (BSI) on the front side (no need to cover rear side if rear irradiance conditions is the same, it cancels out).
2. **Update the Bifi Slope and extrapolated BSI and BNPI power ratings** of the modules produced afterwards

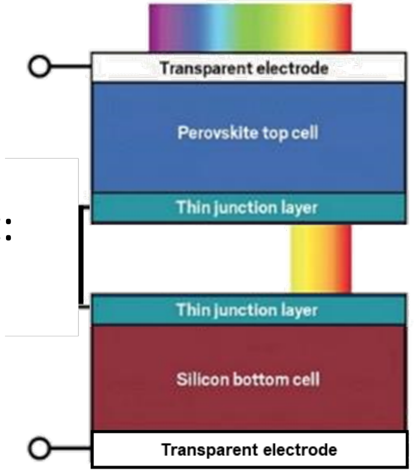
φ [-]	G_R [W/m²]	G_E [W/m²]	P_{max} [W]	$Bifi,ref$ [W/(Wm⁻²)]	$Pmax,bifi,DUT$ [W]
80%	0	1000	505	0.39	500
	135	1108	-		559 (BNPI)
	300	1240	-		623 (BSI)

Measurements of Bifacial Modules: Double-sided method

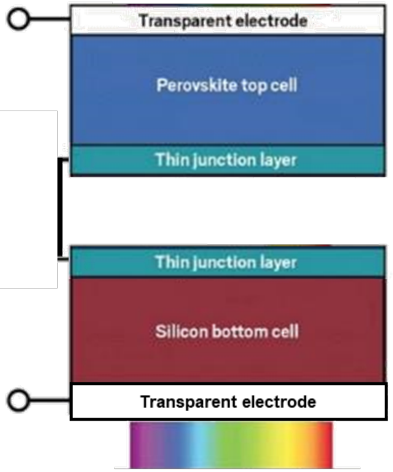
“For asymmetric designs and (2T) bifacial tandem modules”

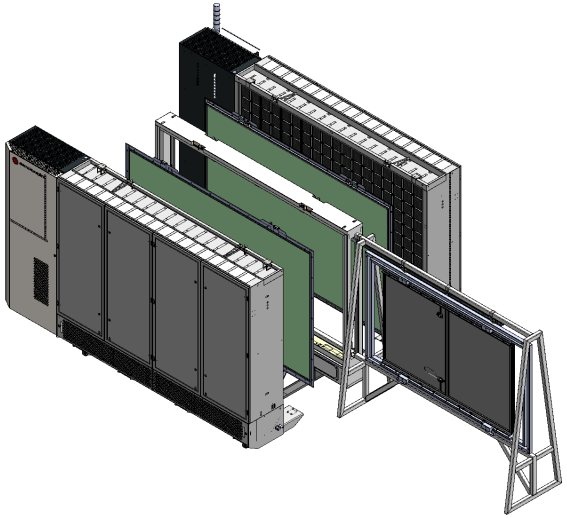
- “Voc-penalty” for modules with asymmetric design with flip method, double-sided yields slightly higher and more realistic BNPI/BSI ratings
- Testing bifacial (2T) tandem modules requires double-sided illumination, since with rear-side illumination the bottom cell blocks the light

Front-side test:
Current match



Rear-side test:
No current match





How to measure (tandem) bifacial PV modules in a production line?

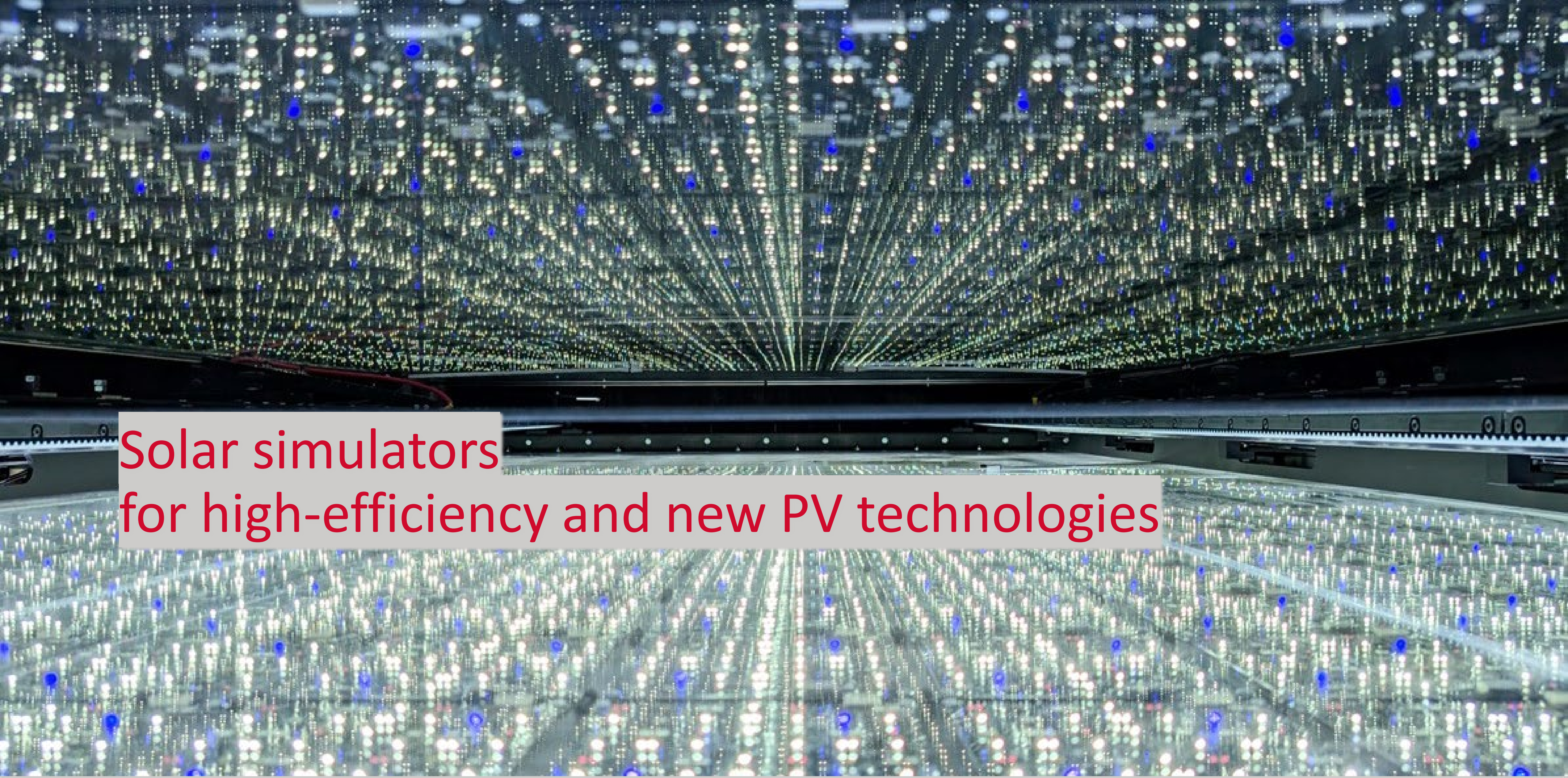
Shown in picture: 6200 double sided LED flasher, optional with automation (conveyors and auto probing) for in-line application

Example of typical test recipe			
Step	Front side irradiance G_F [W/m^2]	Rear side irradiance G_R [W/m^2]	Goal
1	1000	0	Nominal Pmax
2	0	1000	Bifaciality
3	1000	135	BNPI: Bifacial Name Plate Irradiance Pmax
4	1000	300	BSI: Bifacial Stress Irradiance Pmax

IEC 60904-1-2

Double vs single sided method

Double-sided method	Single-sided method
+ Higher throughput for bifaciality/BNPI/BSI	- Requires flipping of modules
+ Slightly higher and more realistic BNPI/BSI ratings	- “Voc-penalty” for modules with asymmetric design
+ Possible to measure bifacial (2T) tandem modules	- Bifacial 2T tandem modules can’t be measured
- Additional cost of second light source	+ Single solar simulator
- Module loading between two light sources	+ More standard temperature chamber



Solar simulators for high-efficiency and new PV technologies

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Solar simulators for high-efficiency and new PV technologies

- **High-efficiency PV technologies** show increased charge built up (capacitance) during fast IV sweeps
  → requires solar simulator with **long pulse** or **steady-state** capability

- **Perovskite solar modules** show metastability and require sweep times > production cycle times
  → standardized characterization methods mainly based on **MPP tracking** in development
  → inline characterization can be performed using a **controlled offset** from offline characterization

- Characterization of **bifacial modules** with asymmetric design or bifacial 2T tandem modules
  → **double-side method** provides **higher accuracy** for BNPI and BSI
  → characterize of **bifacial 2T tandem modules** requires double-sided method

Thank you for your attention! Questions?

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