

Resilienz und Perspektiven der Photovoltaik in Deutschland und Europa

1. Wissenserhalt und Innovation in Kooperation mit Anlagenbauern und Materialherstellern

2. Perspektiven und Kostenstruktur in Europa

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Fraunhofer-Institut für Solare Energiesysteme (ISE)

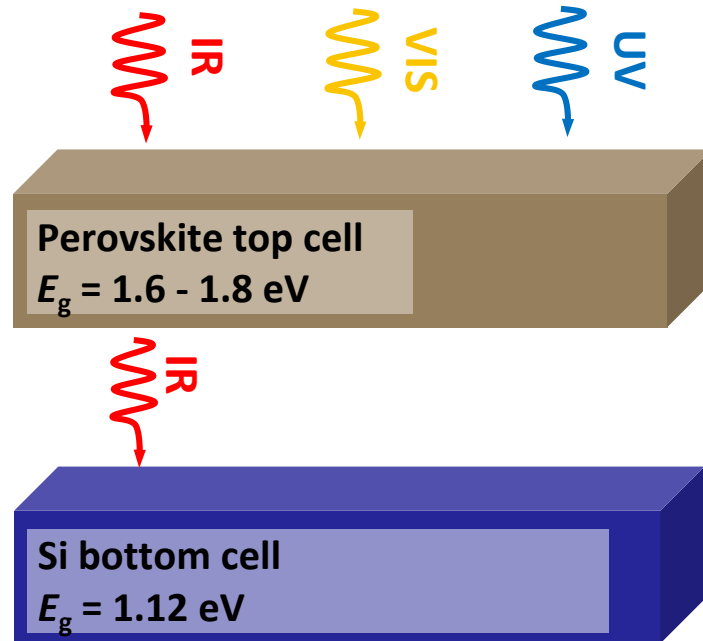
Ulrich W. Paetzold

Karlsruher Institut für Technologie (KIT)

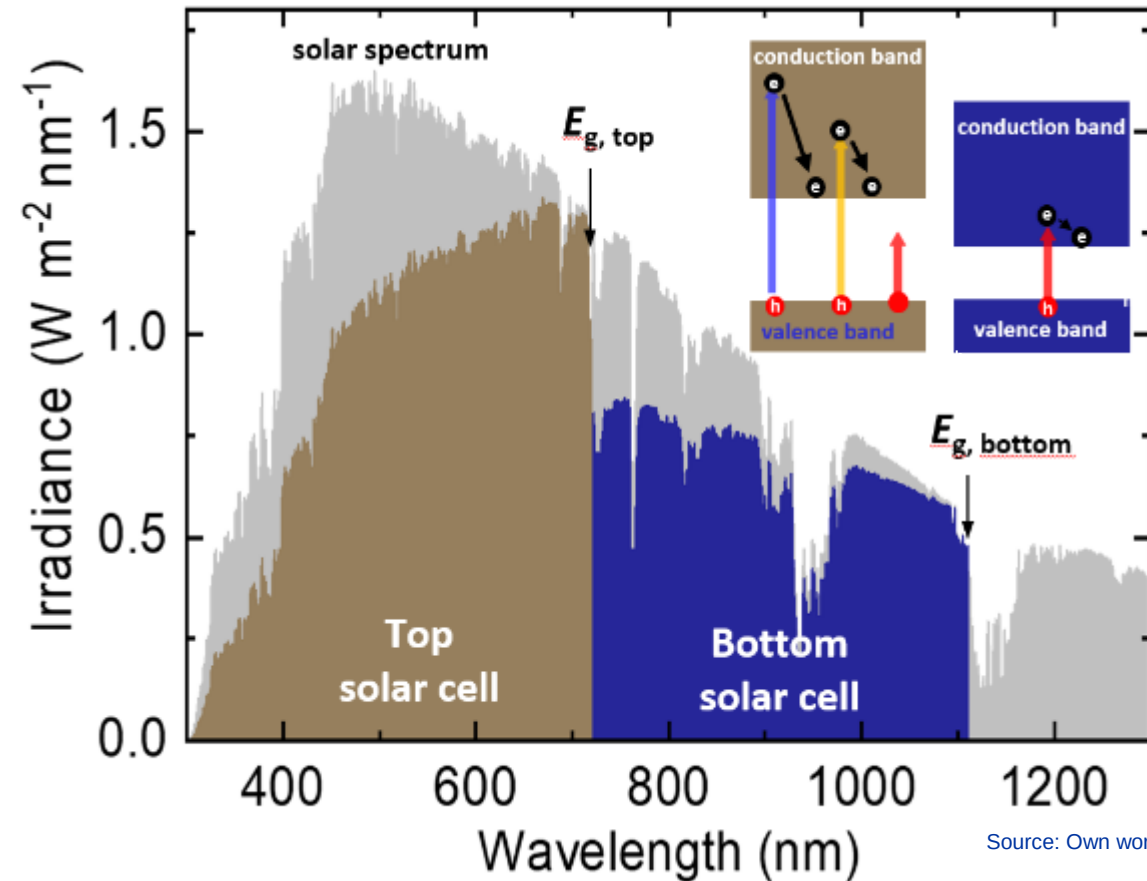


Image generated with help from AI.

Exemplary: High Efficiency Perovskite/Silicon Tandem PV



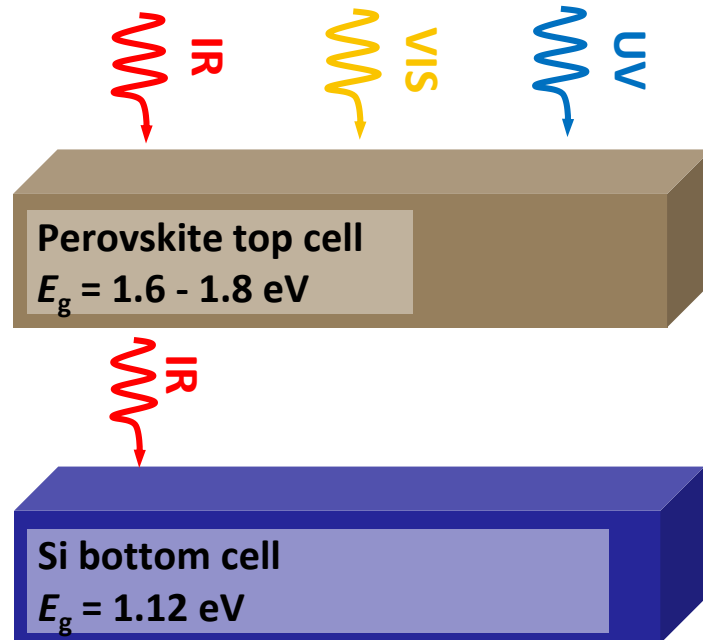
Source: Own work.



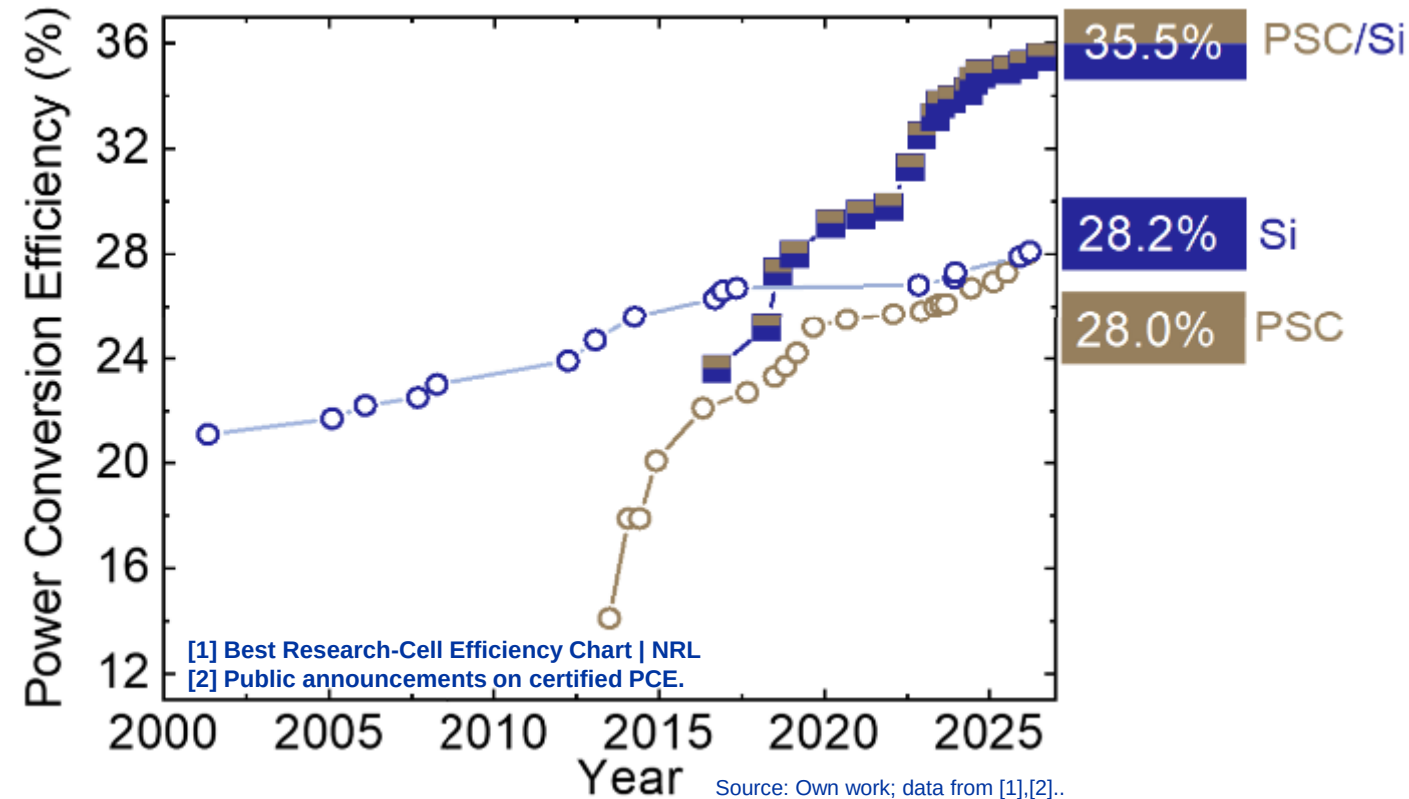
Source: Own work.

Tandem PV reduces intrinsic thermalization losses, thereby enabling much higher power conversion efficiencies (thermodynamic limit > 40%).

Exemplary: High Efficiency Perovskite/Silicon Tandem PV



Source: Own work.



Tandem PV reduces intrinsic thermalization losses, thereby enabling much higher power conversion efficiencies (thermodynamic limit > 40%).

Perovskite/Si and other Tandem PV on the rise ...



**Series A Financing of Tandem
Startup companies
Q1/Q2 2024**



Source: <https://tiny-url.tech/LkEzOE>.

**World record 34.6% for
perovskite/Si solar cell
LONGi, SNEC, June 2024**



Source: <https://shorturl.at/i346T>.

**World record 34.85% for
perovskite/Si solar cell
LONGi, April 2025**



Source: <https://shorturl.at/RV03D>.

**Swift Solar secures Meyer
Burger technology for
perovskite tandem cells**

2025

2026



Source: <https://tiny-url.tech/CAkJIT>.

**30.1% Perovskite/Si solar
cell on M6 wafer
LONGi, Intersolar, June**



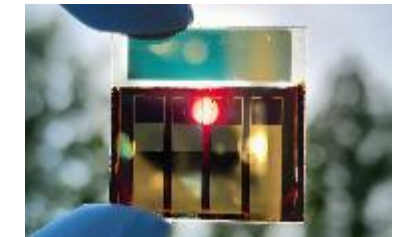
Source: <https://tiny-url.tech/UKsYLc>.

**First Perovskite/Si solar modules
on market (24.5%) Oxford
Photovoltaics, 09/2024**



Source: <https://shorturl.at/QwJmi>.

**Trina shows 800+W
module, May 2025**

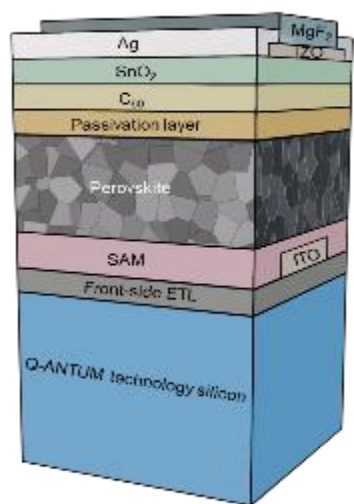


Source: <https://shorturl.at/tRLrJ>.

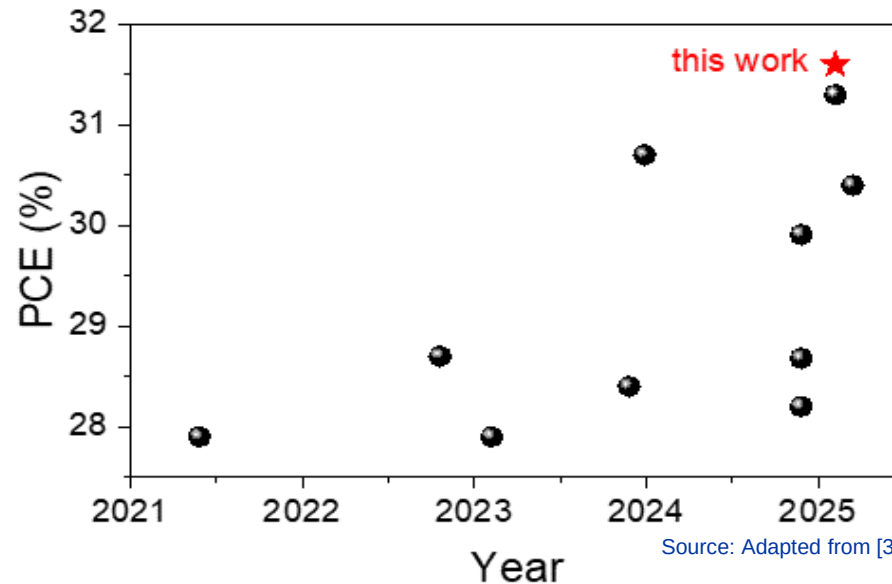
**World Record CIGS/Pero
Tandem 26,7 % by Korean
Institute KIER, Sep 2026**

Perovskite/Si Tandem PV Research @KIT

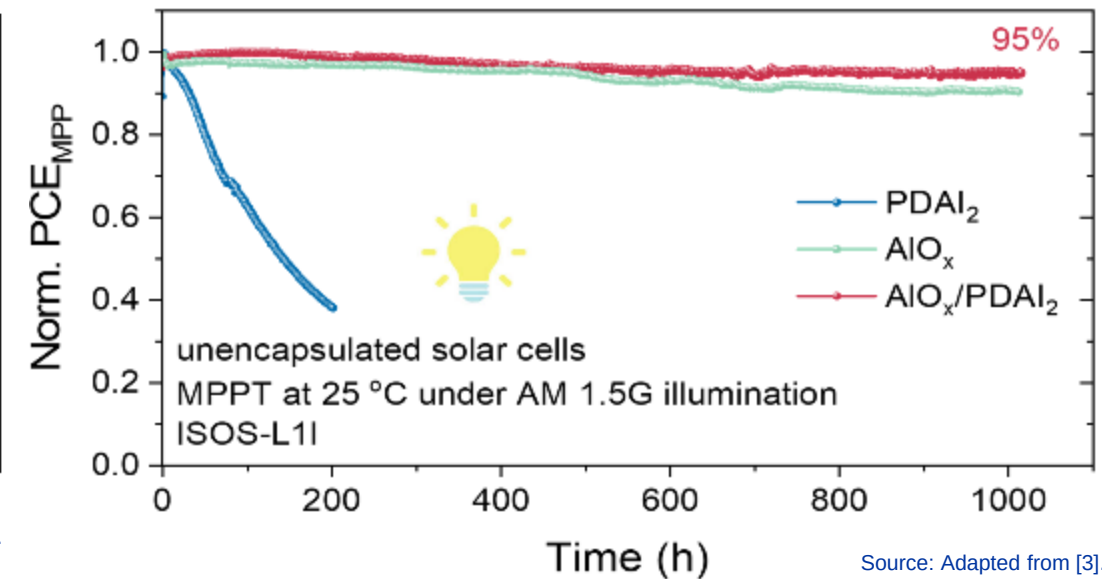
Interfacial design strategies for stable and high-performance perovskite/silicon tandem solar cells on industrial silicon cells



Source: Adapted from [3].



Source: Adapted from [3].



Source: Adapted from [3].

nature communications 

[3] L. Fang et al. Nat. Commun., **16**, 8881 (2025), DOI: 10.1038/s41467-025-64467-y.

Replacing C₆₀ in Perovskite/Si Tandem Solar Cells

Fullerene C₆₀:

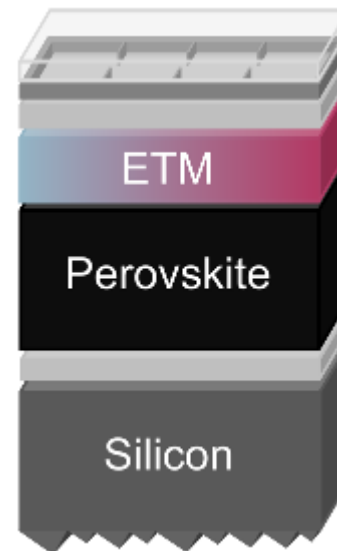
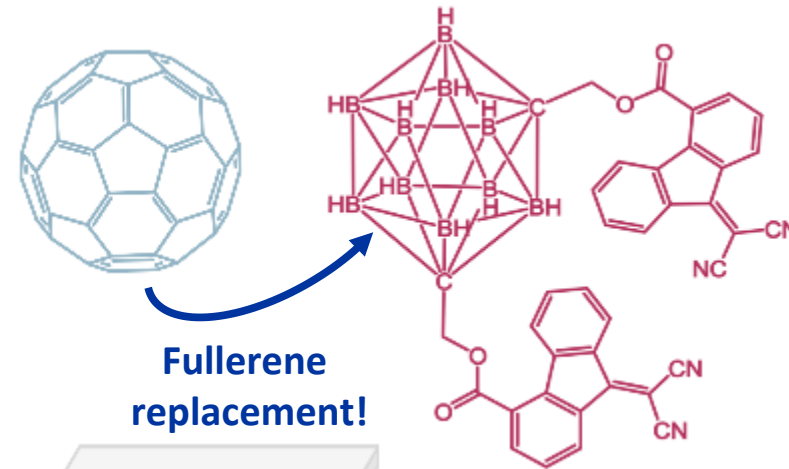
- established ETM for high-efficiency perovskite/Si tandems
- optical + electrical **losses limit PCE**

Carborane mCB-FMN:

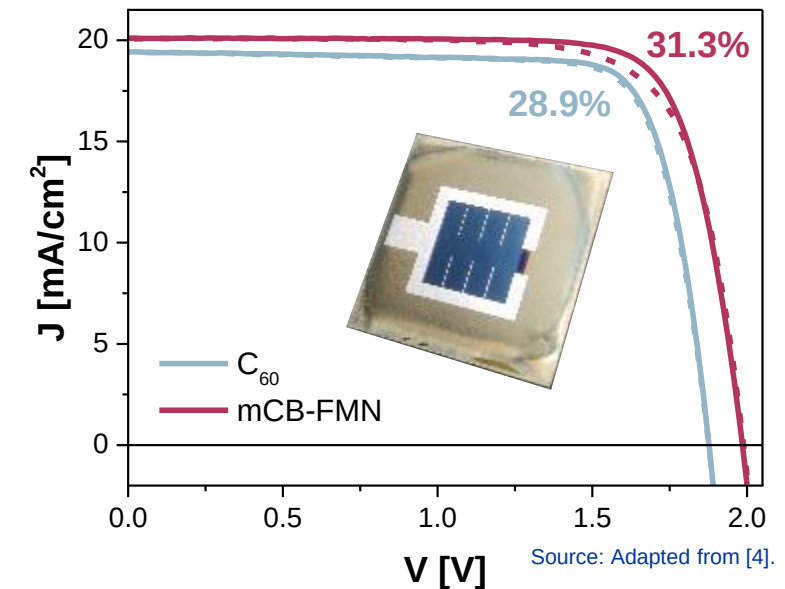
- **+2.4%_{abs.} PCE**
- reduced ETM-related losses
- improved robustness
- **mechanical reliability** ↑
- **SnOx growth** ↑
- **air sensitivity** ↓

Industrial readiness:

- patented
- licensed
- **commercially available at Dyenamo AB (SE)**



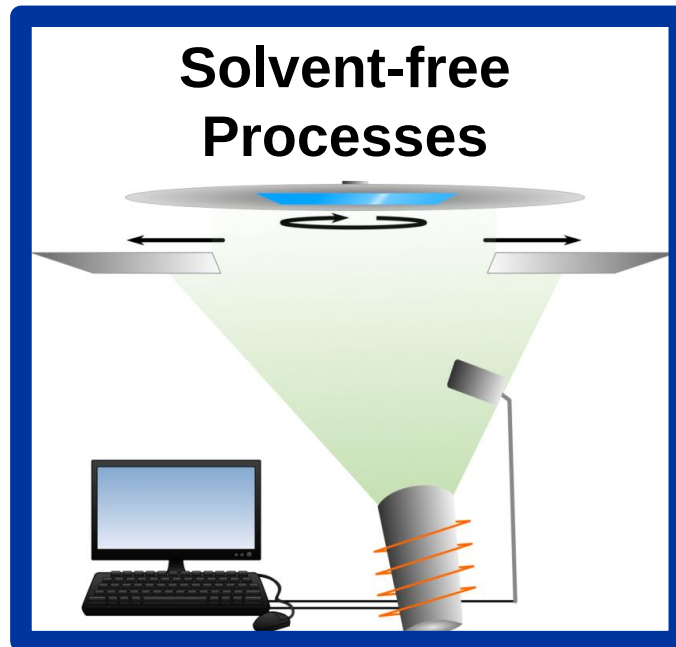
Source: Adapted from [4].



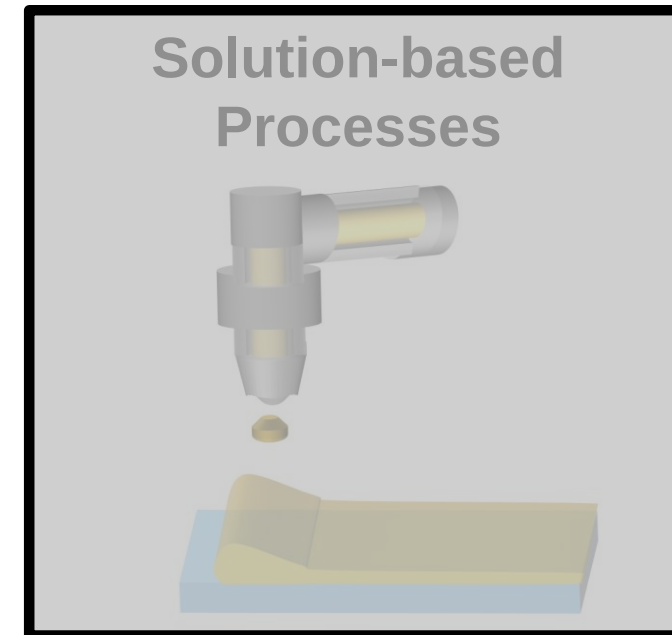
[4] L. Zimmermann *et al.*, *Energy Environ. Sci.* **19**, 4734 (2026), DOI: 10.1039/d6ee01246a

Versatile routes for scalable fabrication of perovskite thin films

Developing Scalable, Reliable, and High Throughput Fabrication Methods Side by Side with German and European PV Industry.



Source: Own image .



Source: Adapted from [12].

Strategies to achieve high throughput



Federal Ministry
for Economic Affairs
and Energy

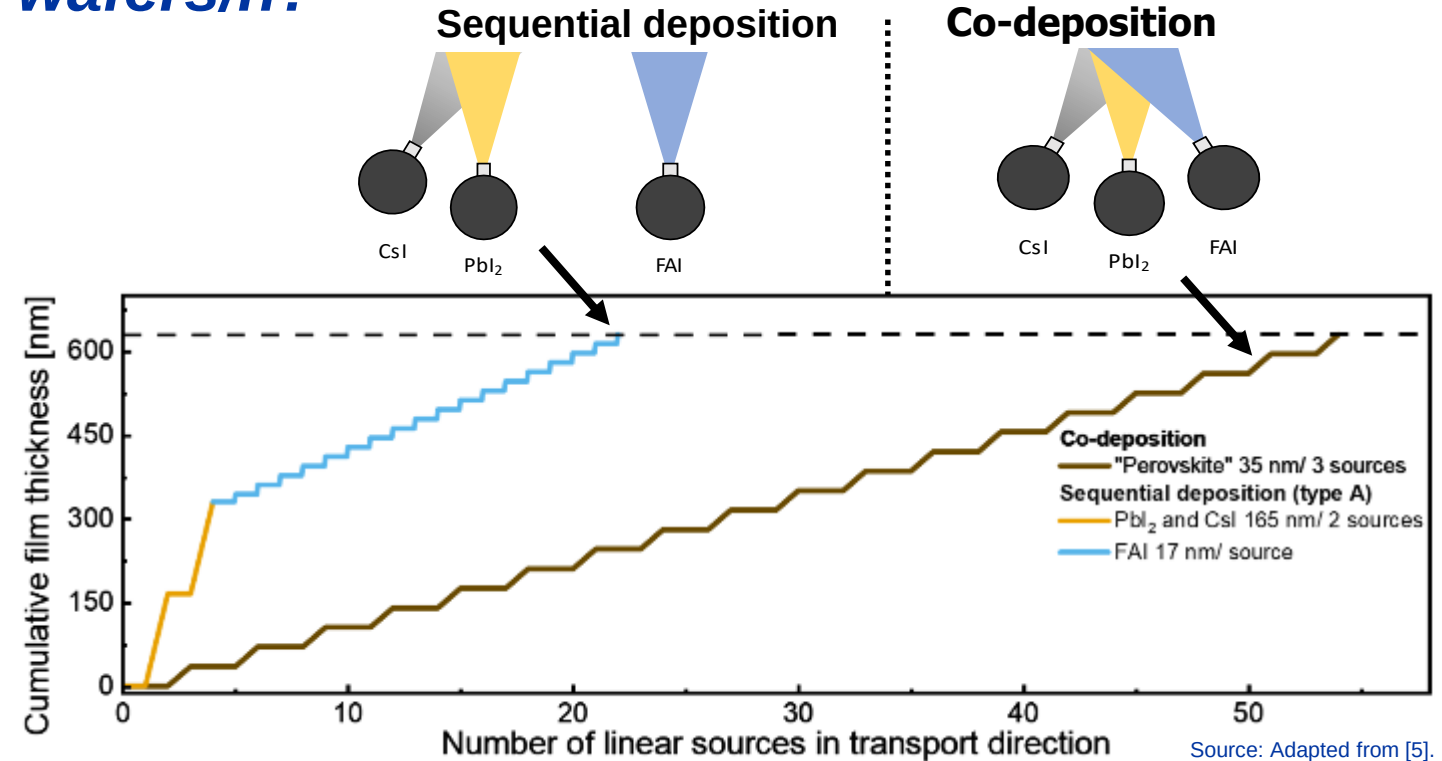
HZB Helmholtz
Zentrum Berlin



VON ARDENNE

*How to scale up vapor phase deposition processes
from the laboratory to > 10.000 wafers/h?*

- **Co-deposition: CsI/PbI₂/FAI**
 - Rate-limiting: **FAI** = 60 sources
 - Total: 180 sources
- **Sequential deposition:**
 - Total: $2 \cdot 7 + 60 = 74$ sources



Source: Adapted from [5].

Deposition rates of FAI too low for conventional vapor phase deposition!

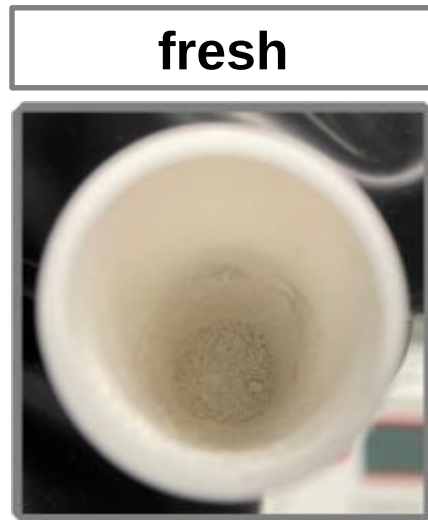
[5] J. Petry et al., *EES Solar* 1, 404, (2025), DOI: 10.1039/D5EL00069F

Strategies to achieve high throughput

UNIVERSITÄT
PADERBORN

Vapour phase deposition for all transport layers?

- Fully **solvent-free** processing of Pk solar cells?
- Evaporated SAM based HTLs → **material degradation!**
- Adjusted parameters → **similar results as solution processing**



Source: Own image.

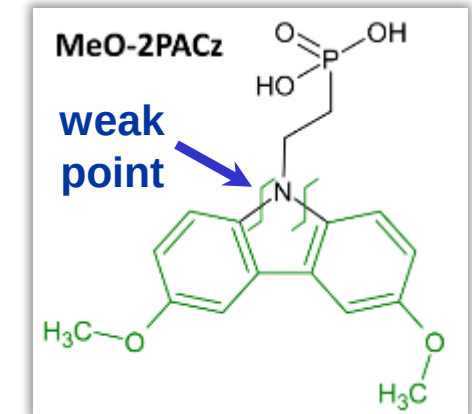


Source: Own image.

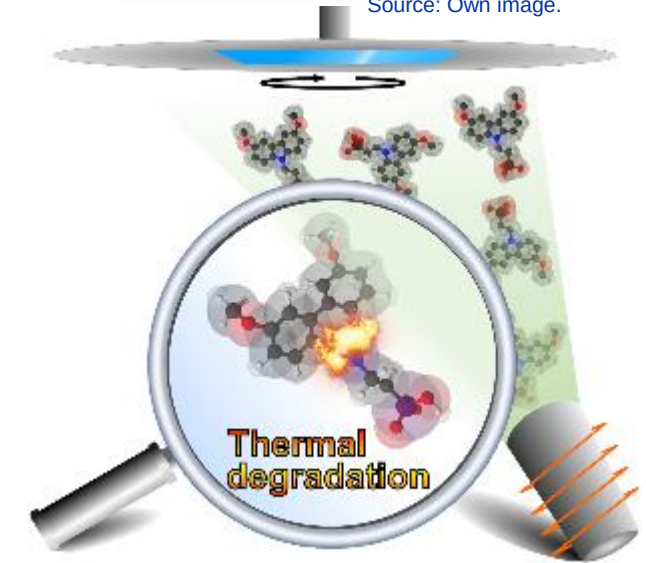


Source: Own image.

[6] J. Vollbrecht *et al.*, *Solar RRL* 9(17), 2500429, (2025), DOI: 10.1002/solr.202500429



Source: Own image.

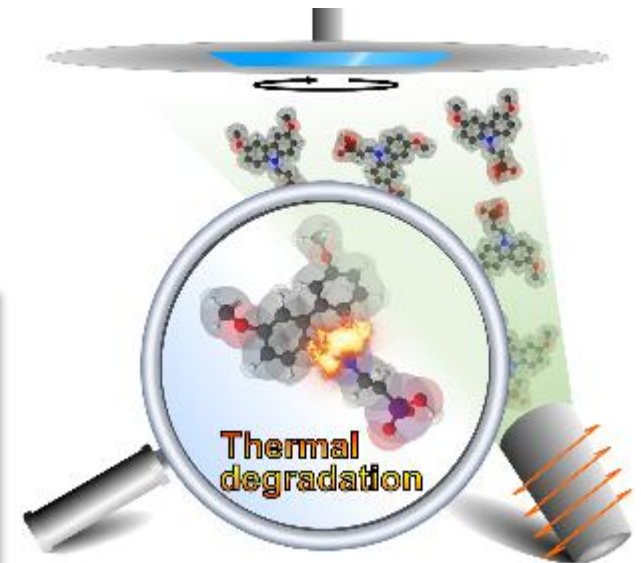
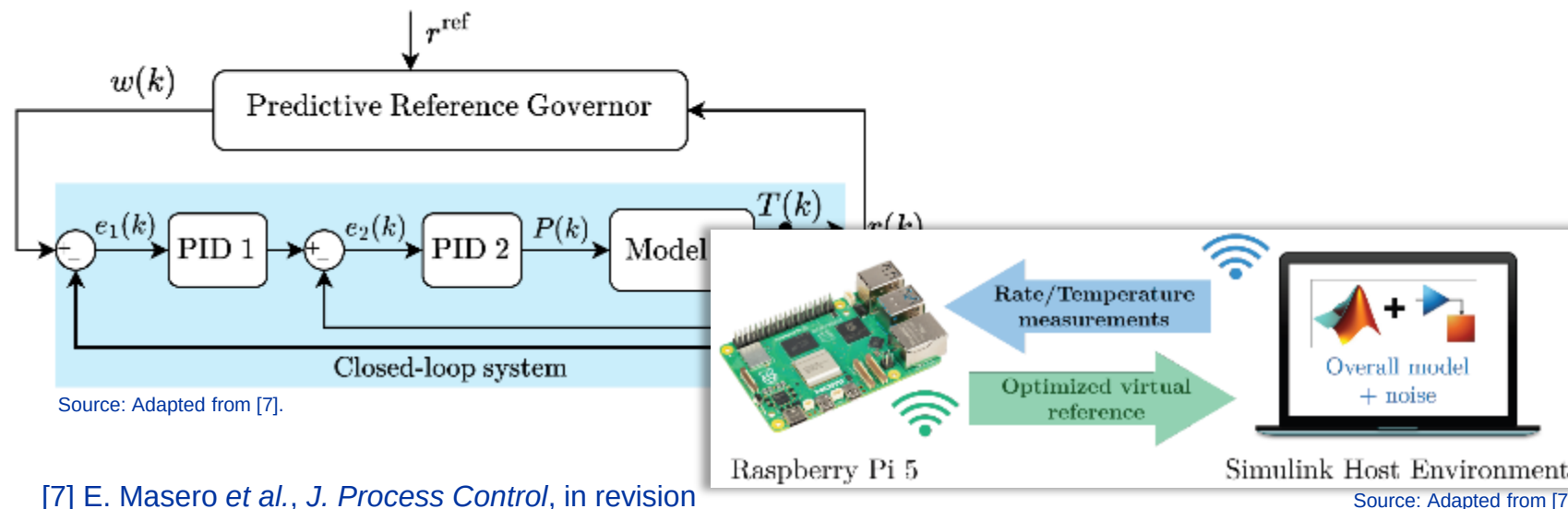


Source: Own image.

Strategies to achieve high throughput

Vapour phase deposition for all transport layers?

- Fully solvent-free processing of Pk solar cells?
- Evaporated SAM based HTLs → material degradation!
- **Adjusted parameters → data-driven model-predictive control**
- **More efficient and reproducible vapour phase deposition**

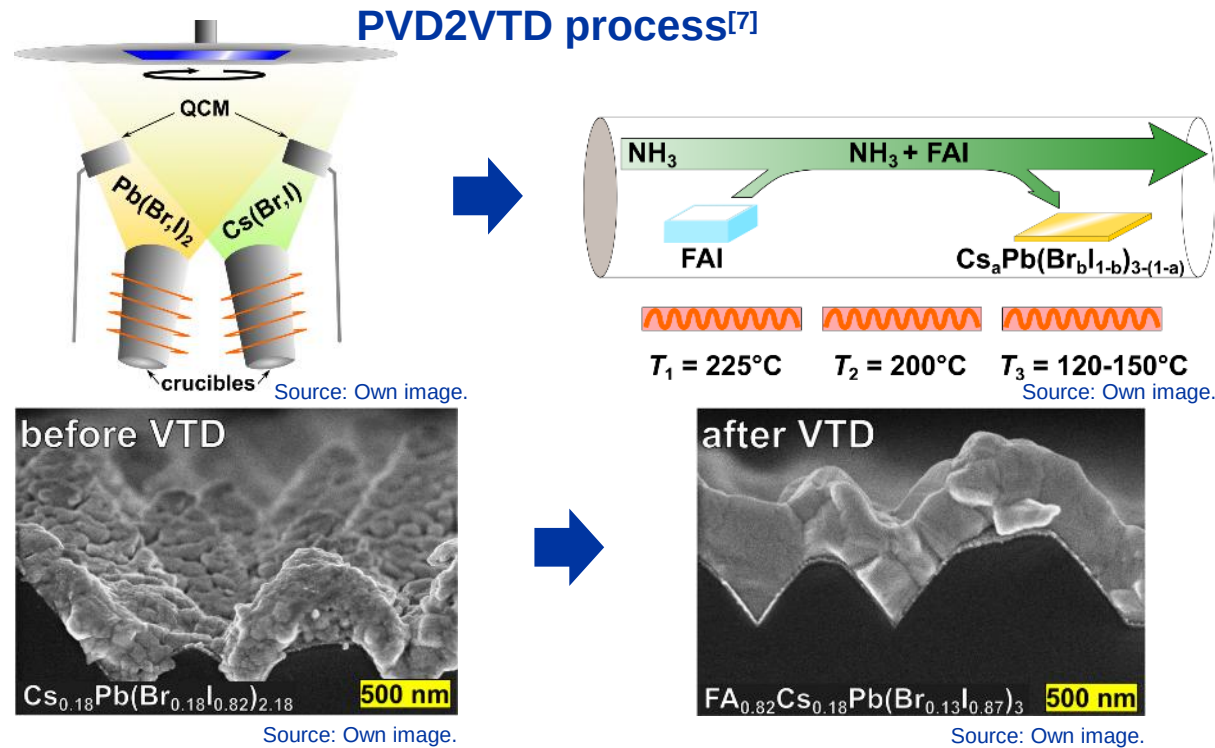


Source: Own image.



Hybrid-PVD + Gas Phase Transport Deposition (VTD)

- **Advantages:** solvent-free, conformal deposition of batch-processable perovskites
- **High throughput potential:** 18.6% efficient, fully solvent-free perovskite single-junction cells^[8]
- **Halide exchange:** observed for Br-containing perovskite scaffolds
- **Sequential VTD:** e.g. FAI → FABr; patent application filed^[9]
- **Industrialization:** initiated within new project HOPP (BMW)



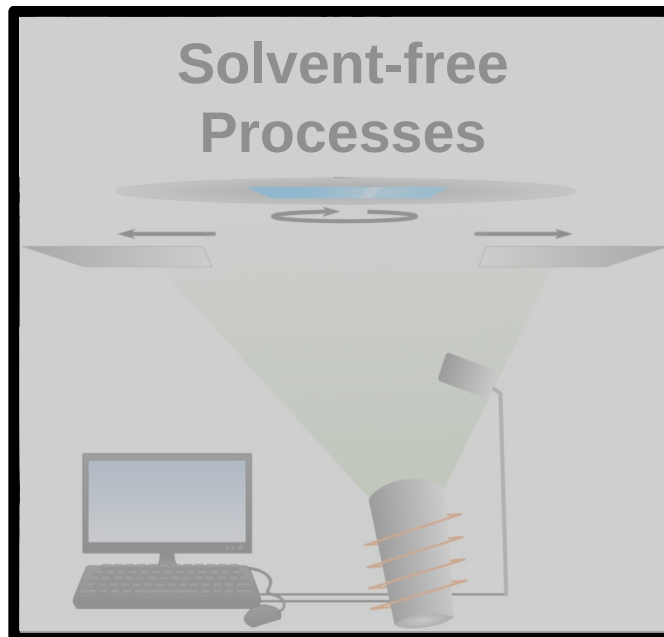
Source: Own photo.

[8] R. Clausing *et al.*, manuscript in revision

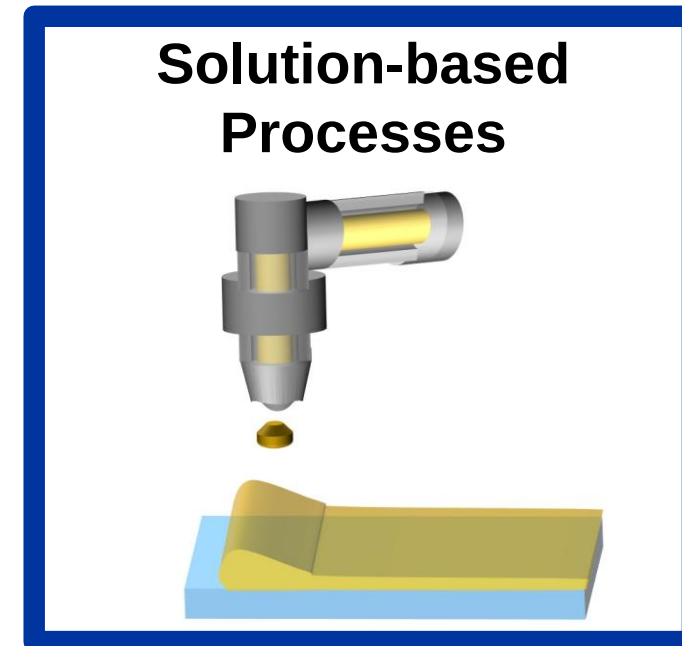
[9] Patent application, I0461P-DE

Versatile routes for scalable fabrication of perovskite thin films

Developing Scalable, Reliable, and High Throughput Fabrication Methods Side by Side with German and European PV Industry.



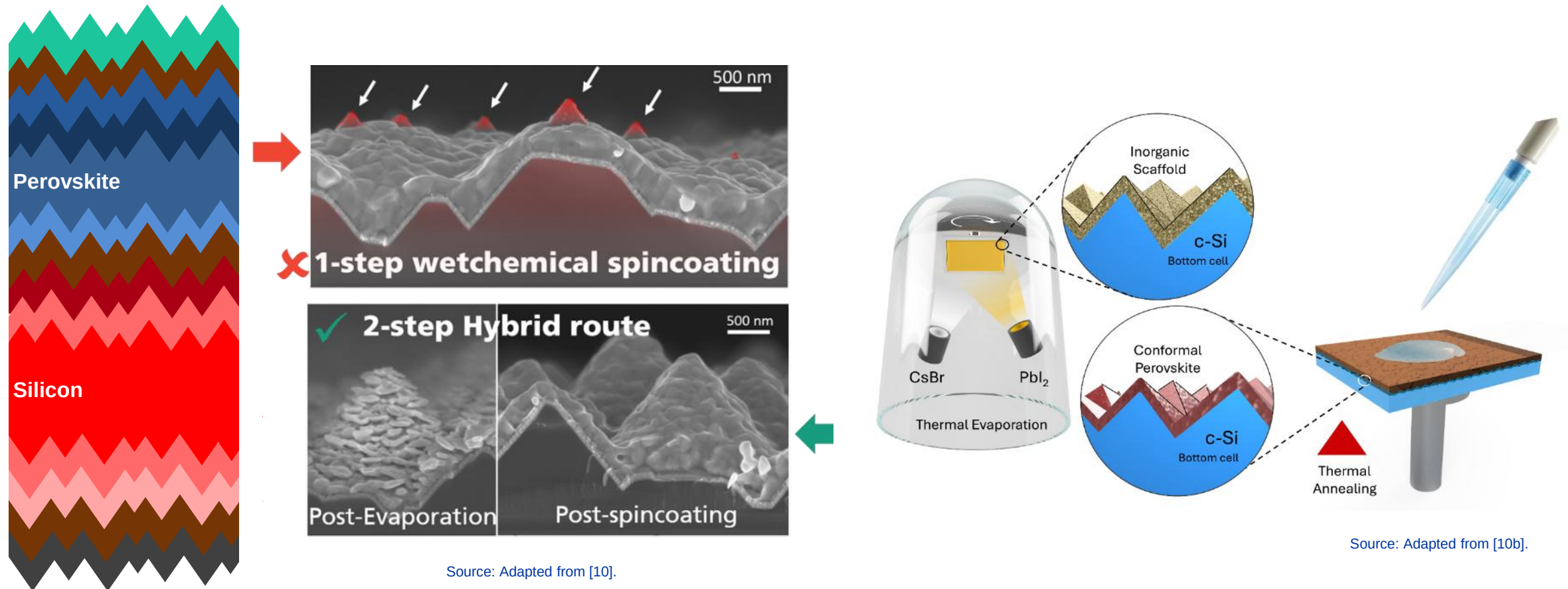
Source: Own image .



Source: Adapted from [12].

Perovskite-Silicon Tandem Solar Cells

Hybrid Route Processing for Perovskite on Industrial Textured Silicon



Source: Fraunhofer ISE

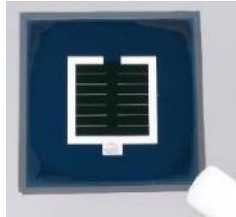
[10] P. Schulze *et al.*, *Thin Solid Films*, 704, 137970, (2020) DOI: 10.1016/j.tsf.2020.137970

[10b] Oussama Er-raji, Dissertation, March 2025 University of Freiburg

Industry Compatibility

New Methods, Upscaling and Throughput

Cell area: 1 cm²



Source: Fraunhofer ISE



Source: Fraunhofer ISE

Throughput

Scaling the
area

Developing
the method

M12
210 x 210 mm²

Source: T. Daschinger, ISFH

210 mm

Overview Pero-Si-SCALE Labs

VON ARDENNE 
centrotherm

Source: Fraunhofer ISE

 **Fraunhofer**
ISE

 Federal Ministry
for Economic Affairs
and Energy

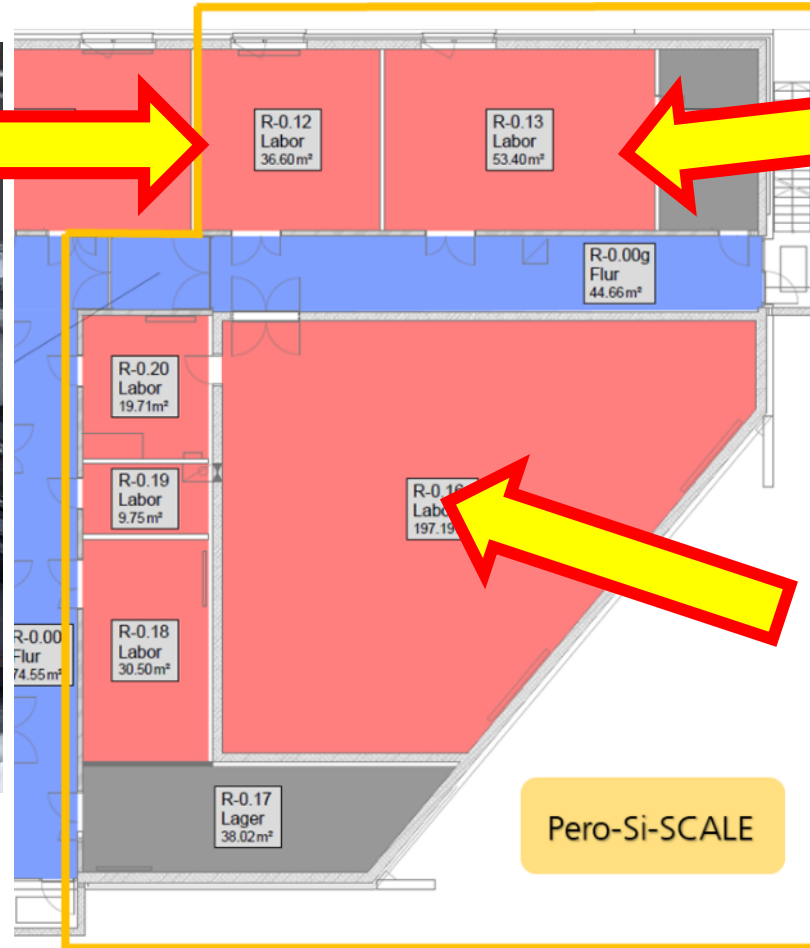
 **SUSS**

 **SALD** SPATIAL ALD
INNOVATORS



**Ink Jet
Slot-die
Coating**

Source: Fraunhofer ISE



Source: Fraunhofer ISE



Spatial ALD

**Spray
Coating**

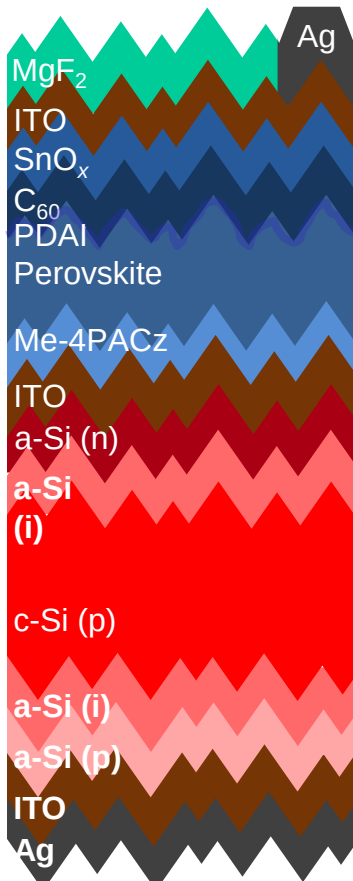


Linear Evaporation

Sputter

Source: Fraunhofer ISE

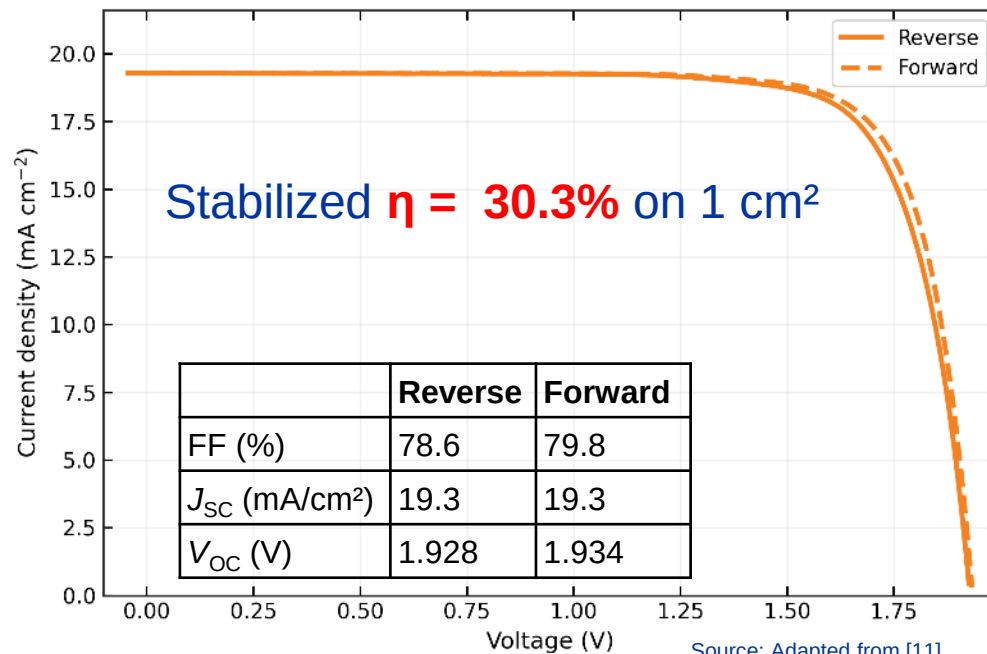
Overview Pero-Si-SCALE Labs



Source: Fraunhofer ISE

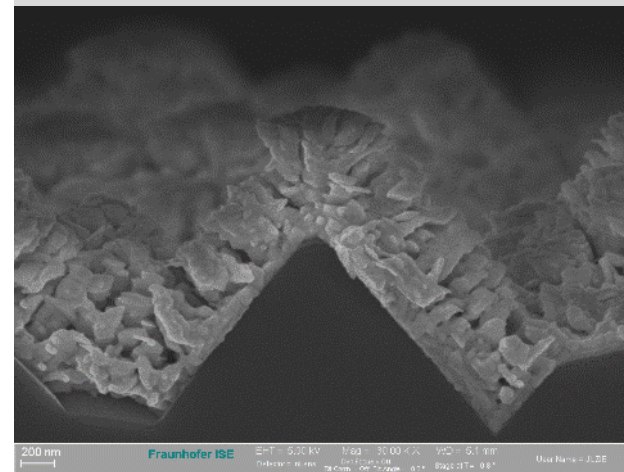
Pero/Si Tandem Cell using Industrial Evaporation Processes

Best IV pair: 250351-08-6



Source: Adapted from [11].

Homogeneous and conformal porous film on six G12 wafers



Source: Adapted from [11].

VON ARDENNE 
centrotherm

Fraunhofer
ISE

 Federal Ministry
for Economic Affairs
and Energy

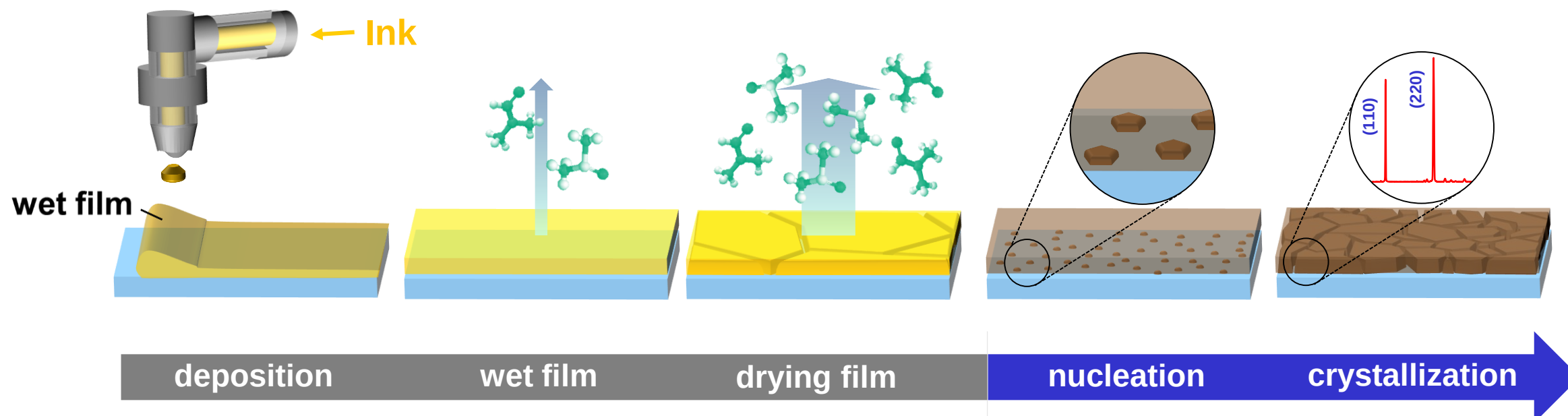
 SUSS

 SPATIAL ALD
INNOVATORS

[11] P.Saint-Cast *et al.*, "High-Throughput Vacuum Deposition of PbI_2/CsI scaffolds and C_{60} Films for Perovskite/Silicon Tandems" Vacuum Deposited Perovskite Conference 2026

Solution-Processed Perovskite Thin Film PV

Key Challenge: *Several Entangled Processes Define the Perovskite Thin Film Photovoltaics.*



Source: Adapted from [12].

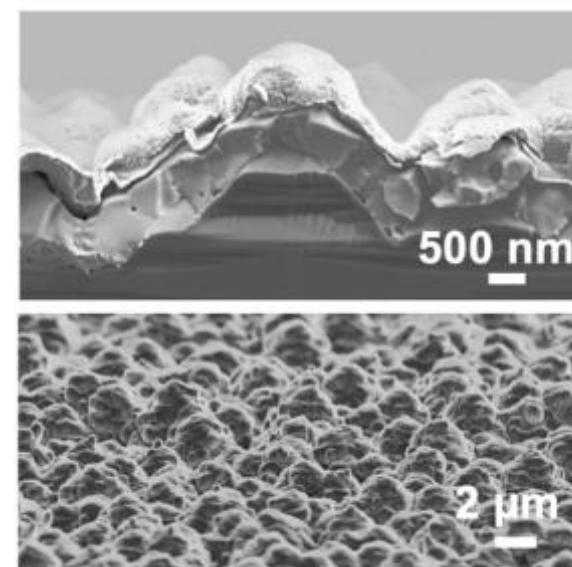
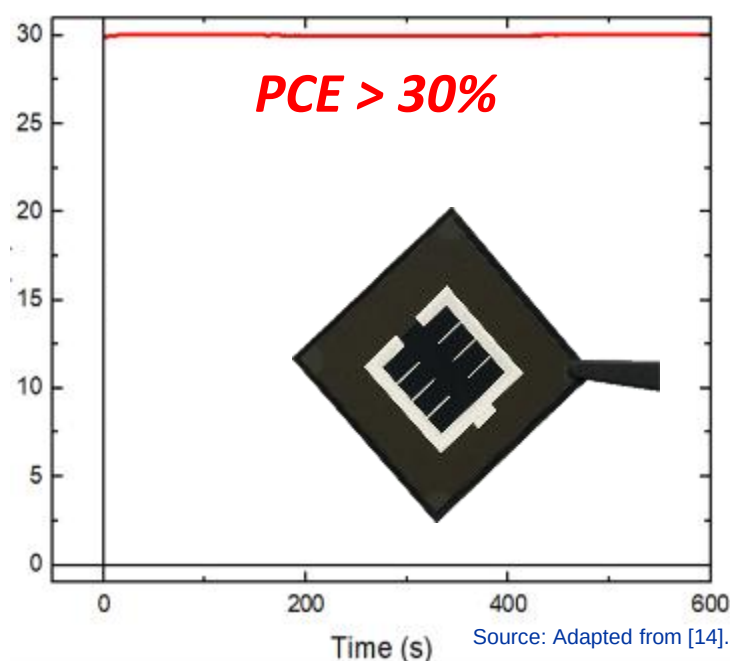
[12] I. A. Howard *et al.*, *Adv. Mater.* **31**(26), 1806702 (2019), DOI:10.1002/adma.201806702

Inkjet-Printed Perovskite/Si Tandem Solar Cells

High performance tandems on industrial textures Si bottom solar cells

NOTION
SYSTEMS

Qcells



Source: Adapted from [14].

[13] R. Pesch *et al.*, *under review* (2026).

[14] R. Pesch *et al.*, *Small Science*, 5(11) 2500362 (2025).

[15] R. Pesch *et al.*, *Solar RRL*, 2400165 (2024).

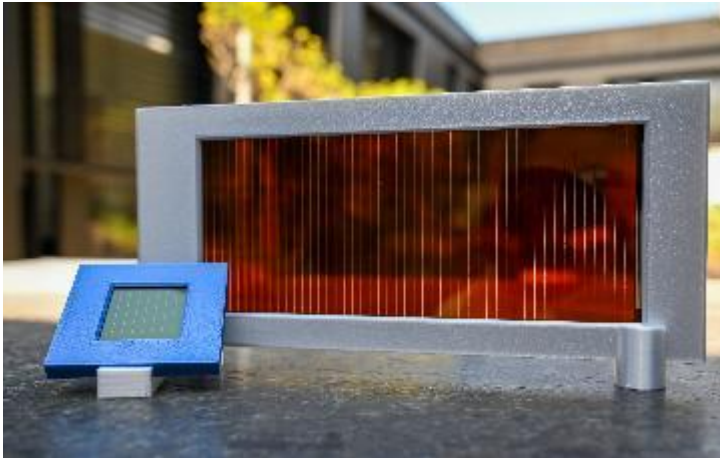
[16] F. Schackmar *et al.*, *Advanced Materials Technologies* 6(2), 2000271 (2021).

[17] H. Eggers *et al.*, *Advanced Energy Materials* 10(5), 1903184 (2020).

[18] I. Howard *et al.*, *Advanced Materials* 31(26), 1806702 (2019).

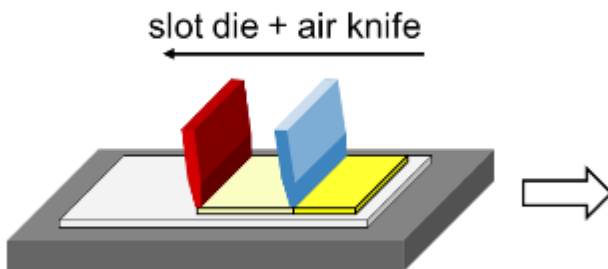
[19] F. Mathies *et al.*, *ACS Applied Energy Materials* 1(5), 1834-1839 (2018).

Perovskites processed solely by slot die coating – all solutions based on green solvent formulations



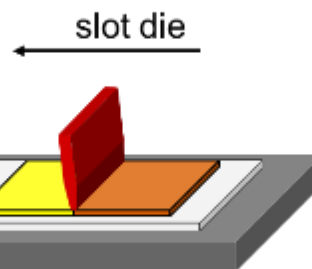
substrate
sizes: 5×5
and 10×24
cm²

first step:



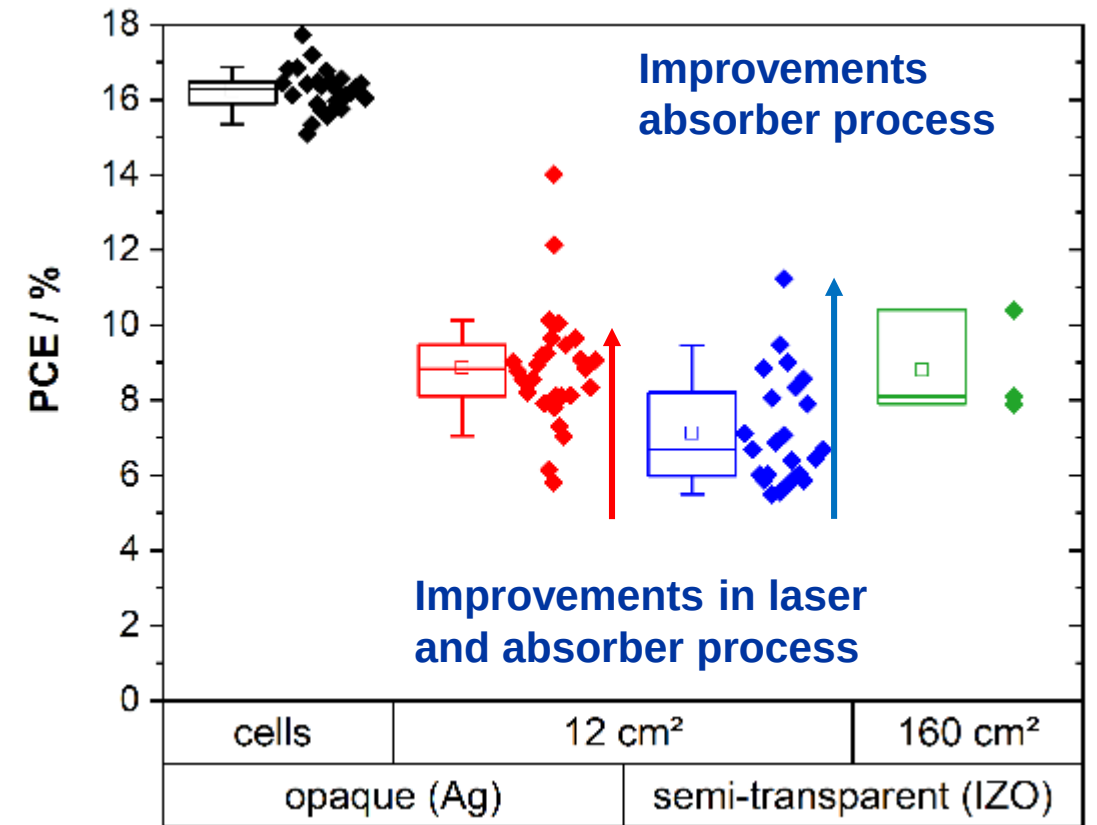
- e.g. PbI_2 , CsI ...
- in DMSO

second step:



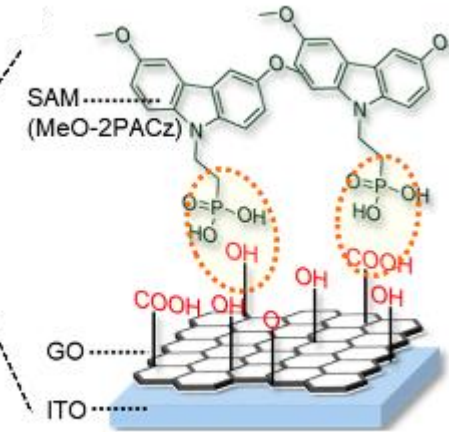
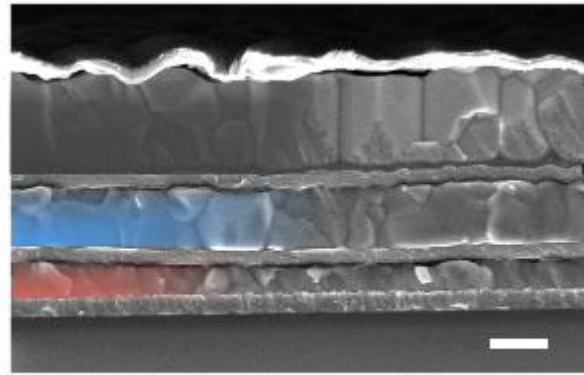
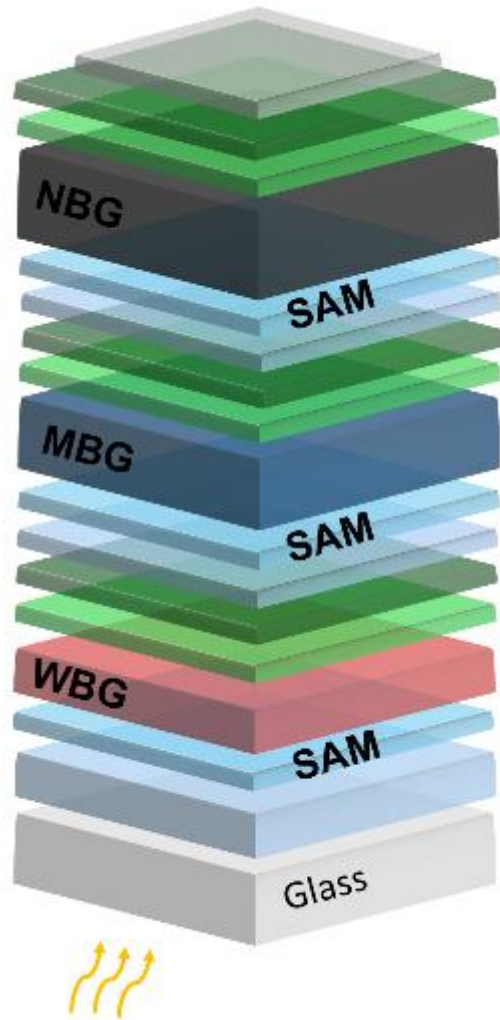
- organic components like FAI, FABr...
- in isopropyl alcohol

Source: Own image.



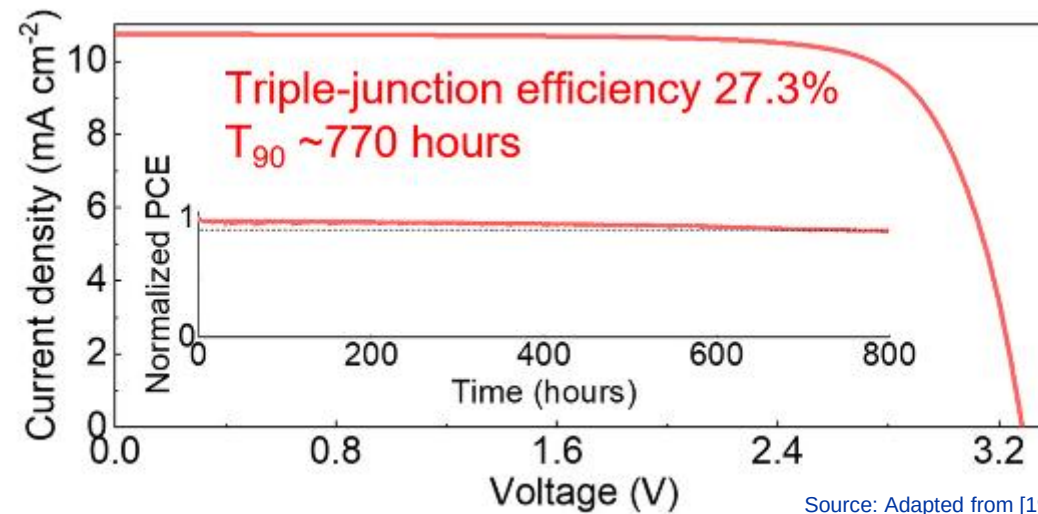
Source: Own plot.

Triple Junction All-Perovskite Solar Cells With SAMs in All Subcells



HZB Helmholtz
Zentrum Berlin

GO/SAM bilayer mitigates ionic and current losses in SnPb NBG subcell



Source: Adapted from [19].

Triple junctions yields promising efficiency and stability at 25°C

[20] Y. Yun *et al.* *Joule* (2026), DOI: 10.1016/j.joule.2026.102575

Perovskites on the rise: Several Start-Ups have been founded in recent years



Development perovskite–silicon tandem modules, with emphasis on material efficiency, scalability and lifetime. **2025**



Commercializing lightweight flexible perovskite PV using roll-to-roll production. **2026**



Development of bifacial 4-terminal perovskite–silicon tandem modules and an industrial pilot line. **2025**



Printable perovskite PV and thin-film optoelectronics, targeting scalable, sustainable manufacturing. **2025**



Perovskia

Digitally printed, customizable perovskite solar cells, IoT, wearables and indoor energy harvesting. **2021**



Ultra-lightweight flexible solar film based on proprietary microgroove architecture and low-cost roll-to-roll manufacturing. **2012**

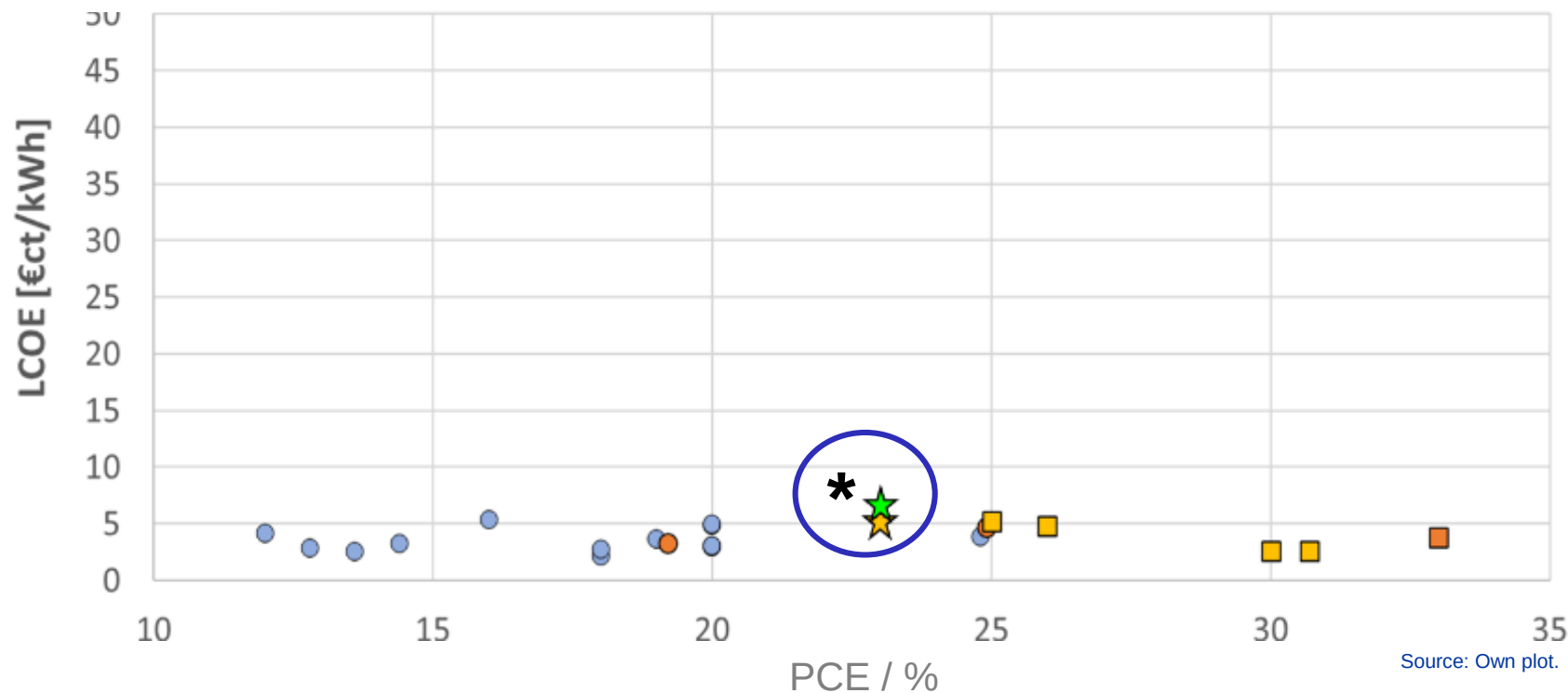
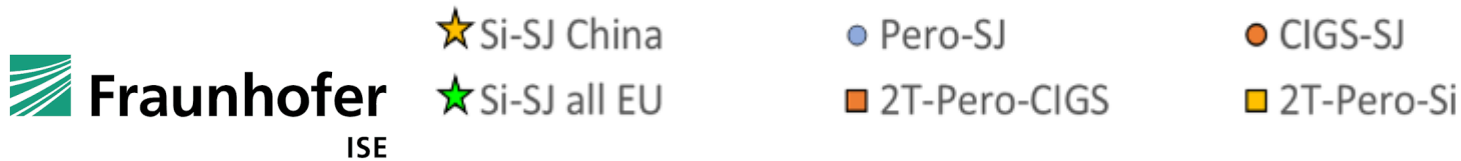


Specialty-chemicals company for perovskite materials, transport materials, passivation chemicals and scale-up synthesis. **2009**



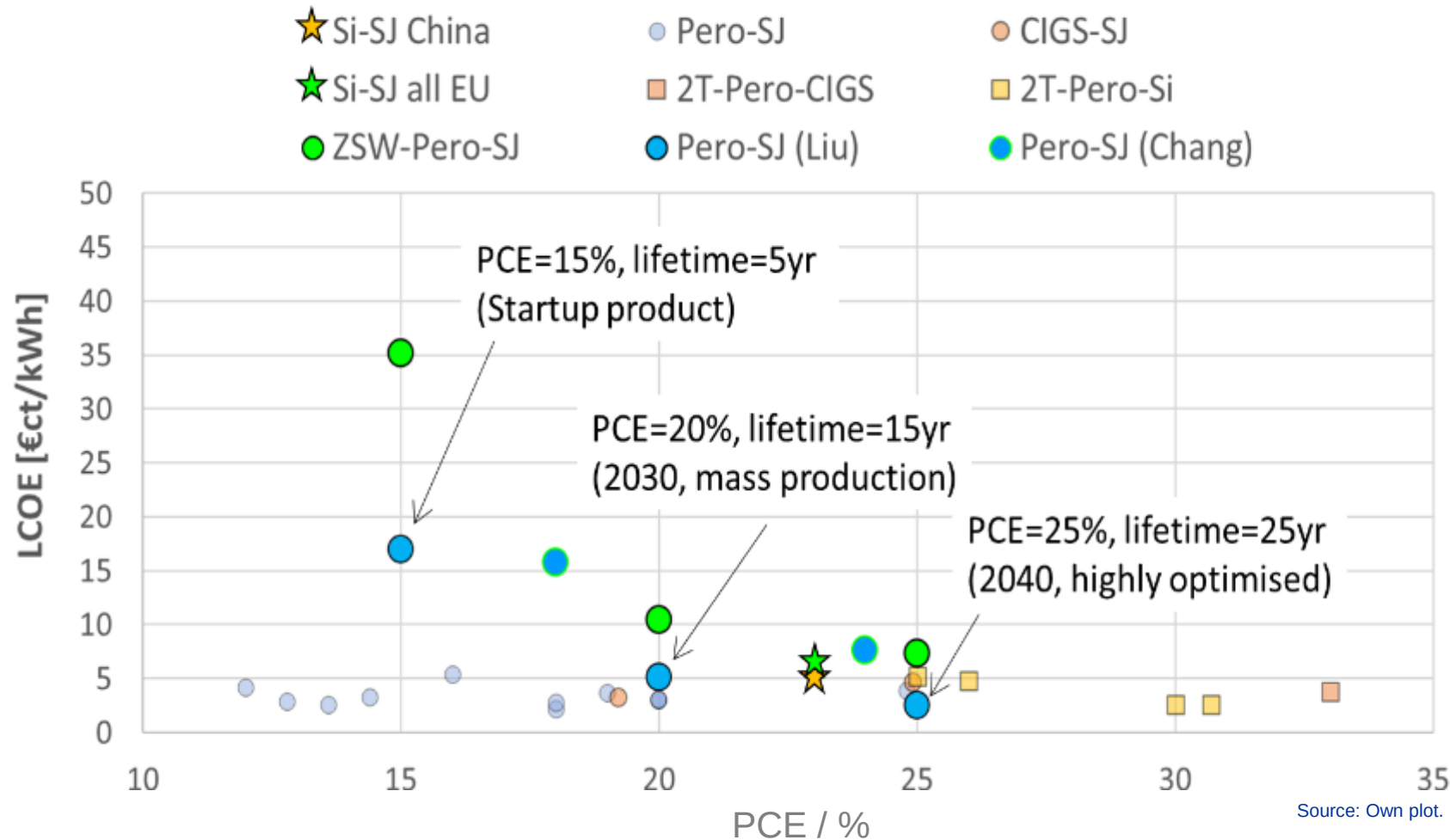
Advanced luminescence characterization equipment for perovskite, tandem and other optoelectronic devices. **2021**

Meta-study: Literature review on costs for thin-film module production – at same level as Si for all technologies



- **Prices for GW scale**
→ investment hurdle still to overcome
- Most papers assume **similar production yields and lifetimes >25 years** → still to be proven for perovskites

Cost model shows strong dependency on yield, PCE and life. Costs in Chinese study well below ours.

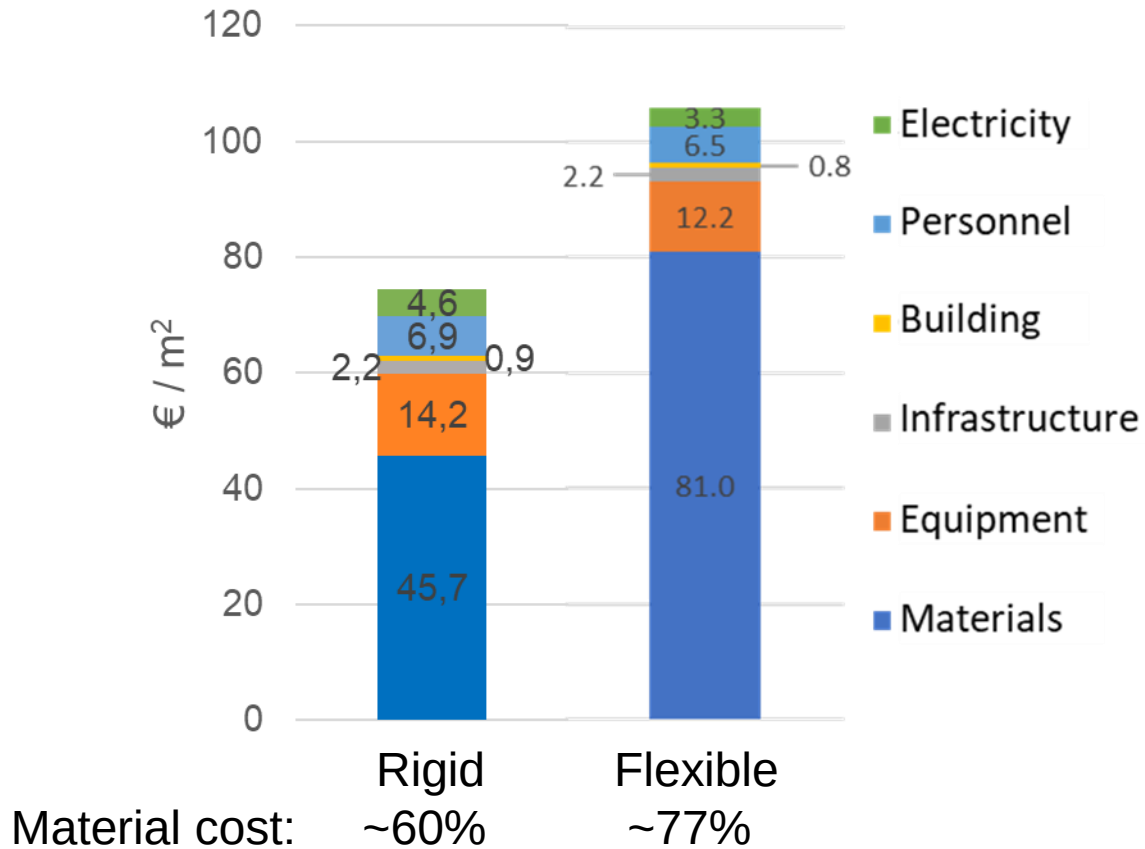


- A minimum of **PCE=20%**, **yield=90%**, **lifetime=15yrs** is required to get into a prize competitive range
- Current record efficiency: **22,1% PCE** (Renshine - [NLR Charts](#))

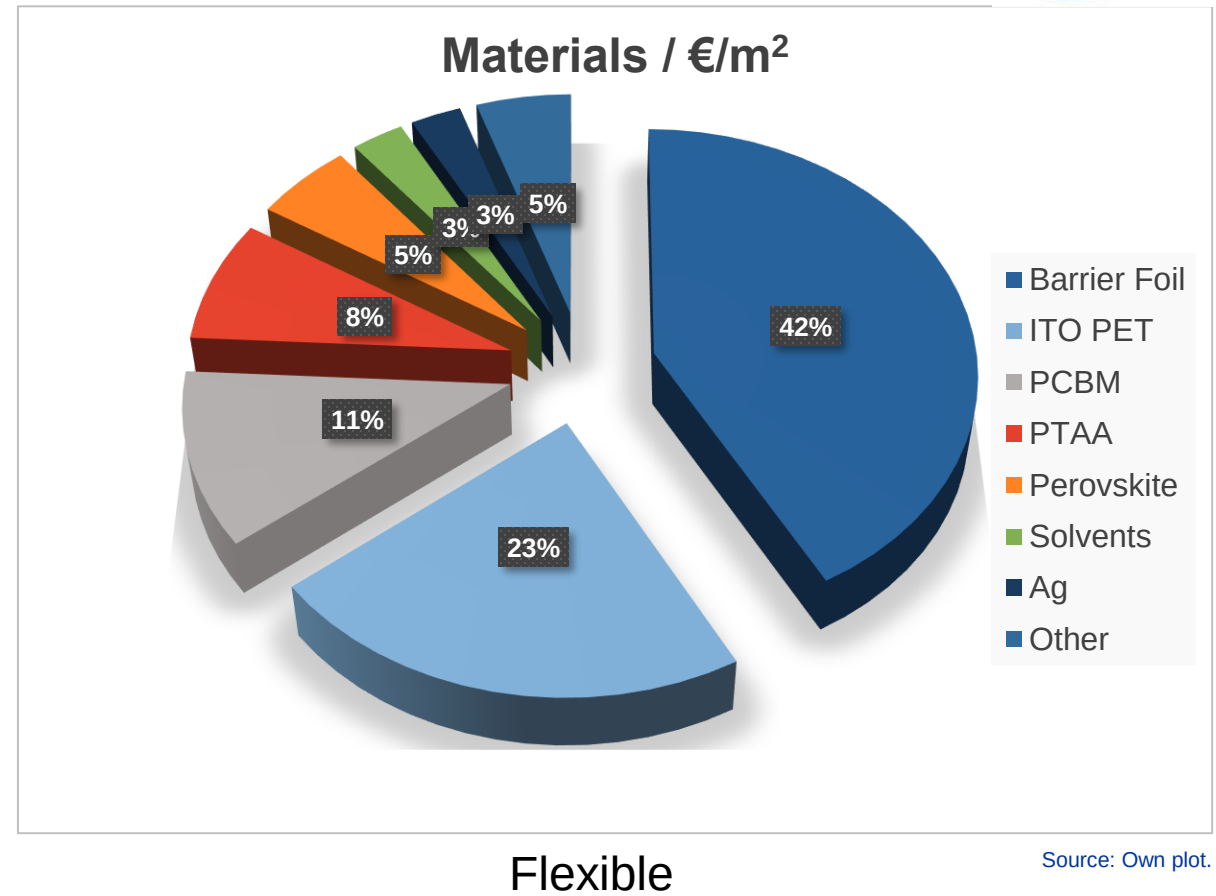
*Chang et al., Prog. Photovolt: Res. Appl. (2017)

*Liu et al., Nano-Micro Lett. (2025) 17:219

Perovskite Module costs: As well for flexible as for rigid substrates, substrate material and encapsulation are the cost drivers.



Source: Own plot.



Source: Own plot.

Thank you very much for your attention!

Thanks to all contributors!