

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

Joachim Vollbrecht, Robby Peibst

Institut für Solarenergieforschung Hameln (ISFH)

Eva-Maria Hammer, Jonas Hanisch, Tina Wahl

Zentrum für Sonnenenergie- und Wasserstoff-Forschung (ZSW)

Lars Korte

Helmholtz-Zentrum Berlin (HZB)

Juliane Borchert, Martin Hermle, Stefan Glunz

Fraunhofer-Institut für Solare Energiesysteme (ISE)

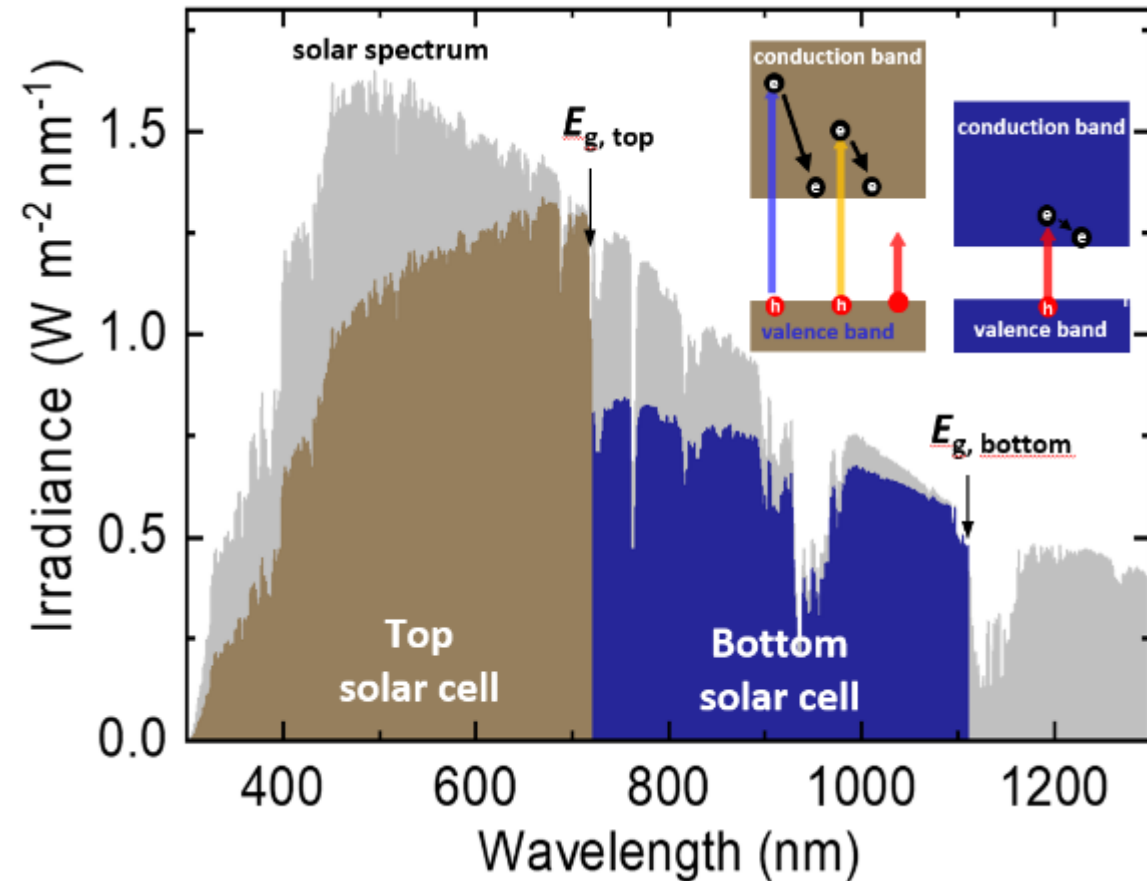
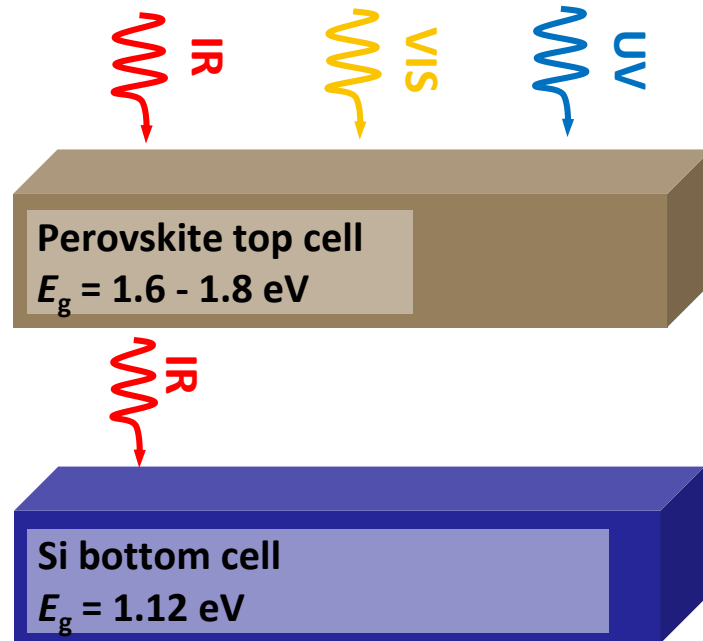
Ulrich W. Paetzold

Karlsruher Institut für Technologie (KIT)



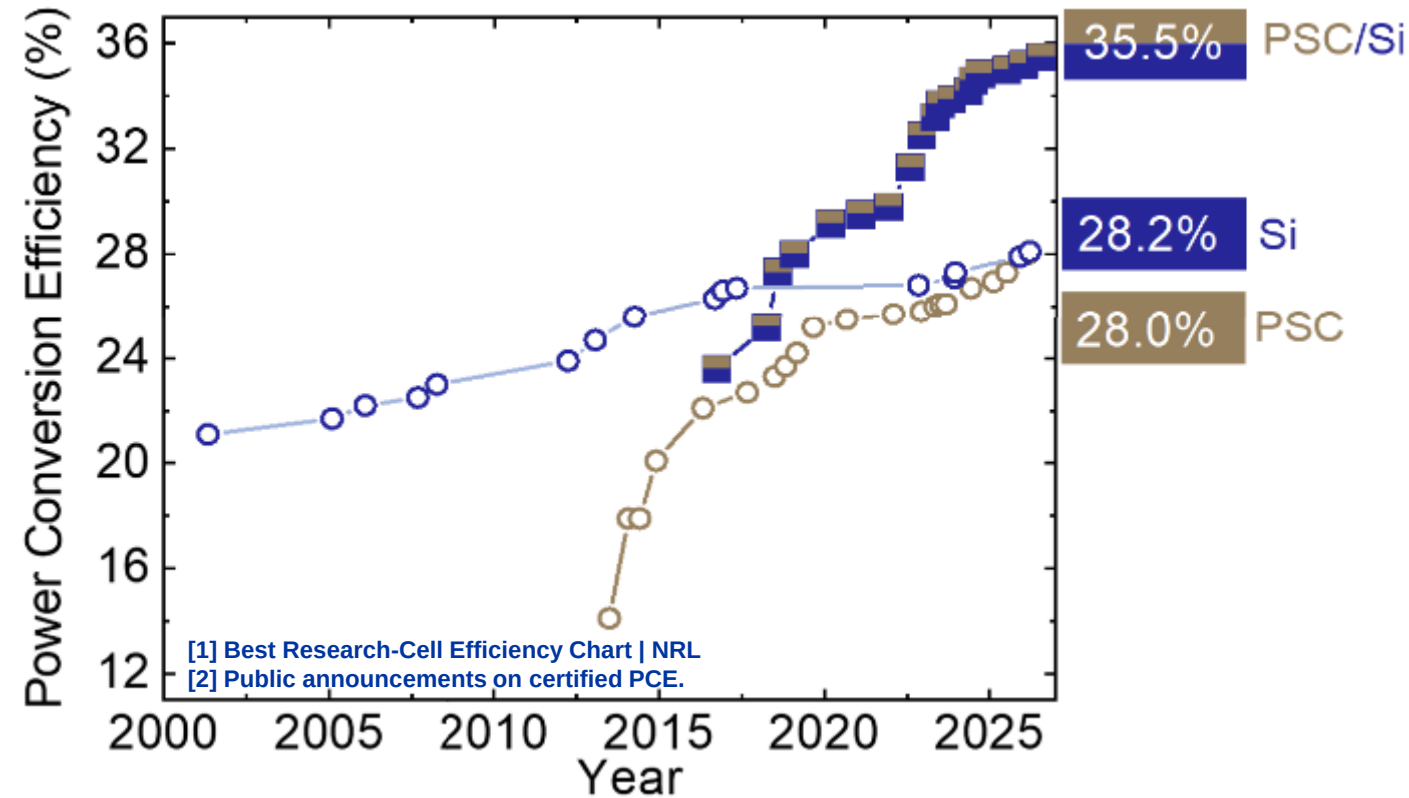
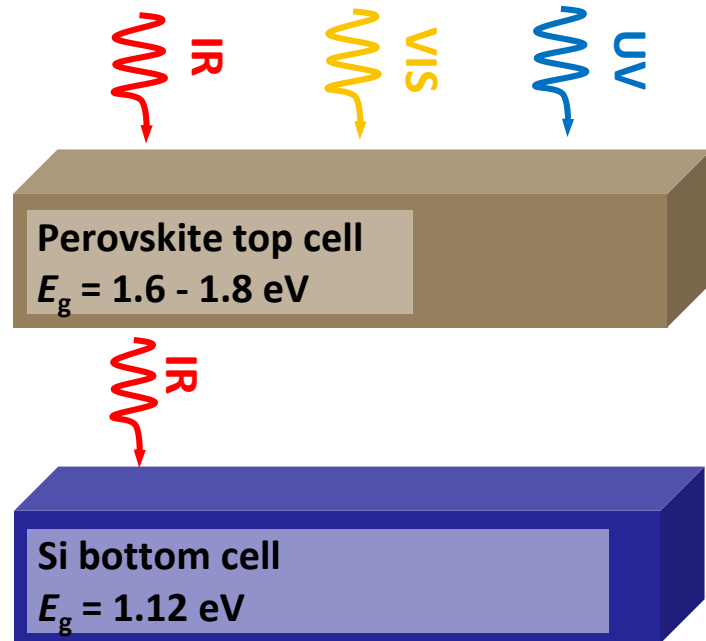
Image generated with help from AI.

Exemplary: High Efficiency Perovskite/Silicon Tandem PV



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

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



Series A Financing of Tandem
Startup companies
Q1/Q2 2024



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



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



Swift Solar secures Meyer
Burger technology for
perovskite tandem cells

2025

2026



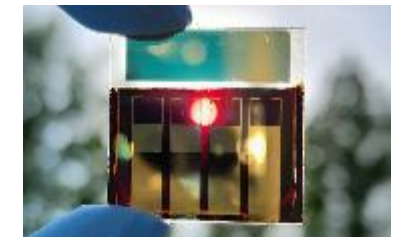
30.1% Perovskite/Si solar
cell on M6 wafer
LONGi, Intersolar, June



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



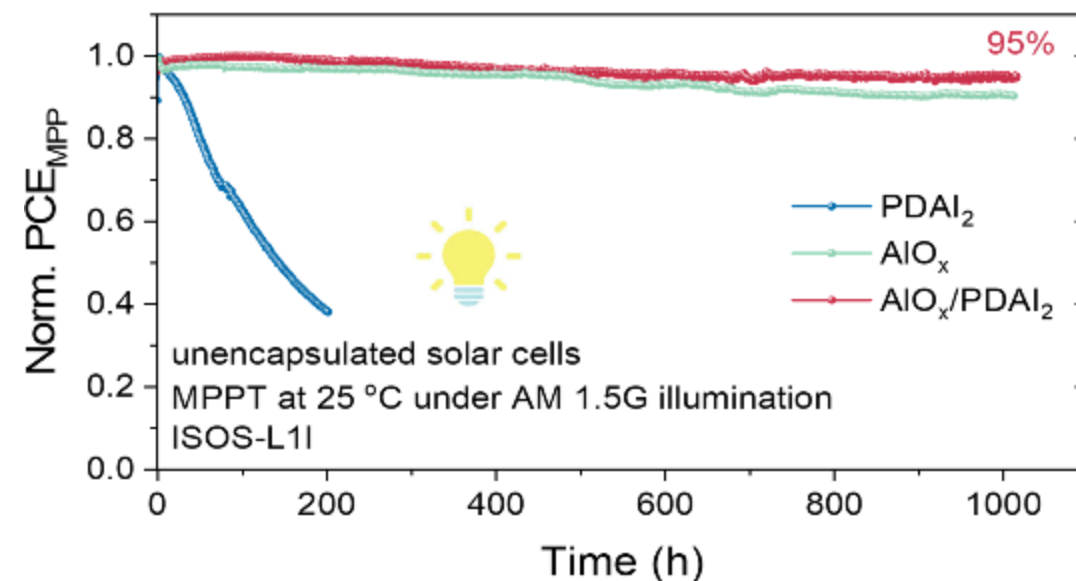
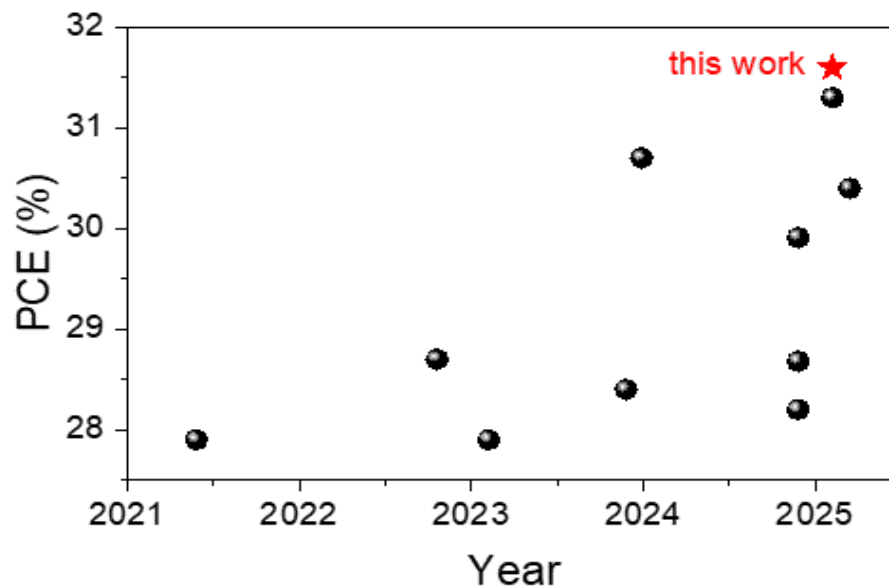
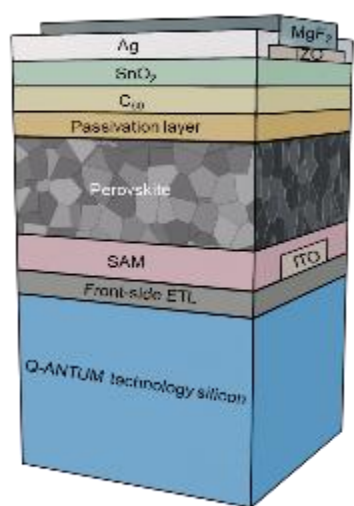
Trina shows 800+W
module, May 2025



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



nature communications 

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:

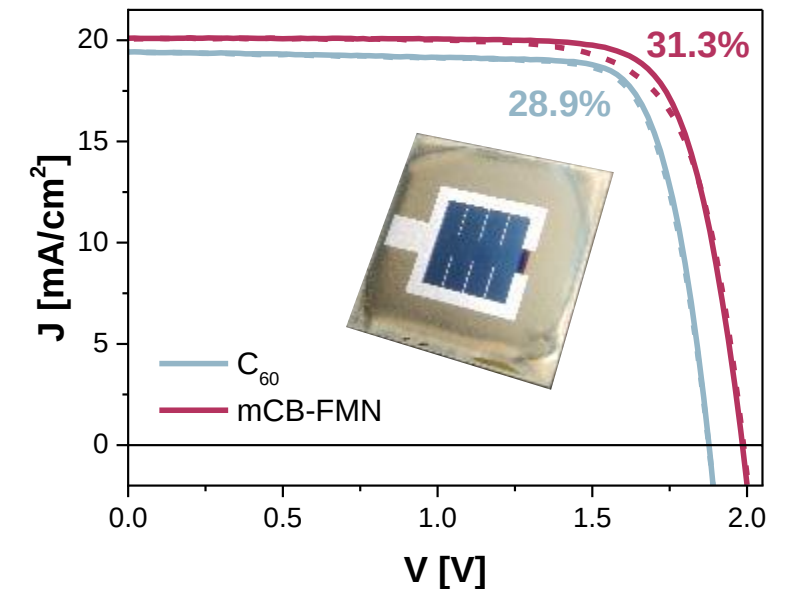
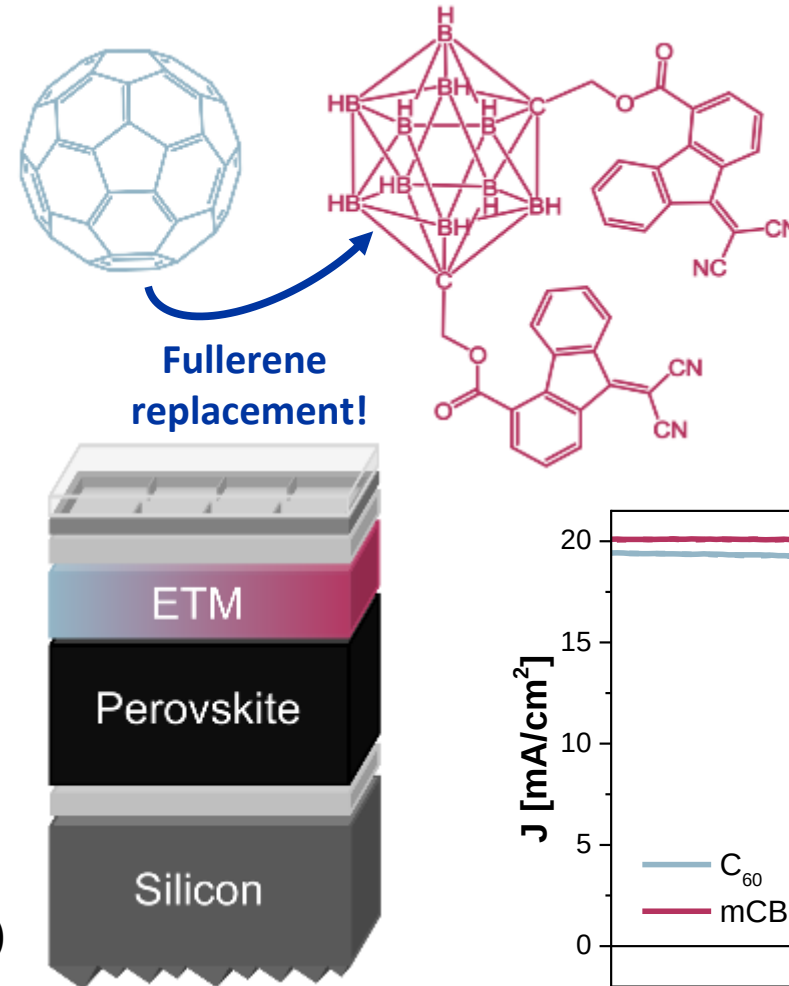
- established ETM for high-efficiency perovskite/Si tandems
- optical + electrical **losses limit PCE**

Carborane mCB-FMN:

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

Industrial readiness:

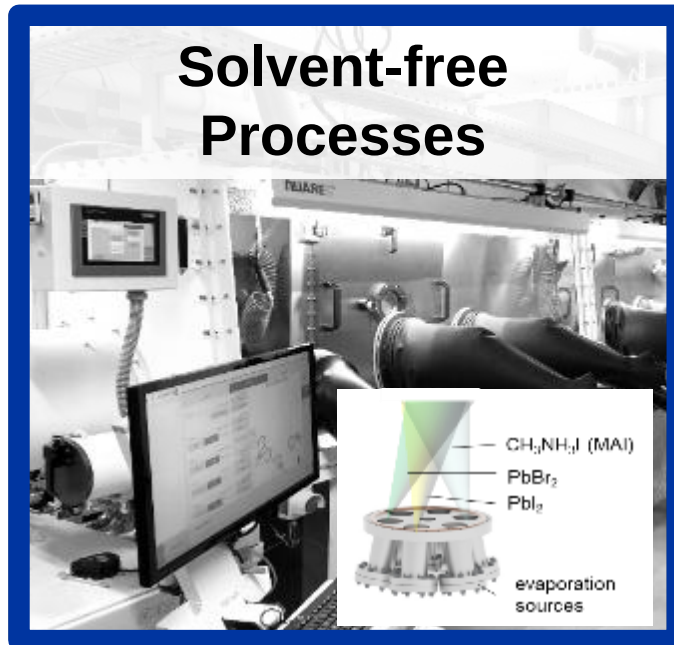
- patented
- licensed
- commercially available at Dyenamo AB (SE)**



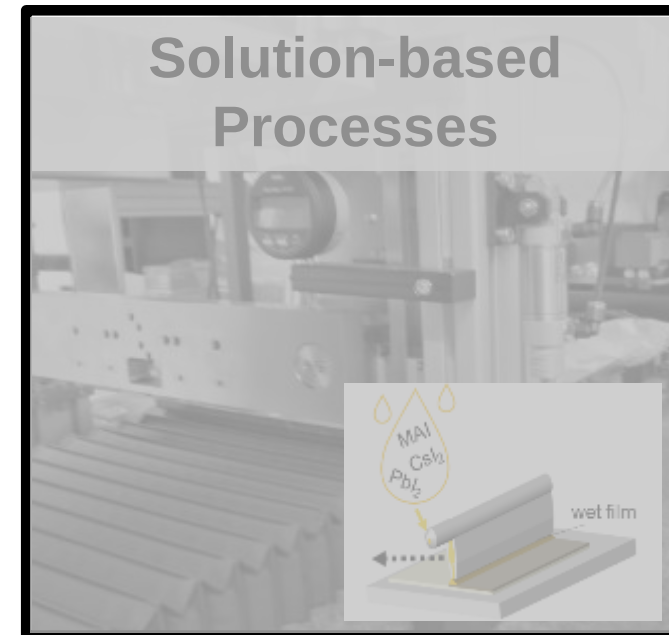
Versatile routes for scalable fabrication of perovskite thin films

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

Solvent-free Processes



Solution-based Processes

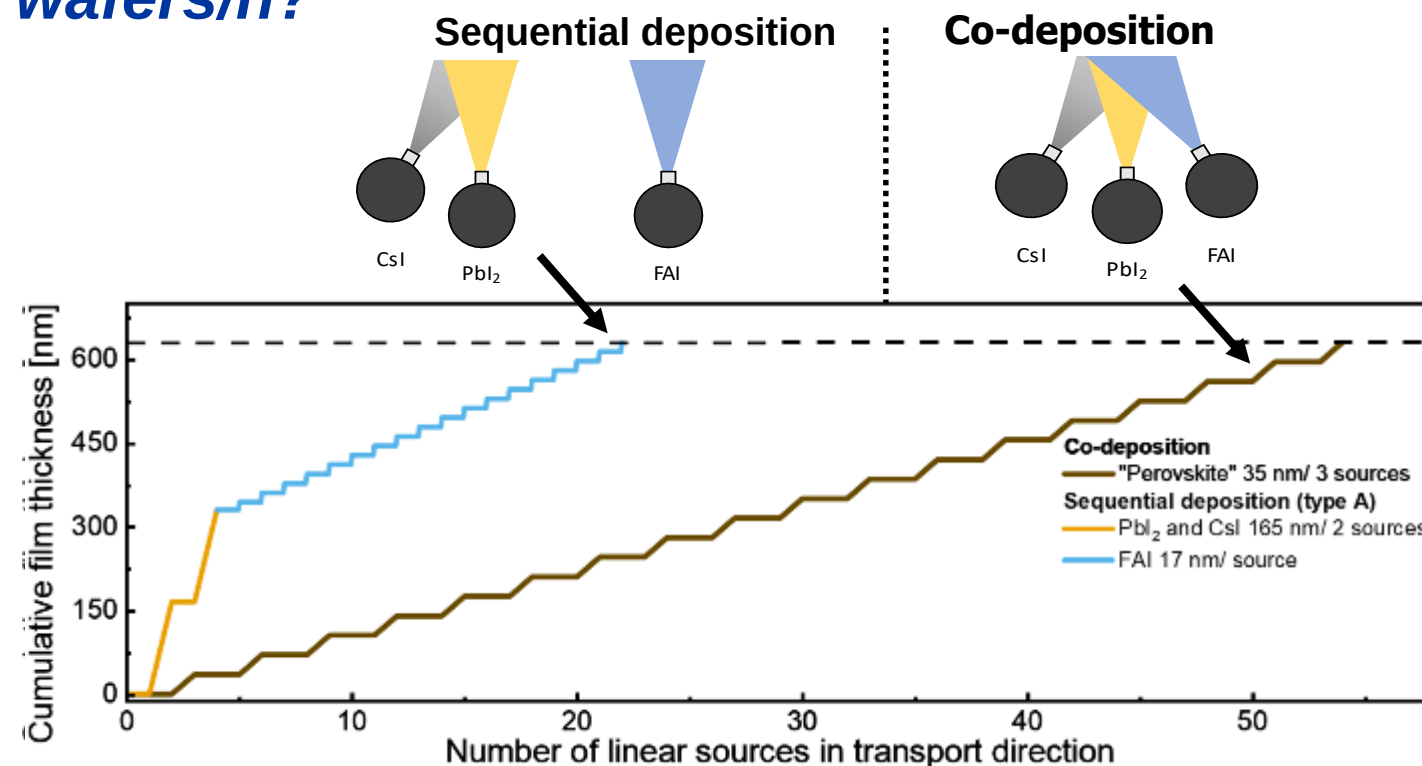


Strategies to achieve high throughput

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

VON ARDENNE 

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



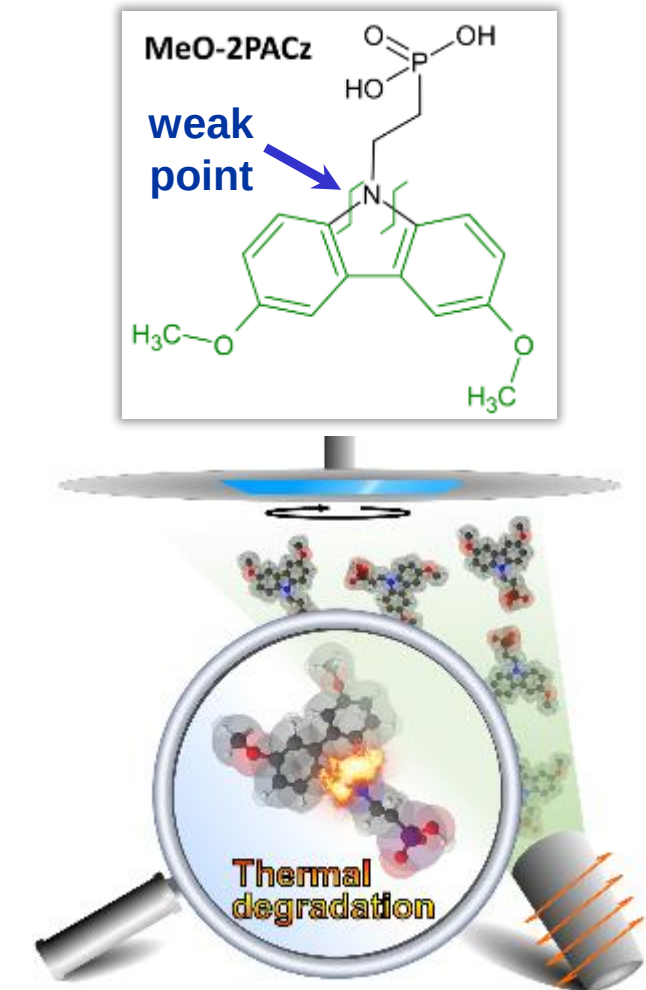
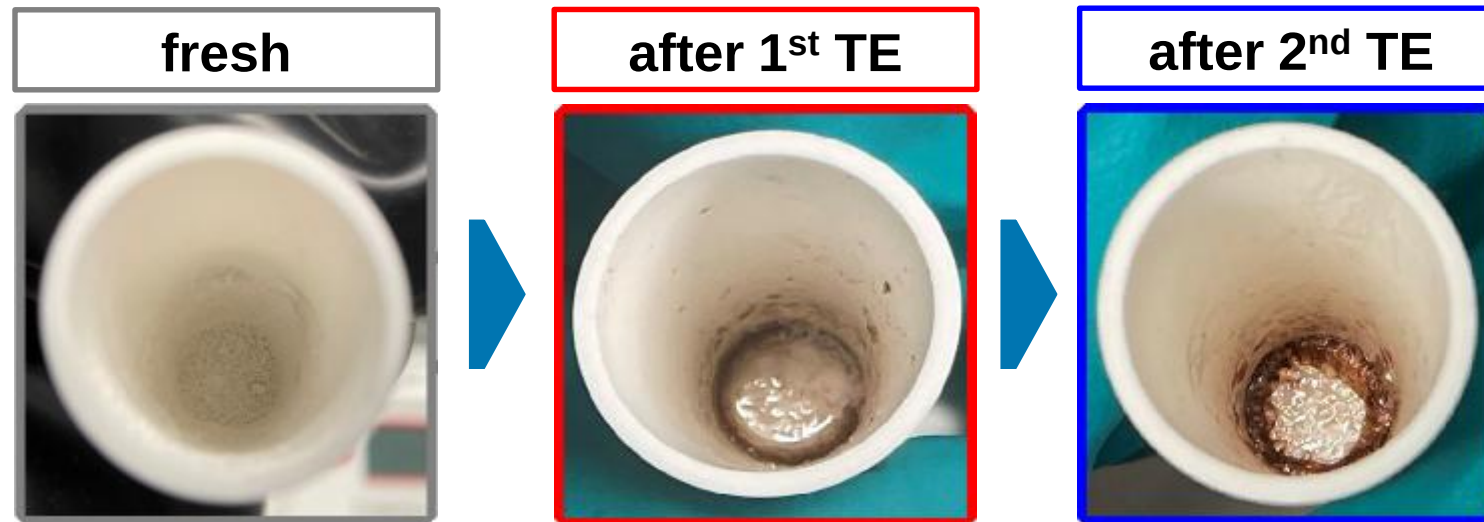
Deposition rates of FAI too low for conventional vapor phase deposition!

UNIVERSITÄT
PADERBORN

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 → **similar results as solution processing**

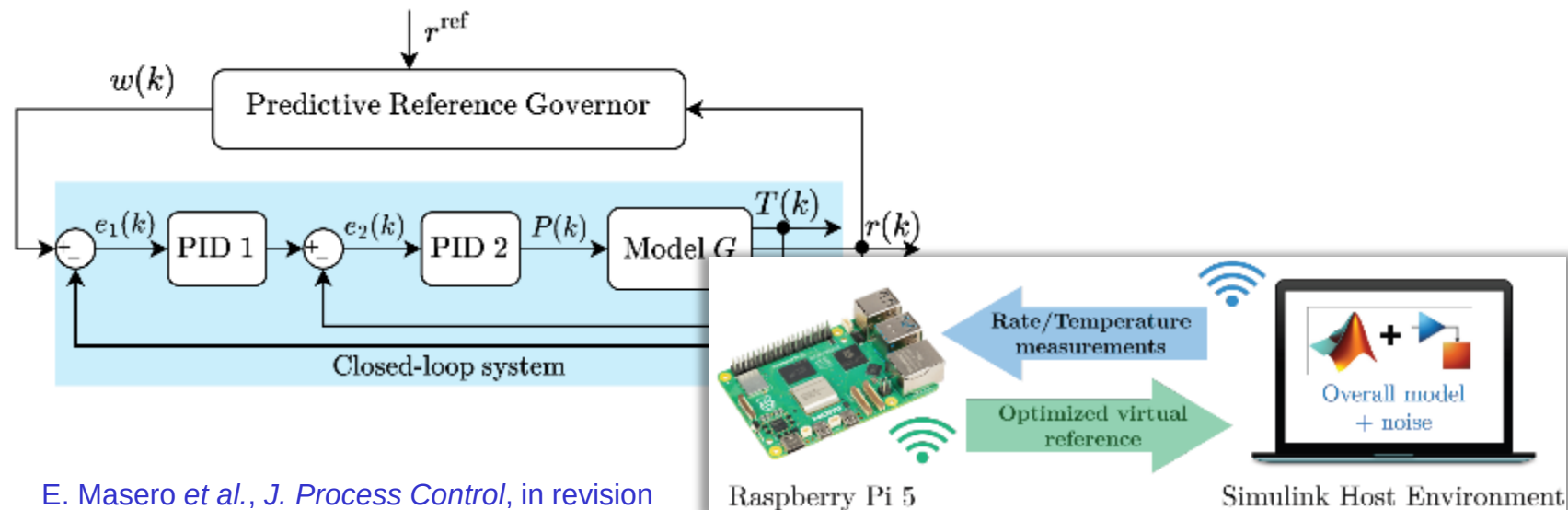


J. Vollbrecht *et al.*, *Solar RRL* 9(17), 2500429, (2025), DOI: 10.1002/solr.202500429

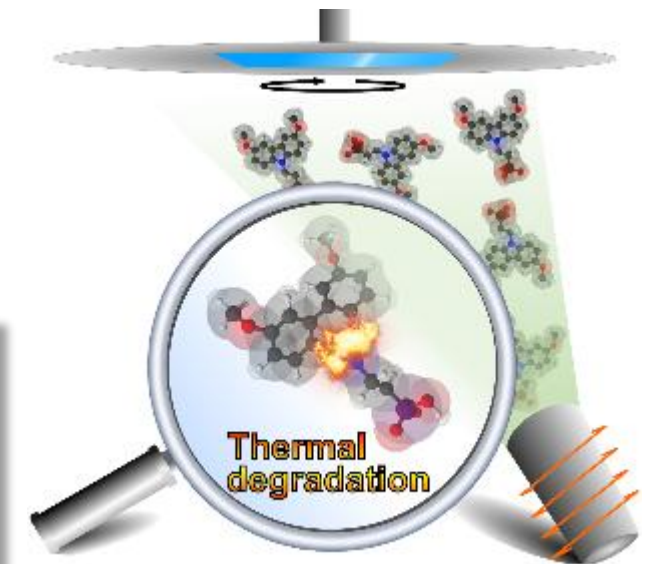
Strategies to achieve high throughput

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**



E. Masero et al., J. Process Control, in revision

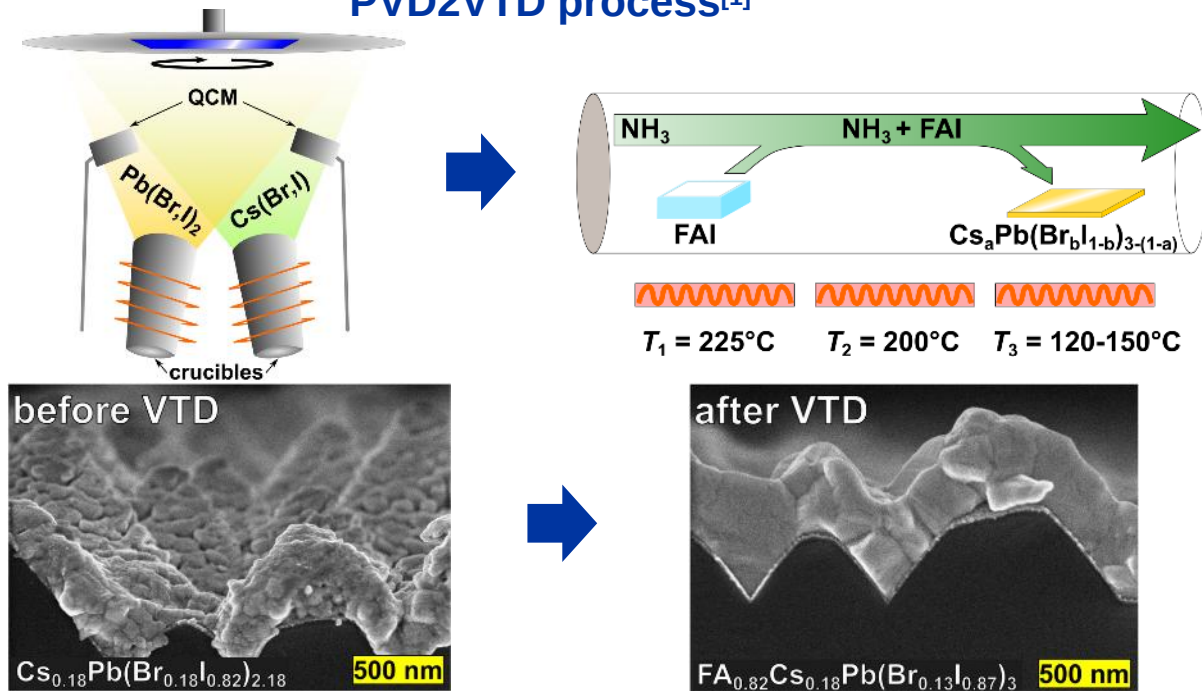


Hybrid-PVD + Gas Phase Transport Deposition (VTD)

- **Advantages:** solvent-free, conformal deposition of batch-processable perovskites
- **High throughput potential:** 18.6% efficient, fully solvent-free perovskite single-junction cells^[1]
- **Halide exchange:** observed for Br-containing perovskite scaffolds
- **Sequential VTD:** e.g. FAI → FABr; patent application filed^[2]
- **Industrialization:** initiated within new project HOPP (BMW)



PVD2VTD process^[1]

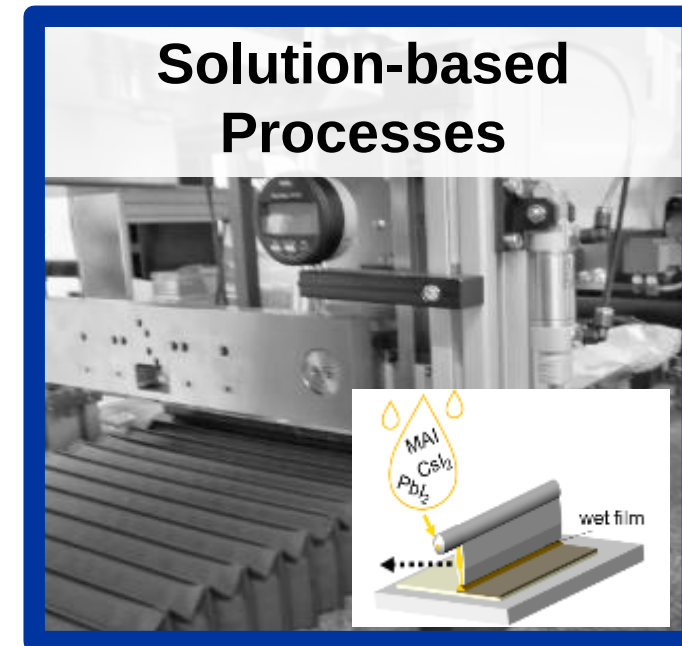
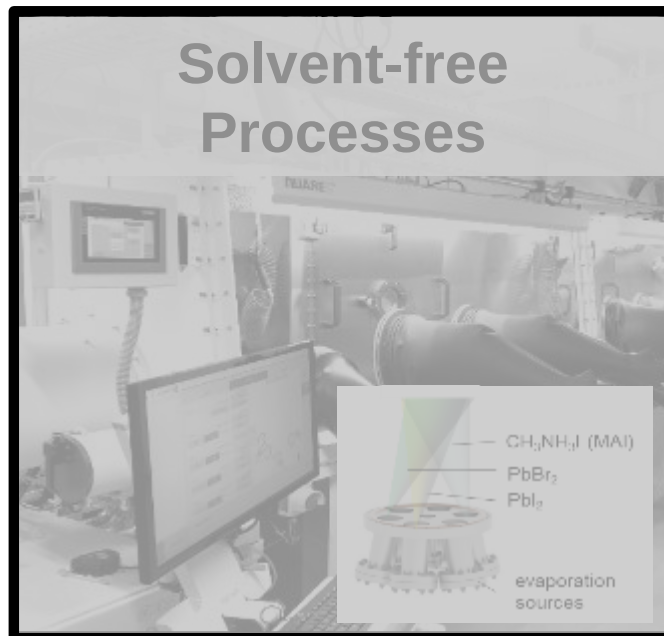


[1] R. Clausing *et al.*, manuscript in revision

[2] Patent application, I0461P-DE

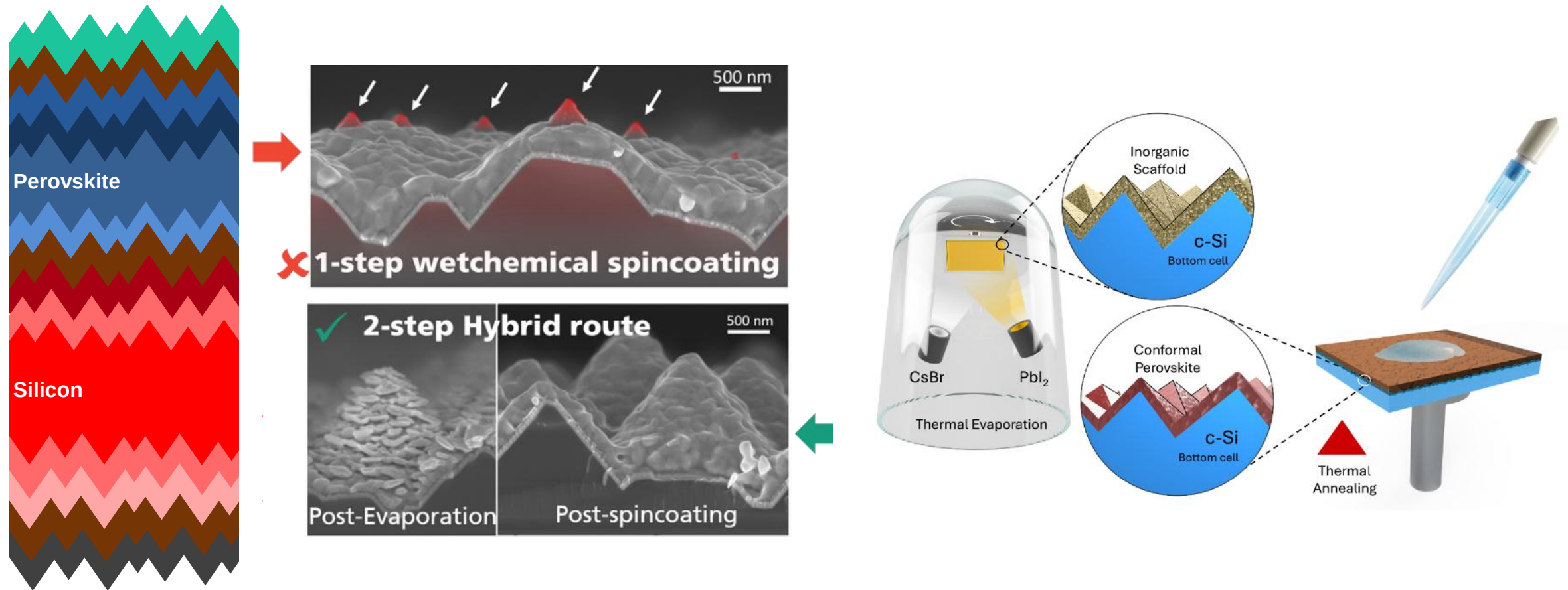
Versatile routes for scalable fabrication of perovskite thin films

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Perovskite-Silicon Tandem Solar Cells

Hybrid Route Processing for Perovskite on Industrial Textured Silicon

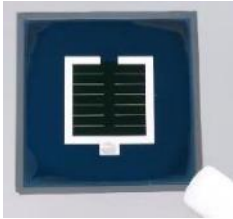


P. Schulze et al., *Thin Solid Films*, 704, 137970, (2020) DOI: 10.1016/j.tsf.2020.137970

Industry Compatibility

New Methods, Upscaling and Throughput

Cell area: 1 cm²

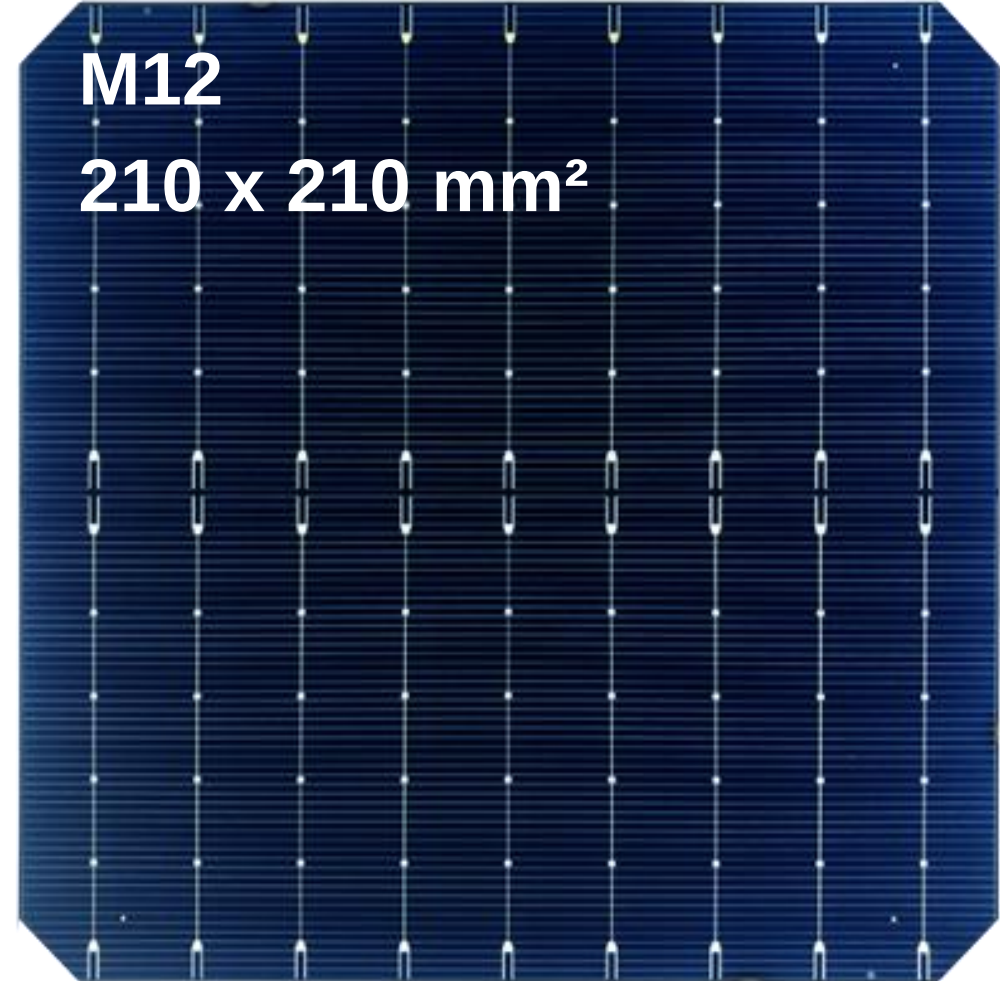


Throughput

Scaling the
area

Developing
the method

M12
210 x 210 mm²



210 mm

Overview Pero-Si-SCALE Labs

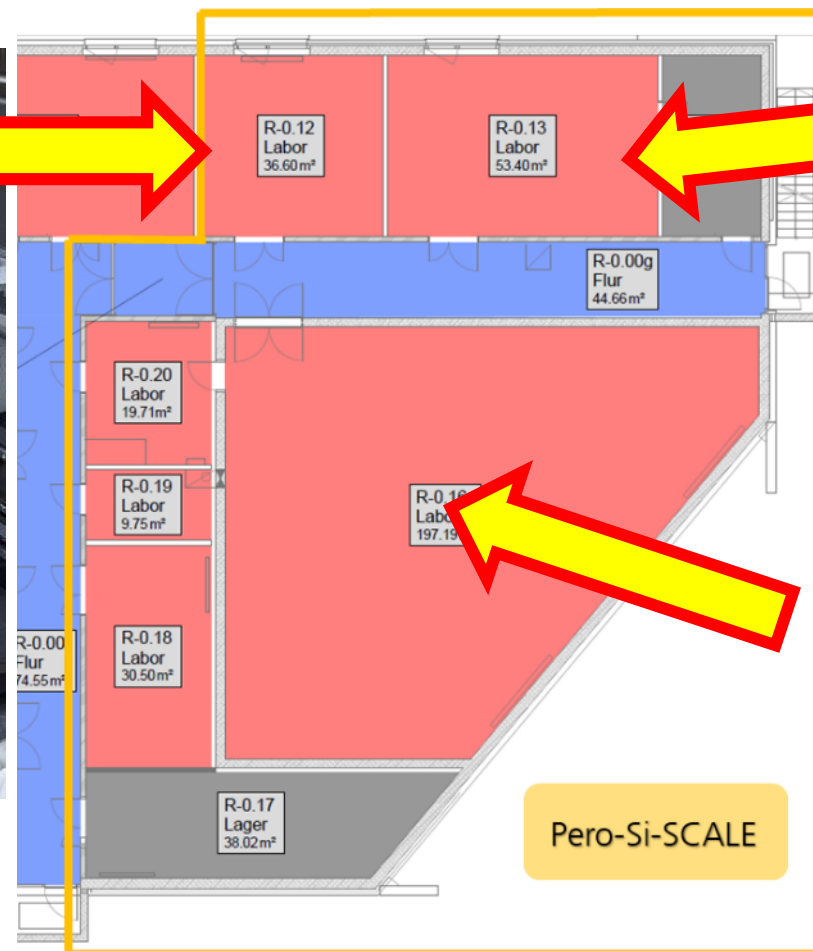
VON ARDENNE 
centrotherm

 **Fraunhofer**
ISE

 Federal Ministry
for Economic Affairs
and Energy

 **SUSS**

 **SALD** SPATIAL ALD
INNOVATORS



Overview Pero-Si-SCALE Labs

VON ARDENNE
centrotherm

Fraunhofer
ISE

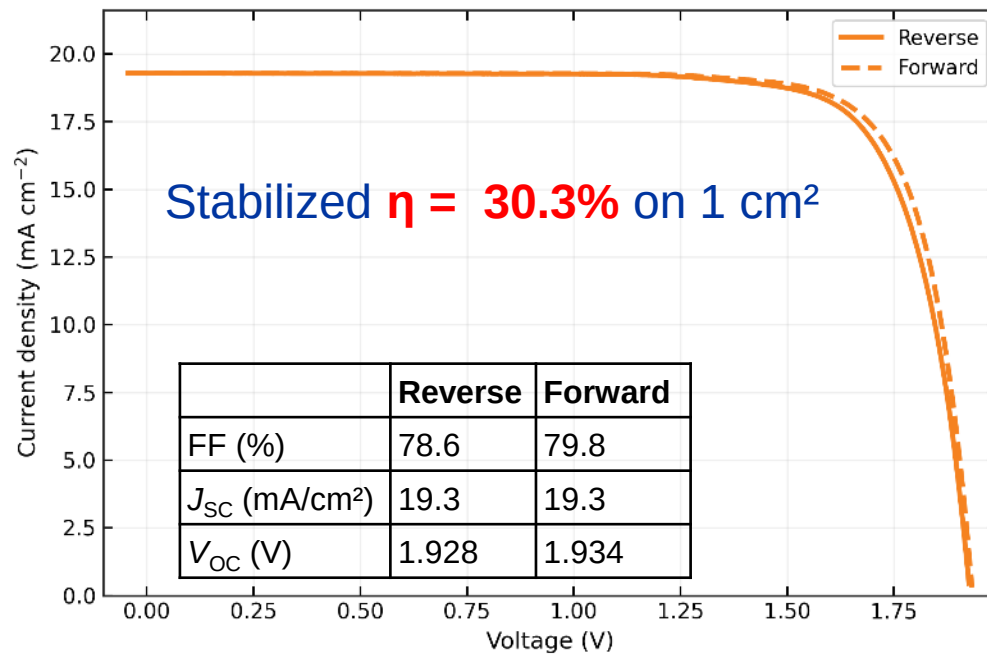
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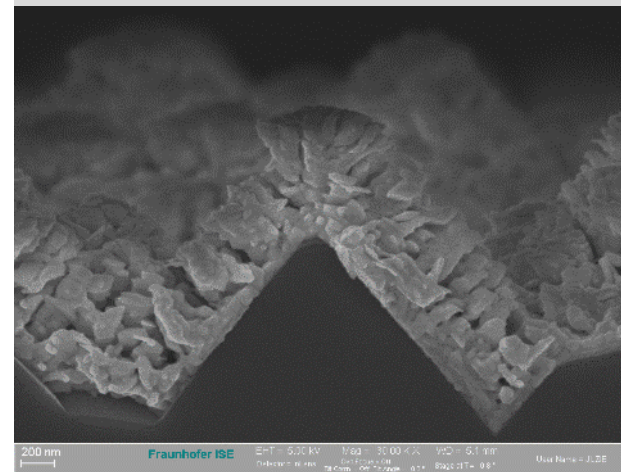
SALD SPATIAL ALD
INNOVATORS

Pero/Si Tandem Cell using Industrial Evaporation Processes

Best IV pair: 250351-08-6



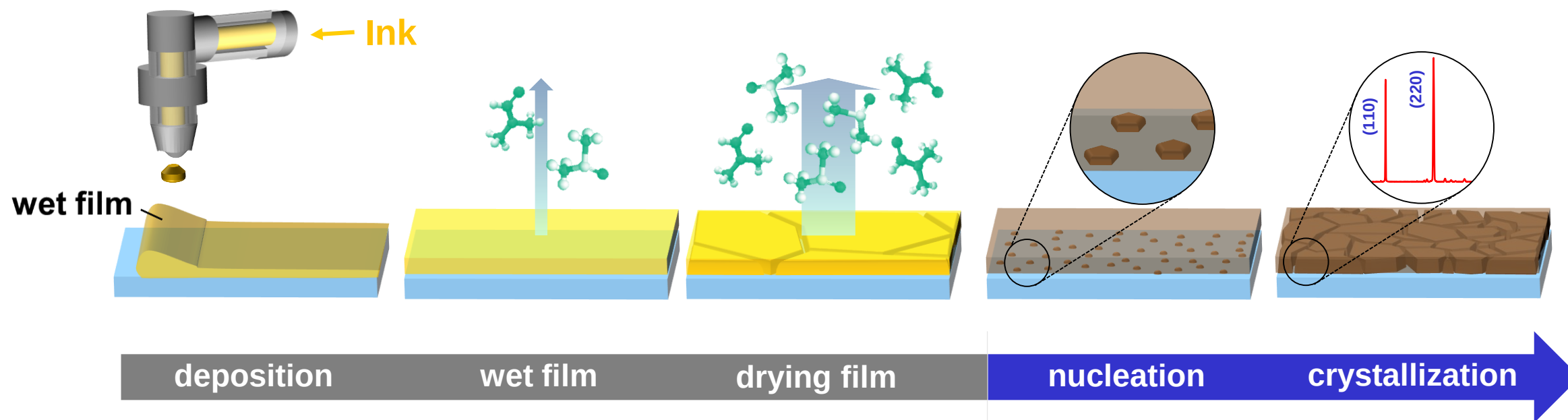
Homogeneous and conformal porous film on six G12 wafers



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.*



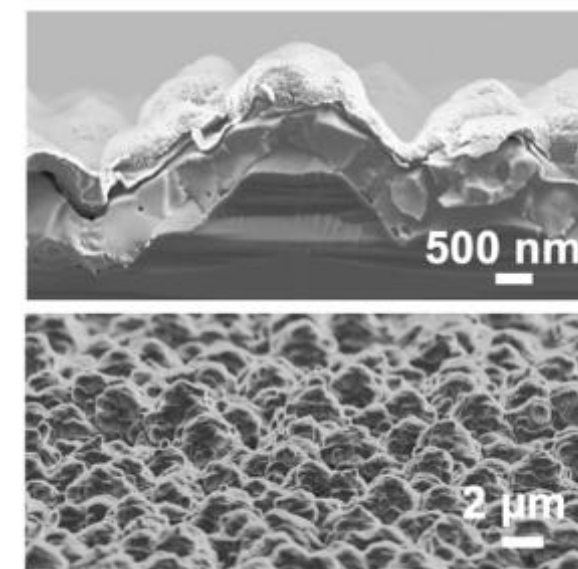
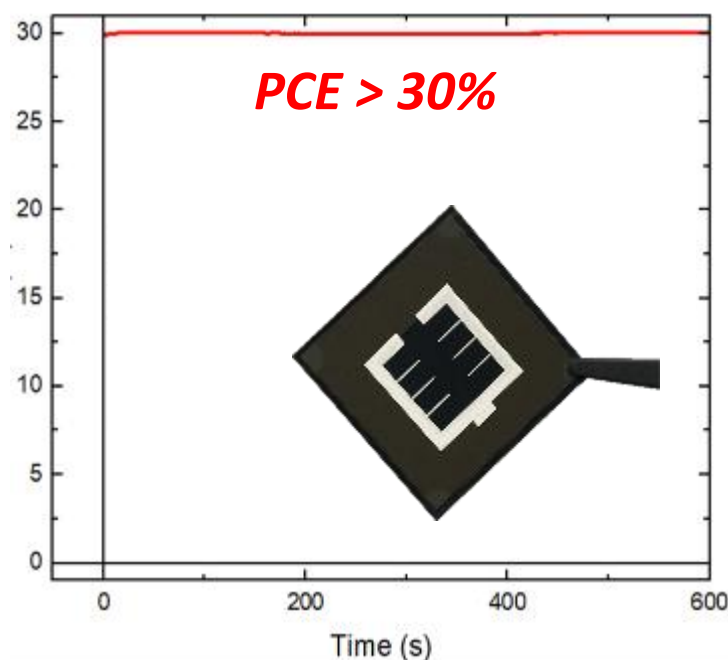
I. A. Howard *et al.*, *Adv. Mater.* **31**(26), 1806702 (2019), DOI:10.1002/adma.201806702

Inkjet-Printed Perovskite/Si Tandem Solar Cells

High performance tandems on industrial textures Si bottom solar cells

NOTION
SYSTEMS

Qcells



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

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

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

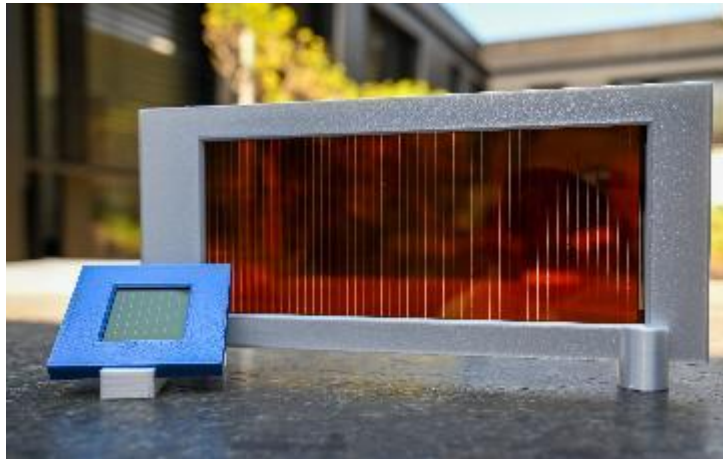
F. Schackmar *et al.*, *Advanced Materials Technologies* 6(2), 2000271 (2021).

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

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

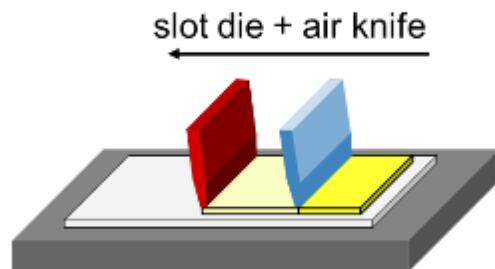
F. Mathies *et al.*, *ACS Applied Energy Materials* 1(5), 1834-1839 (2018).

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



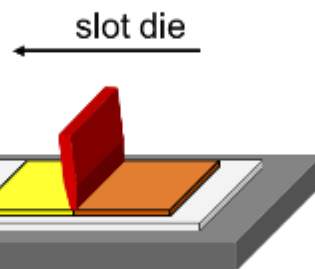
substrate
sizes: 5×5
and 10×24
cm²

first step:

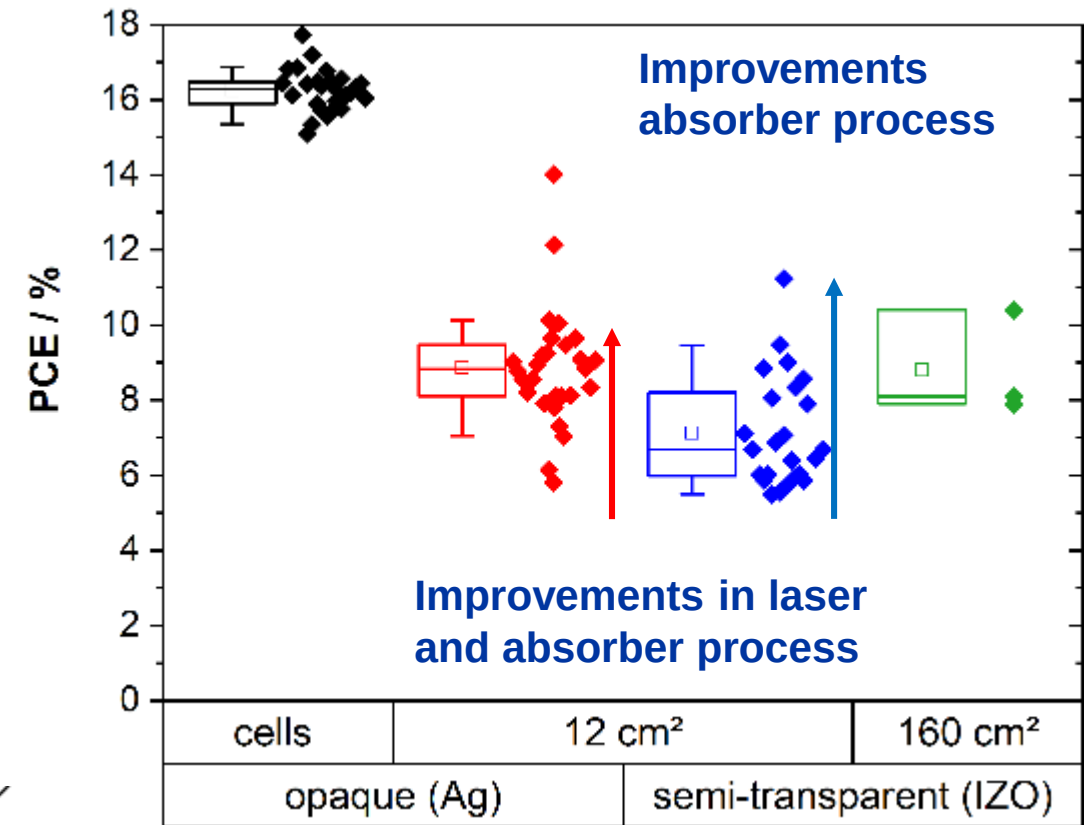


- e.g. PbI_2 , CsI ...
- in DMSO

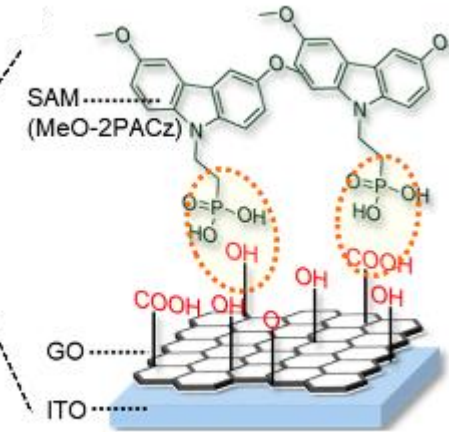
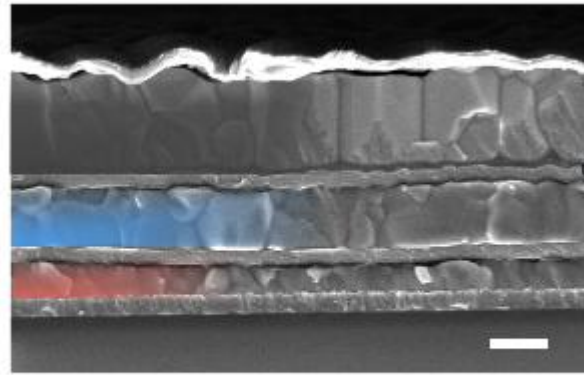
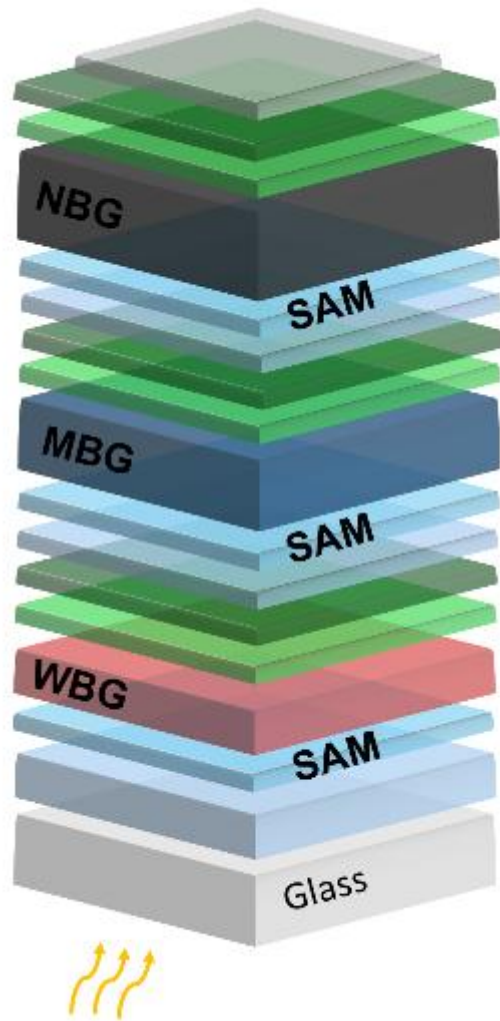
second step:



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

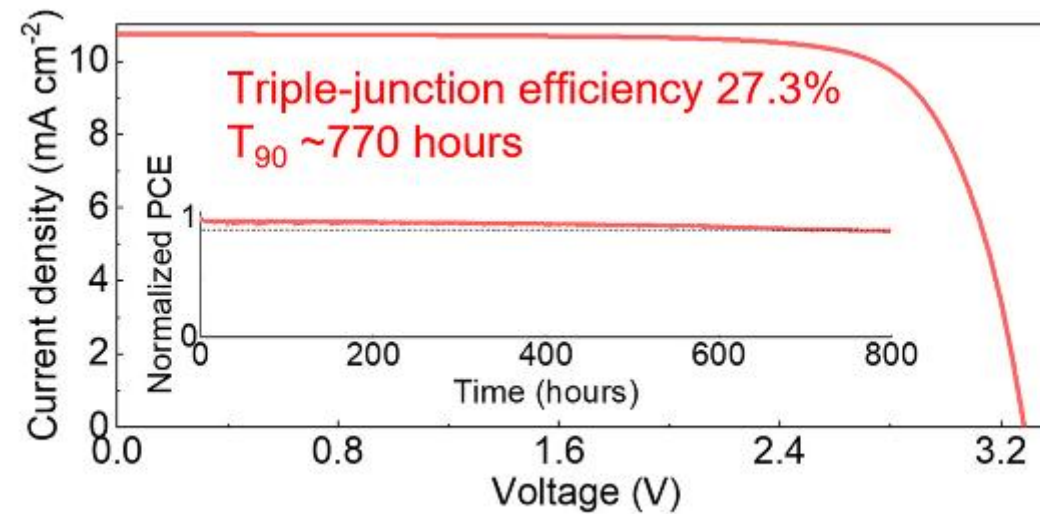


Triple Junction All-Perovskite Solar Cells With SAMs in All Subcells



HZB Helmholtz
Zentrum Berlin

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



Triple junctions yields promising efficiency and stability at 25°C

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**

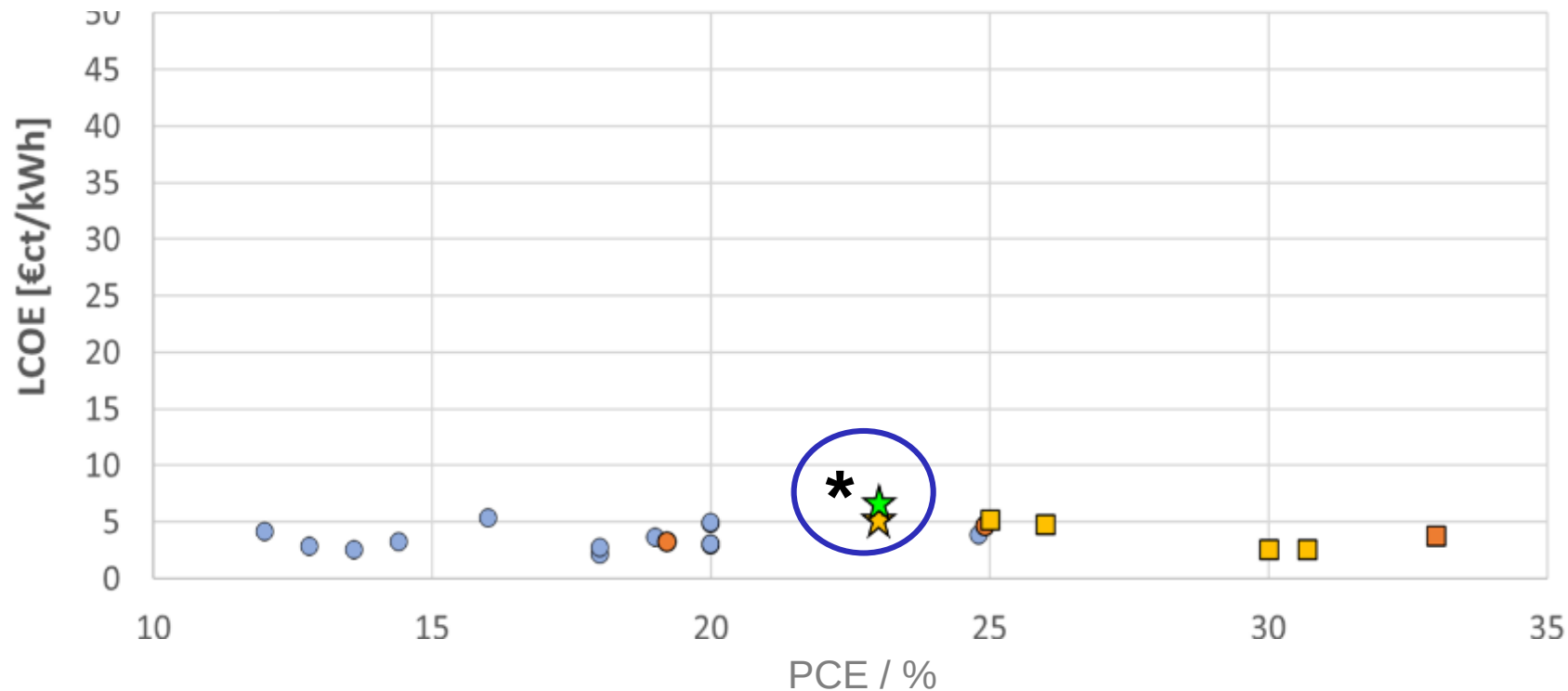
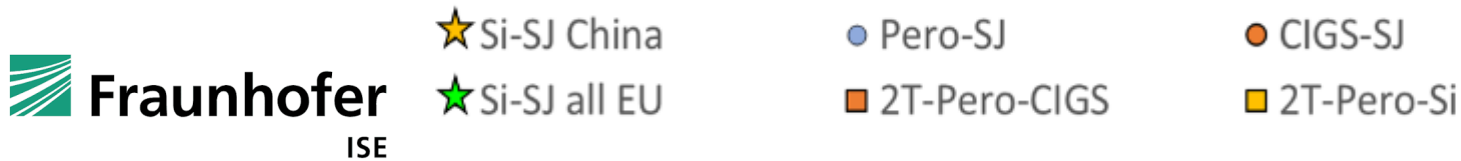


Specialty-chemicals company for perovskite materials, transport materials, passivation chemicals and scale-up synthesis. **2009**



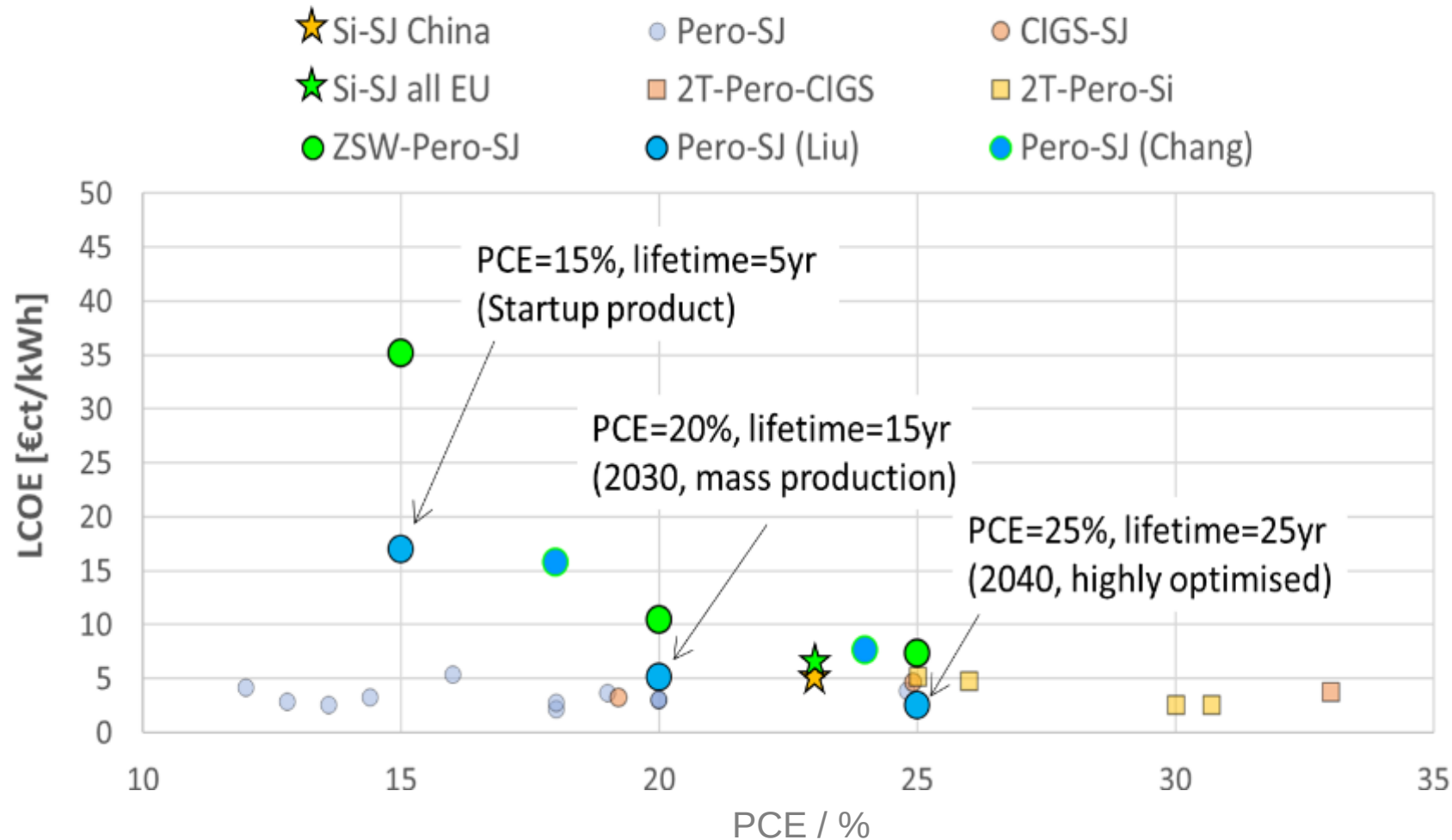
Advanced luminescence characterization equipment for perovskite, tandem and other optoelectronic devices. **2021**

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.

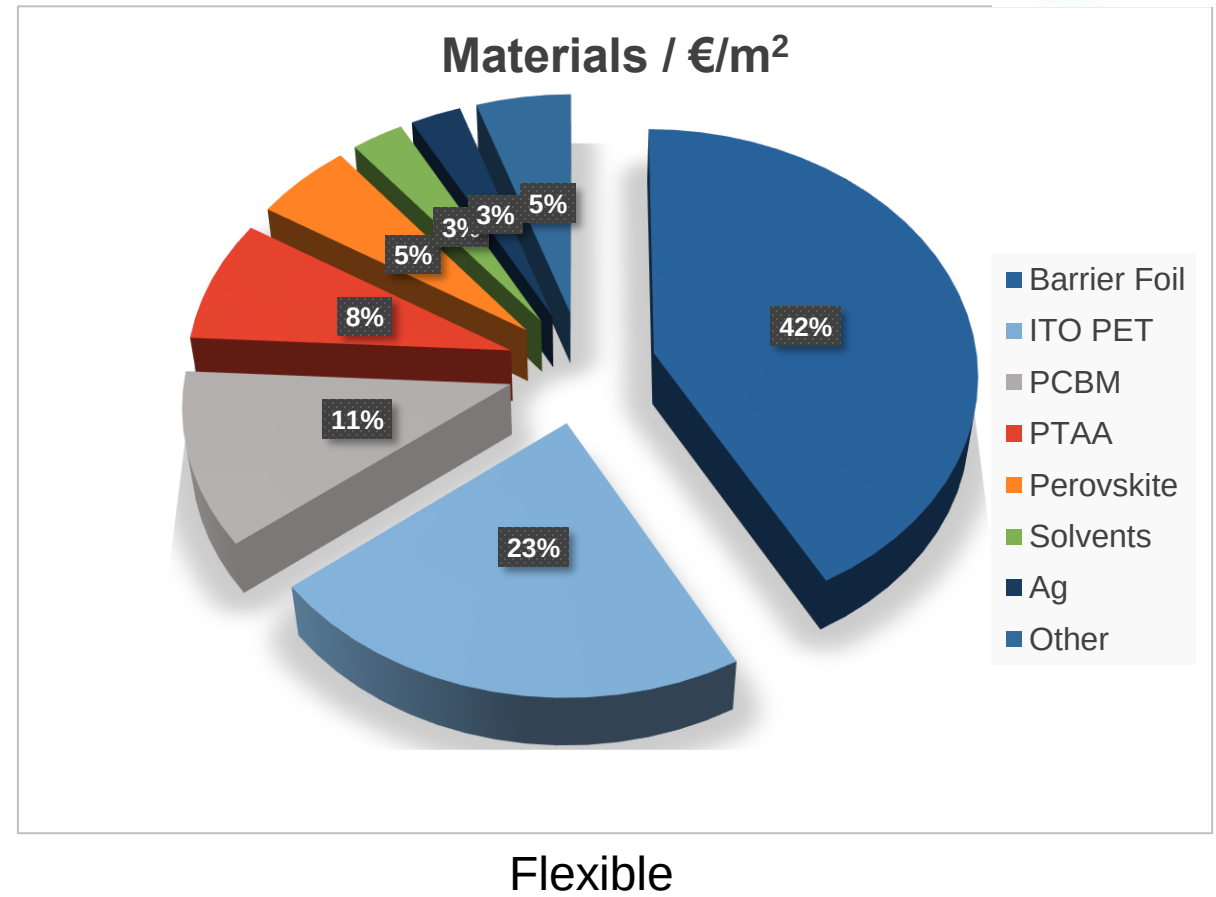
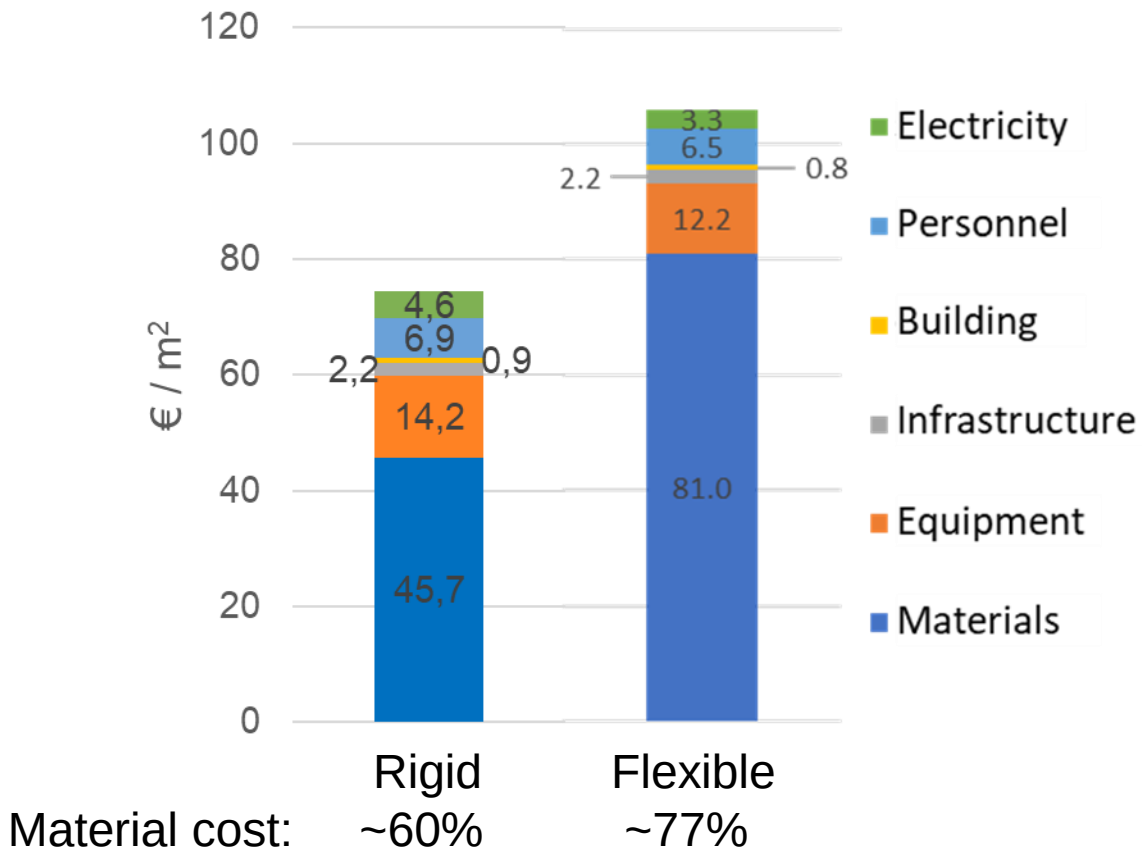


- A minimum of **PCE=20%**, **yield=90%**, **lifetime=15yrs** is required to get into a prize competitive range
- Current record efficiency: **22,1% PCE** (Renshine - [NLR Charts](#))

*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.



Thank you very much for your attention!

Thanks to all contributors!