Perovskite-based Tandem Photovoltaics

State of the art and Outlook

Prof. Dr. Ulrich W. Paetzold

Perovskite-Based Tandem Photovoltaics @KIT

Karlsruhe Institute of Technology

The Research University in the Helmholtz Association

State University

&

HELMHOLTZ

National Research Center

Energy

Mobility

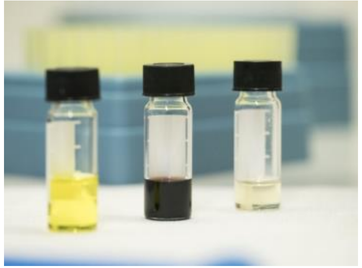
Information

Perovskite Thin-Film Lab

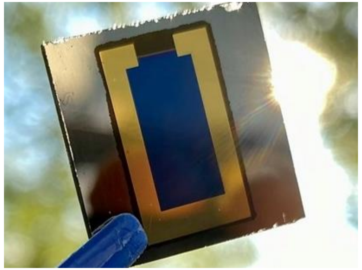
Upscaling Lab

Printing and Coating

Perovskite-Based Tandem Photovoltaics @KIT



Materials



Devices: Perovskite-based Tandem PV

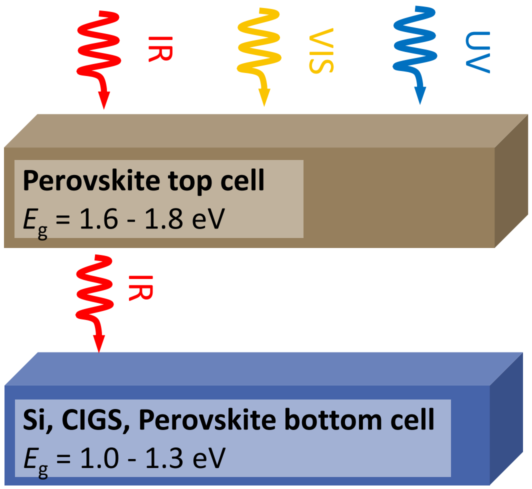
Scalable Fabrication Methods

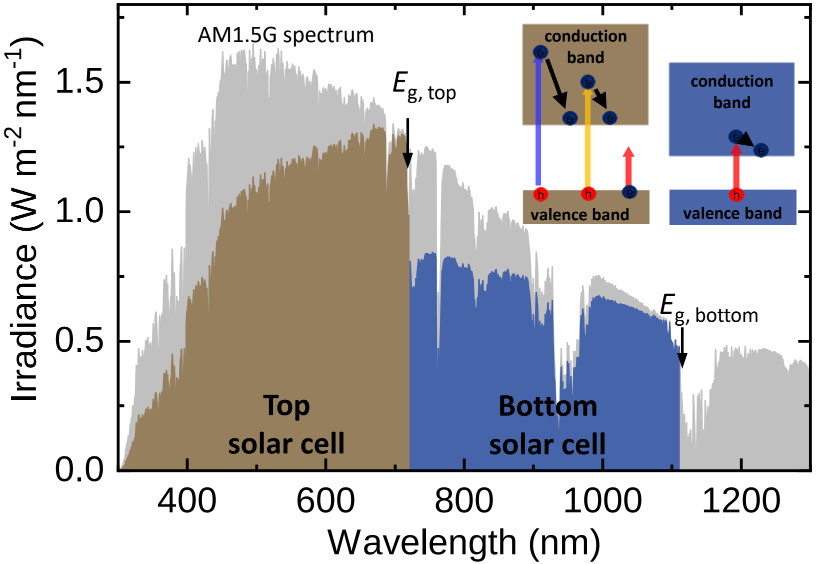
Applications: BIPV, VIPV & AgriPV

Mission: *Advance the* ***stability****,* ***scalability,*** *and* ***performance*** *of perovskite-based tandem photovoltaics.*

Taskforce Perovskite PV at KIT // 28 PhDs and Postdocs

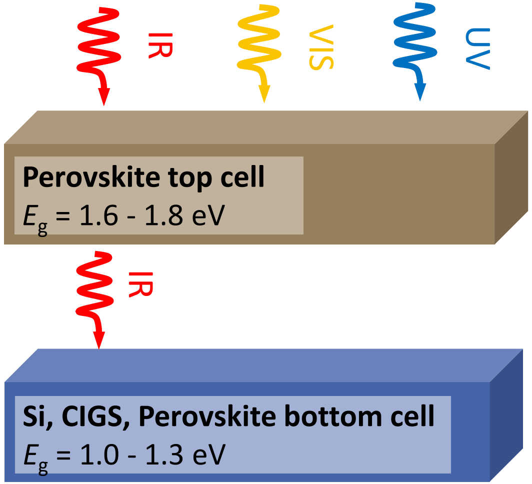
High Efficiency Perovskite-Based Tandem Photovoltaics

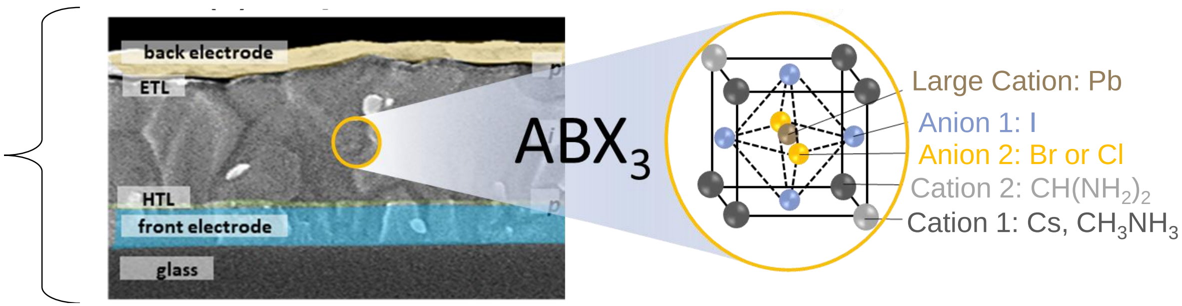




Tandem PV reduces intrinsic thermalization losses, thereby enabling much higher power conversion efficiencies (thermodynamic limit > 40%).

High Efficiency Perovskite-Based Tandem Photovoltaics

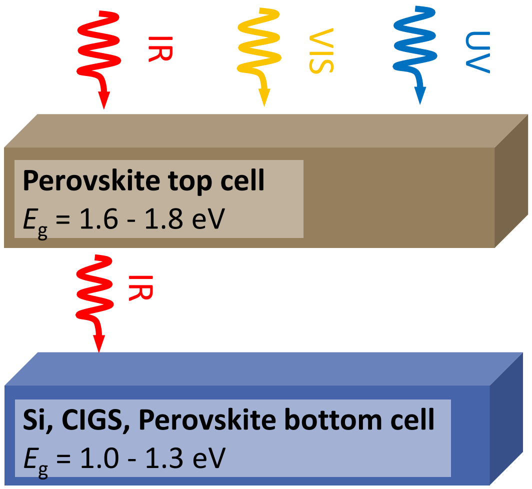


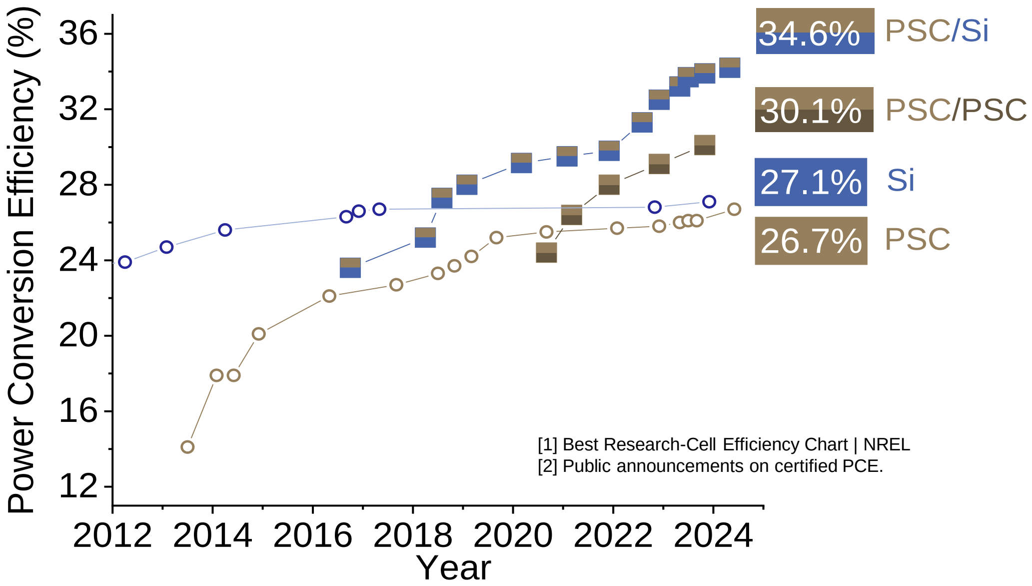


+ **High defect tolerance**
+ **Tunable bandgap**
+ **Long diffusion length**
+ **Short absorption length**

− **Stability**
− **Toxicity**

High Efficiency Perovskite-Based Tandem Photovoltaics

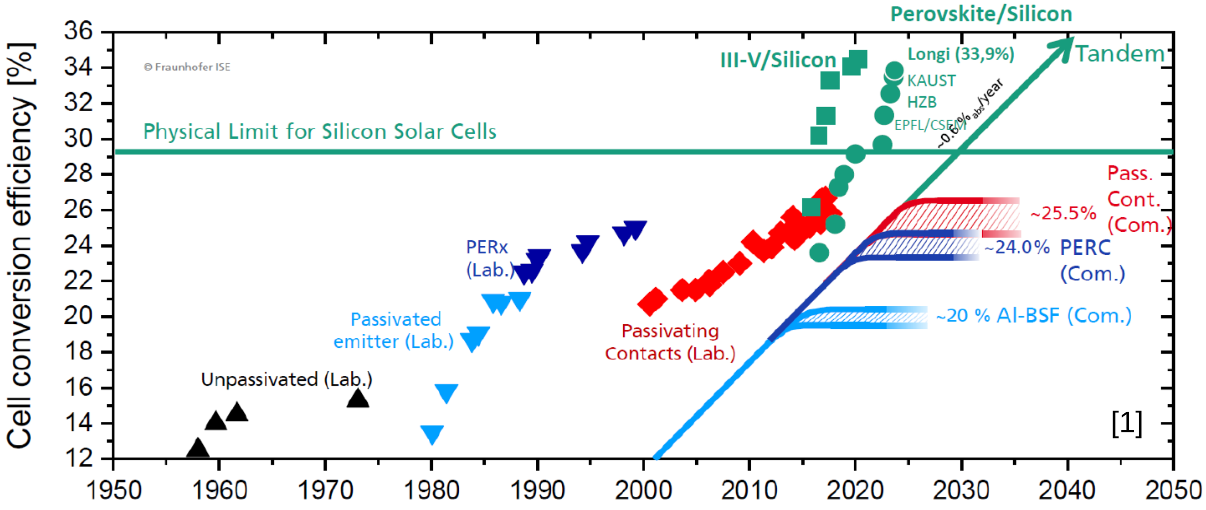




The rapid increase and the efficiency potential inspire the rise of perovskite tandem PV.

Why Perovskite-based Tandem PV?

The efficiency of conventional Si PV converges in ~5 years towards 27%.



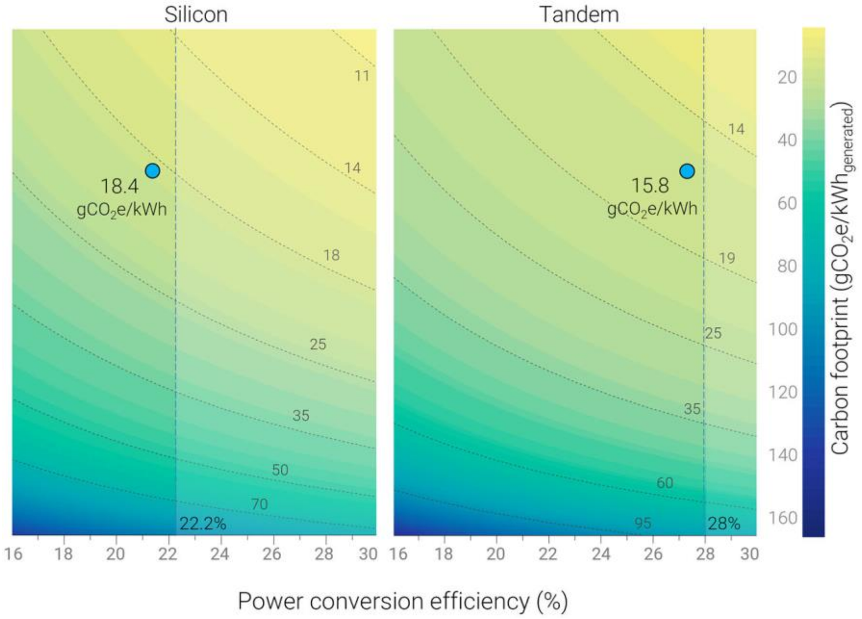
Solution: Tandem PV with…

- Efficiency > 30%,
- Long-term stability,
- Material availability,
- Scalable production.

[1] adapted from M. Hermle | ISE photovoltaics report 2022. [ISE Fraunhofer]

Why Perovskite-based Tandem PV?

Perovskite-based tandem photovoltaics reduce the carbon footprint of PV .



[1] N. Bartie et al. Journal of Industrial Ecology 2023;27:993–1007. [HZB]

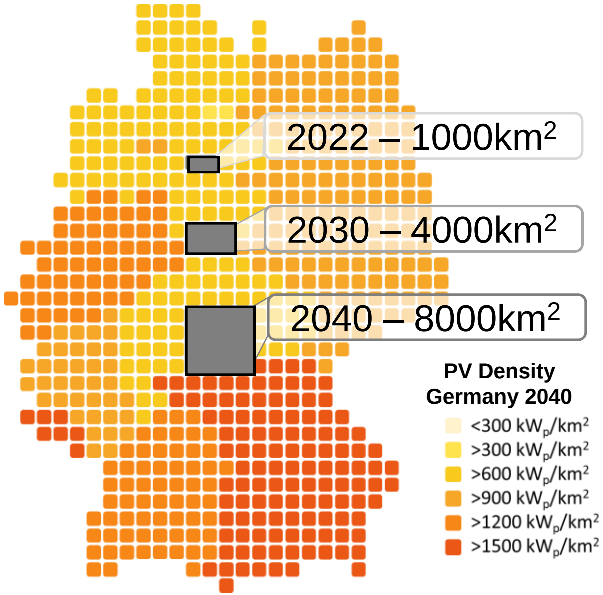
- Many LCAs and circularity evaluations forecast a significantly lower impact for perovskite-based tandem solar cells compared to conventional silicon photovoltaics (Si PV).
- Assuming similar stability, the carbon footprint (measured in gCO2e) is expected to be reduced by at least 15%.

Why Perovskite-based Tandem PV?

Better use of area for PV to meet EU Green Deal & German Osterpacket Goals!

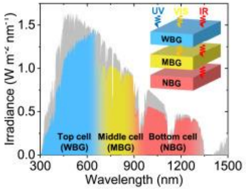
- German Osterpaket[1] Targets:
  - 225 GW_p in 2030
  - 400 GW_p in 2040
- *PV has lowest footprint among all renewables.*
- *But current PV technologies would require ~2% space in Germany in 2040.*

=> ***High Efficiency*** *and* ***Integration*** *are major trends for future PV Technologies.*



[1] Deutscher Bundestag Drucksache 20/1630 20.

BREAKING NEWS in 2024

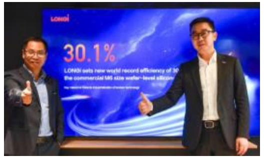


Perovskite/Perovskite/Si Tandem Cells w. PCE > 24% Joule, EES, etc. Q1/2024

SwiftSolar

TANDEM PV

DOE support & Series A Financing of Tandem Startup companies in US Q1/Q2 2024June

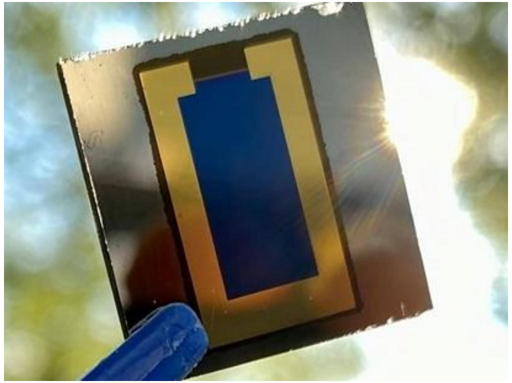


30.1% Perovskite/Si solar cell on M6 wafer Longhi, Intersolar, June

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

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

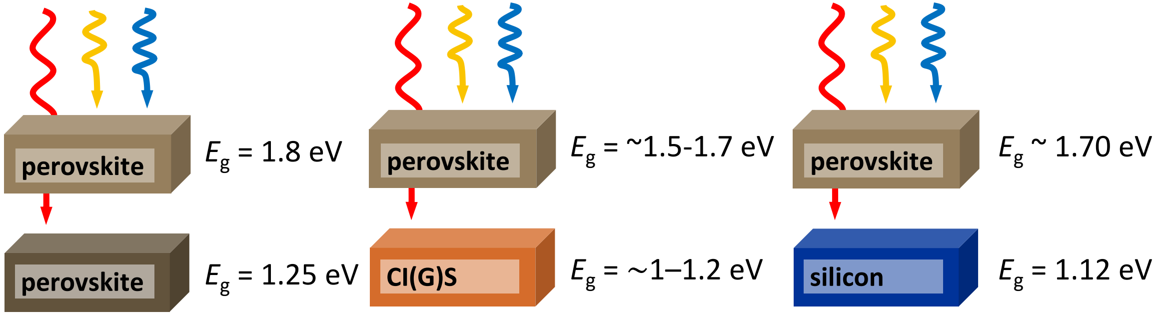
Prof. Dr. U. W. Paetzold

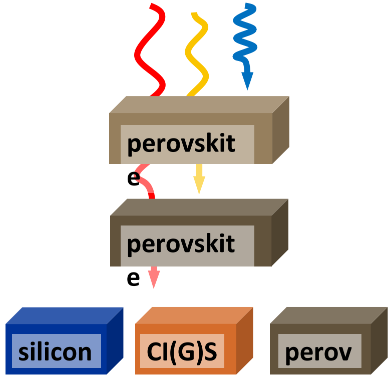


High Efficiency & New Device Architectures

Versatile options …

Tandem PV → **Multijunction PV**





record PCE	30.4% [1]	24.2% [2]	34.6% [3]
PCE potential	> 35%	> 35%	> 39%
all thin film	yes	yes	no

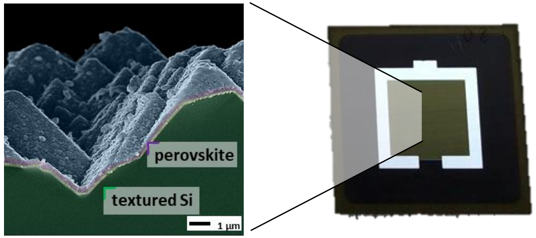
PCE potential >> 40%

[1] Announcement Quangdong Onesolar Technology.
[2] HZB | Best Research-Cell Efficiency Chart | NREL.
[3] Announcement Longhi at SNEC, June 2024.

DEVICES: Perovskite-Based Tandem Photovoltaics

Karlsruhe Institute of Technology

Perovskite/Si Tandem PV



>31%

A. Farag et al., *Adv. Func. Mater*. **33**(3), 2210758 (2023).

J. Roger et al. Adv. Energy Mater. 12(27), 2200961 (2022).

T. Feeney et al., *Solar RRL* **6**(12), 2200662 (2022).

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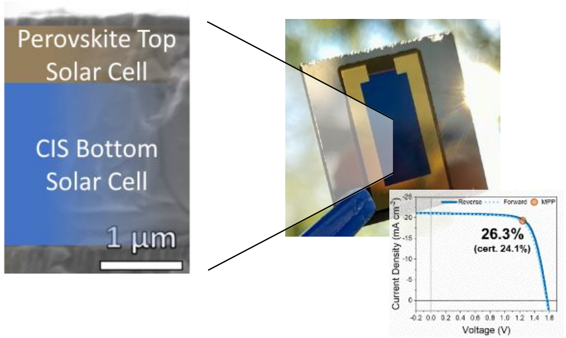
Perovskite/CI(G)S Tandem PV

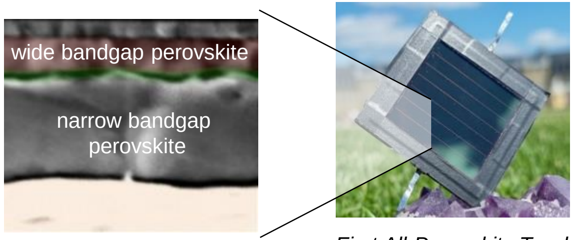


M. Ruiz Preciado et al., *ACS Energy Letters* **7**(7), 2273–2281 (2022).

S. Gharibzadeh et al., *Adv. Func. Mater.***30**(19), 19099196, (2020).

T. Feeney et al., *Solar RRL* **6**(12), 2200662 (2022).

All-Perovskite Tandem PV



First All-Perovskite Tandem Solar Module Fabricated

B. A. Nejand, et al., *Nature Energy* **7**, 620–630 (2022).

H. Hu et al. *Adv. Funct. Mater.* 2107650 (2021).

B. A. Nejand, et al., *Adv. Energy Mater.* 1902583 (2020).

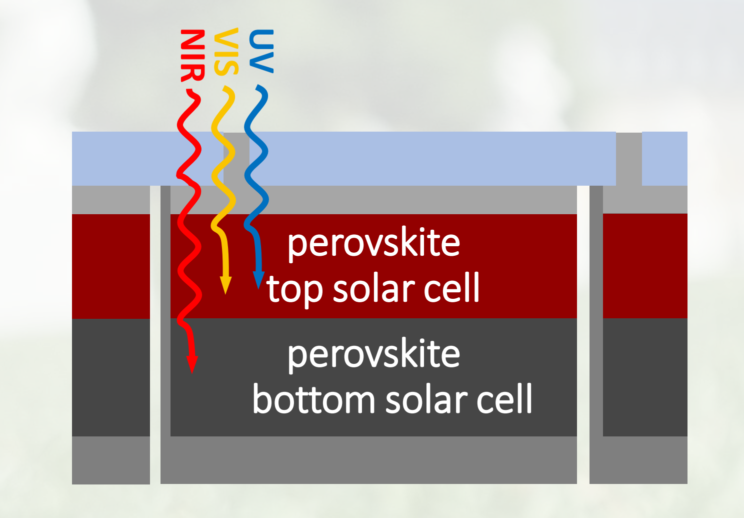
erc European Research Council
PERCISTAND
NEXUS
Federal Ministry for Economic Affairs and Climate Action
HELMHOLTZ ASSOCIATION
Baden-Württemberg Stiftung

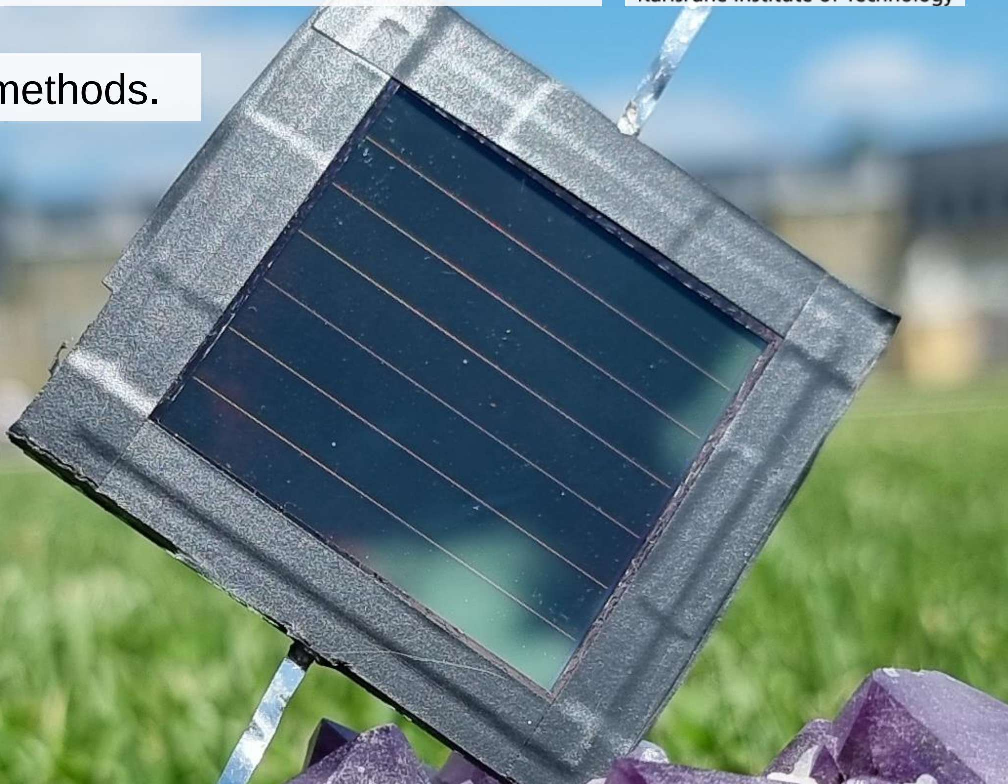
Prof. Dr. U. W. Paetzold

World’s First All-Perovskite Tandem Solar Module Fabricated at KIT!

Karlsruhe Institute of Technology

All layers processed with scalable fabrication methods.

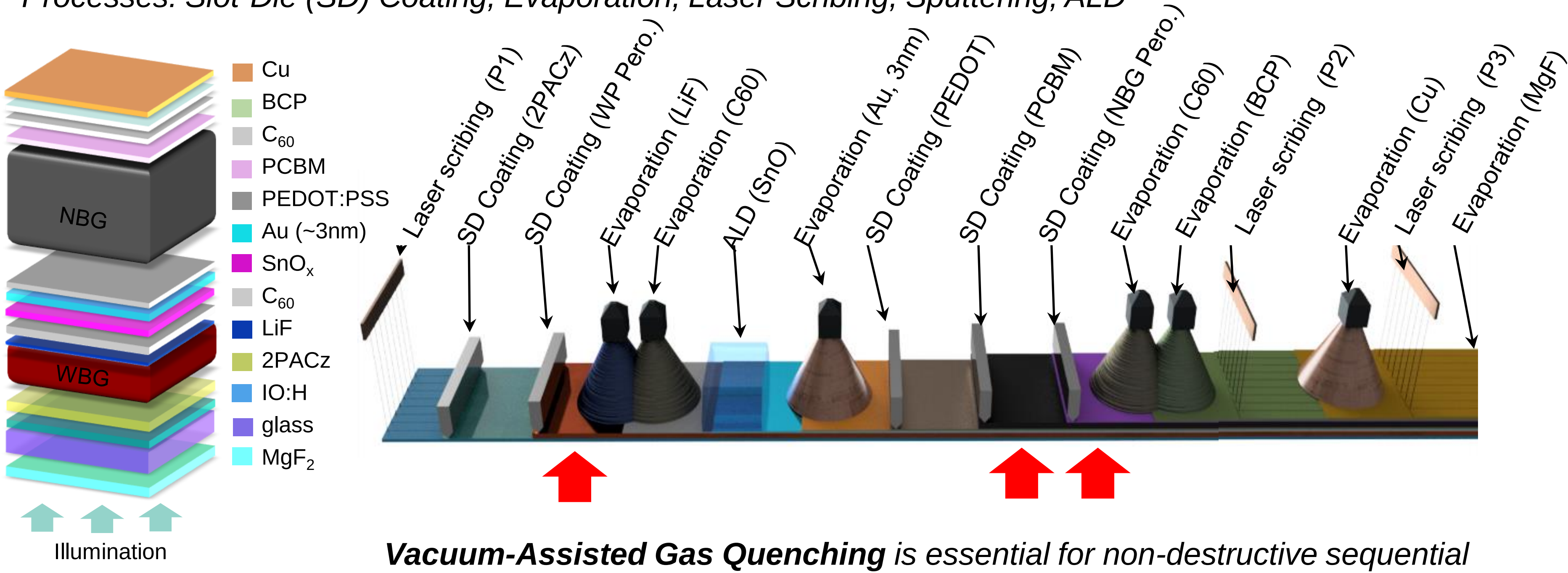




B. Abdollahi et al., *Nature Energy* **7**, 620–630 (2022). DOI: 10.1038/s41560-022-01059-w

All-perovskite tandem modules processed exclusively with scalable fabrication methods

Processes: Slot-Die (SD) Coating, Evaporation, Laser Scribing, Sputtering, ALD

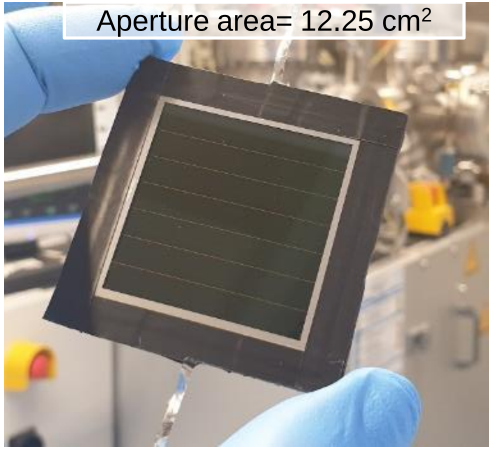


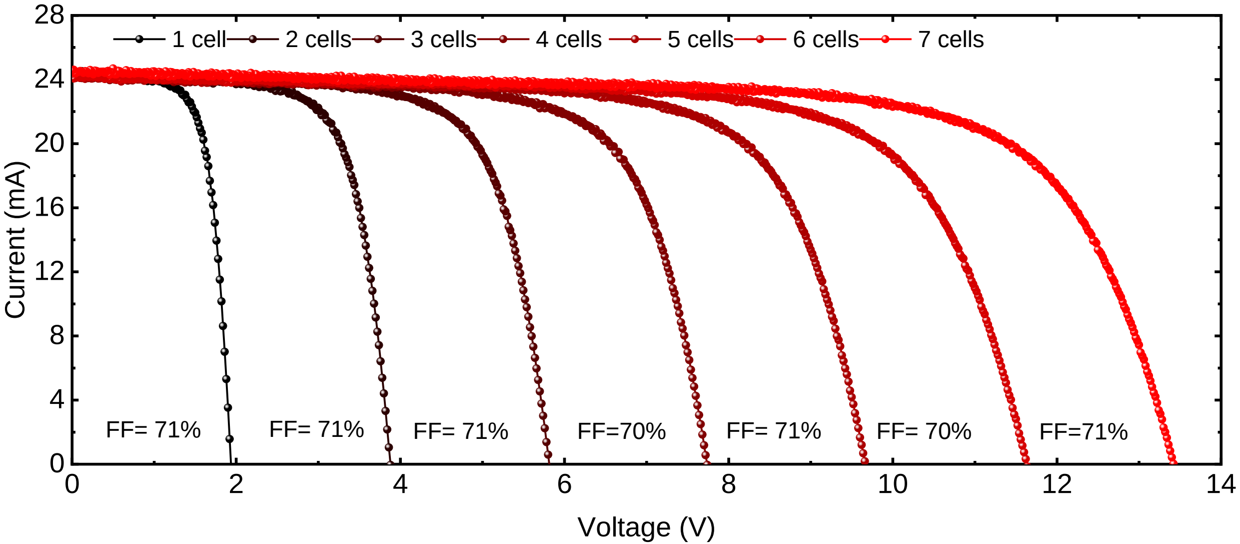
***Vacuum-Assisted Gas Quenching** is essential for non-destructive sequential solution processing!*

B. Abdollahi et al., *Nature Energy* , *DOI: 10.1038/s41560-022-01059-w* (2022).

All-perovskite tandem modules processed exclusively with scalable fabrication methods

Power conversion efficiency of 19.3% and > 23% on an aperture area of 12.25cm² and 4 cm², respectively.



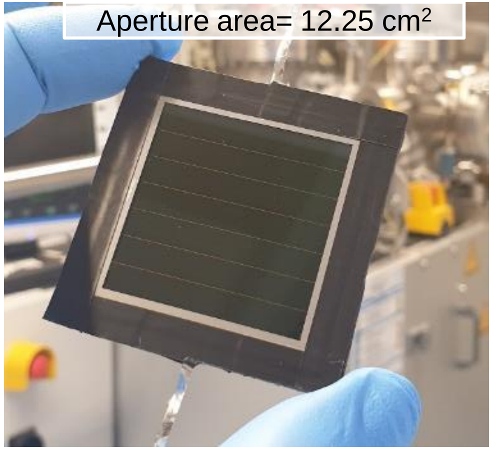


Power generation builds up stripe by stripe.

B. Abdollahi et al., *Nature Energy , DOI: 10.1038/s41560-022-01059-w* (2022).

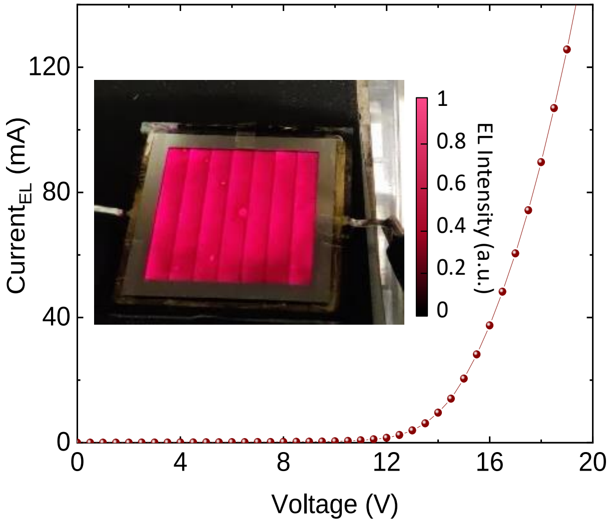
All-perovskite tandem modules processed exclusively with scalable fabrication methods

Power conversion efficiency of 19.3% and > 23% on an aperture area of 12.25cm² and 4 cm², respectively.



Photovoltaic characteristics of module

Device	Area cm^2	V_{oc} (V)	FF (%)	I_{sc} (mA)	PCE (%)
Cell strip (BW)	1.75	1.93	71	24.9	19.4
(FW)	1.75	1.91	70	24.5	18.8
Module (BW)	12.25	13.3	71	24.8	19.1
(FW)		13.1	71	24.8	18.8

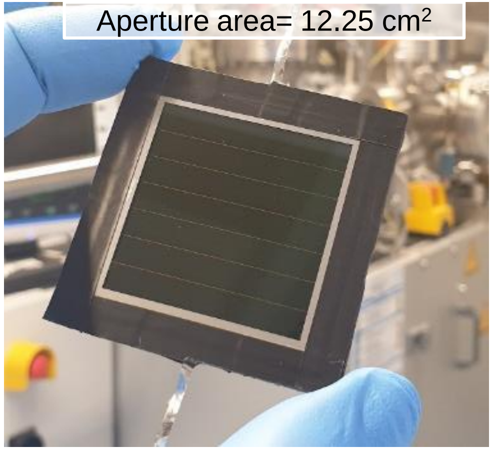


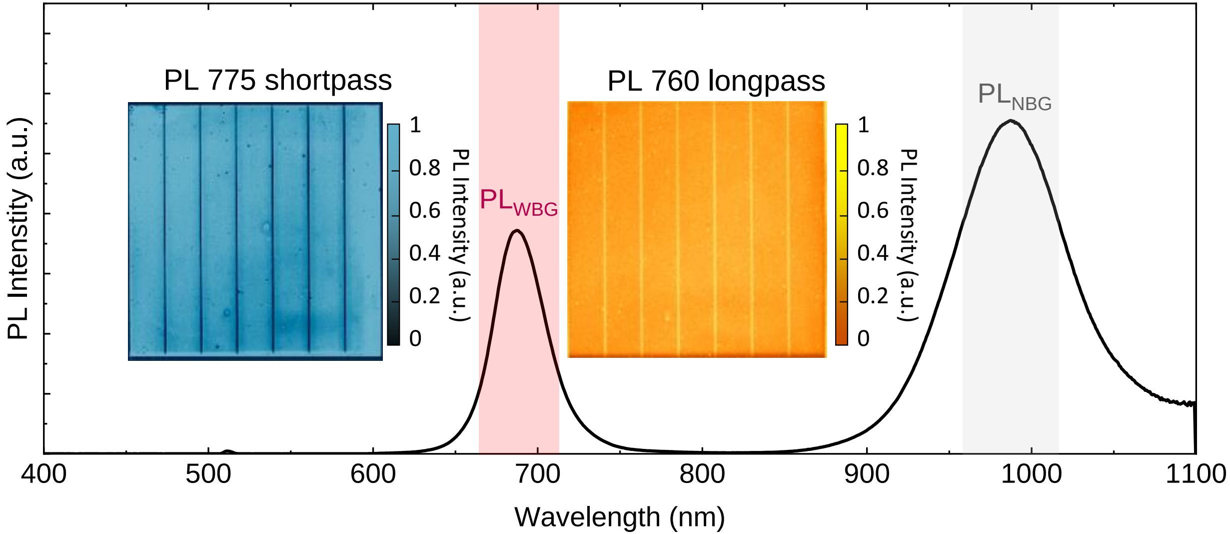
Low scaling losses comparing PCE on cell-stripe level (PCE~19.4%) and module level (PCE~19.1%).

B. Abdollahi et al., *Nature Energy , DOI: 10.1038/s41560-022-01059-w* (2022).

All-perovskite tandem modules processed exclusively with scalable fabrication methods

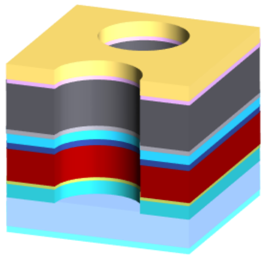
Analysis of Inhomogeneities by Photoluminescence



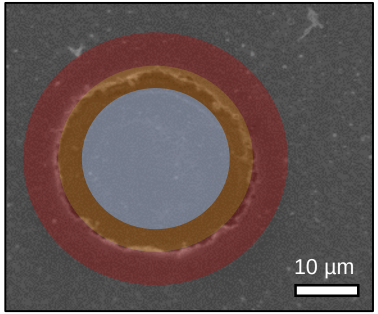


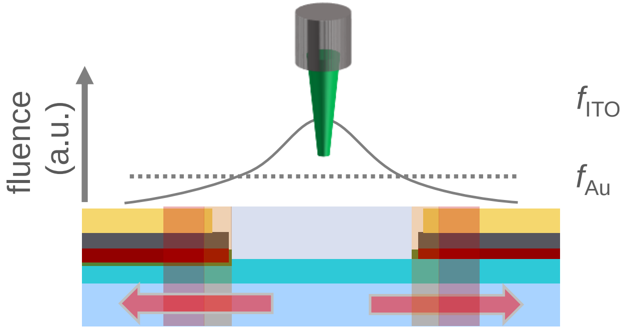
B. Abdollahi et al., accepted for publication in *Nature Energy* (2022).

Translucent All-Perovskite Tandem Photovoltaics



2T tandem all-perov. solar module





Objective:

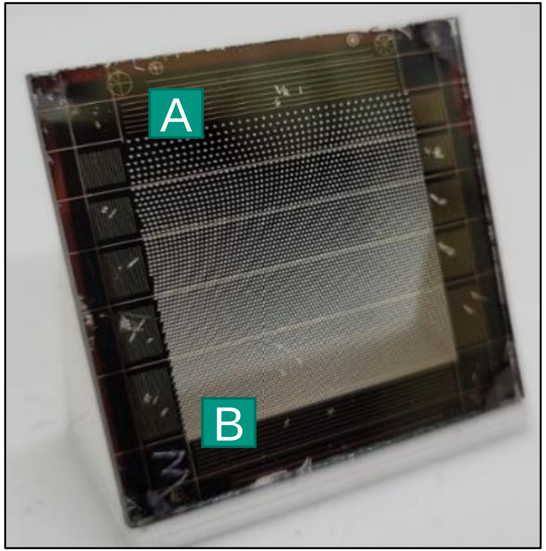
- High average visible transmission (AVT)
- High Color Rendering Index (CRI)
- High Power Conversion Efficiency (PCE)

D. Ritzer et al., *Energy & Environmental Science 2023, DOI: 10.1039/D2EE04137E* (2023).

Translucent All-Perovskite Tandem Photovoltaics

New Design Opportunities for Multi-Use Thin-Film Photovoltaics

VERTICAL GRADIENT



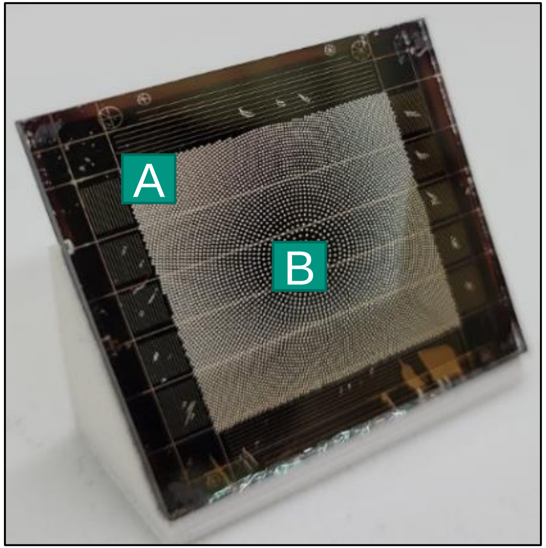
A

AVT: **4.8** %
CRI: 88.0

B

AVT: **32.7** %
CRI:96.4

RADIAL GRADIENT



A

AVT: **28.4** %
CRI: 95.7

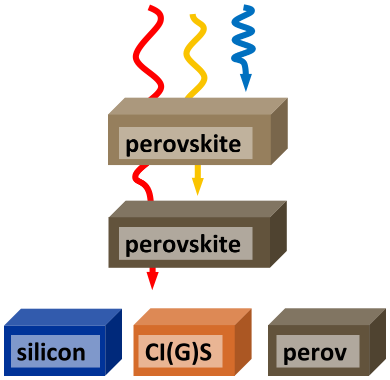
B

AVT: **7.9** %
CRI: 93.5

D. Ritzer et al., *Energy & Environmental Science 2023, DOI: 10.1039/D2EE04137E* (2023).

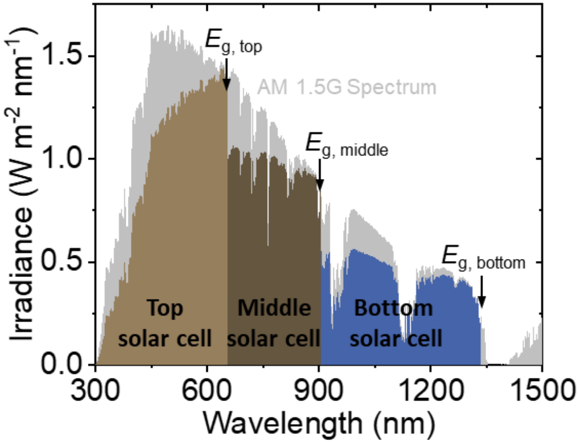
Perovskite-based Multijunction Photovoltaics

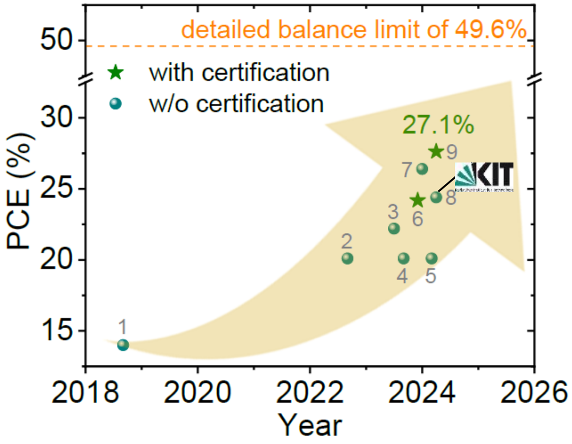
A rising era of perovskite-based triple-junction photovoltaics



PCE potential >> 45%

Early in 2024 a handful of research groups report Perovskite/Perovskite/Si Tandem Cells w. PCE > 24%

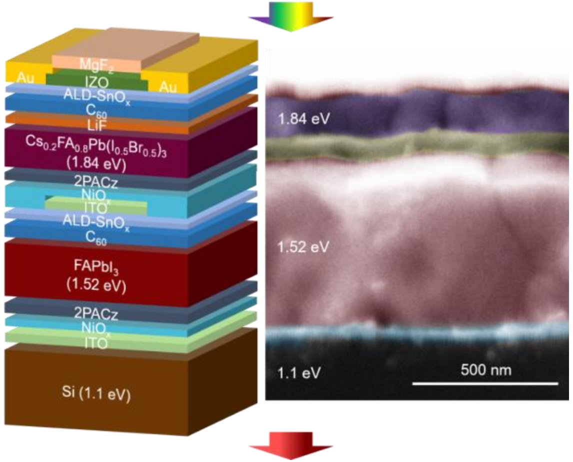


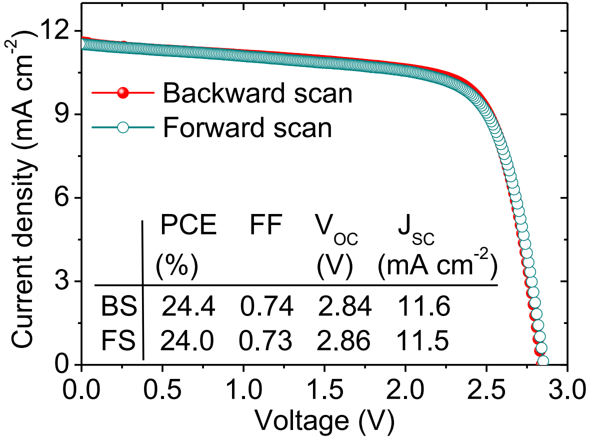


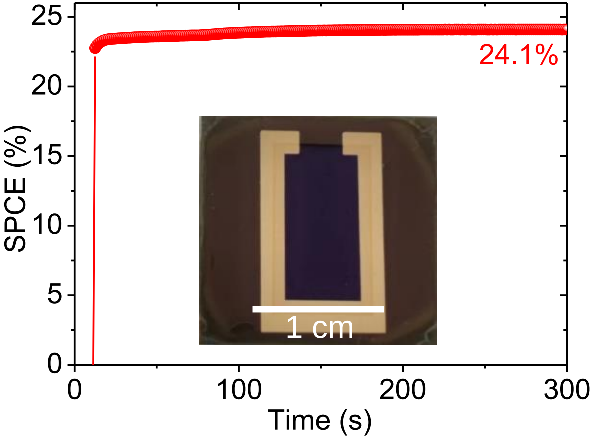
H. Hu, et al., *Joule* 2024, DOI: 10.1016/j.joule.2024.06.025.

High-Performance Pero/Pero/Si Triple-Junction PVs

Stable power output (24.1%) and minimal hysteresis in triple-junction PVs







H. Hu, et al., *Energy Environ. Sci.*, 2024, DOI: 10.1039/D3EE03687A.

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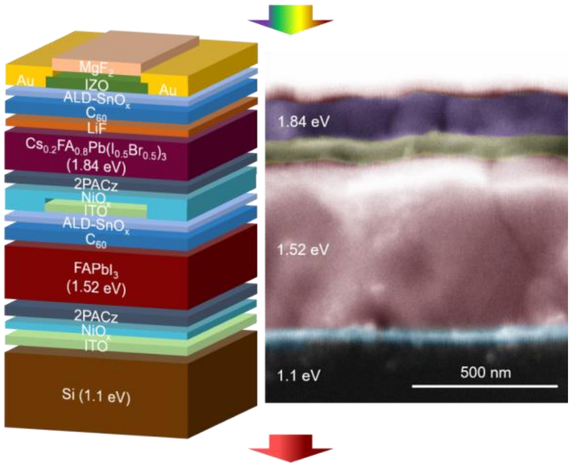
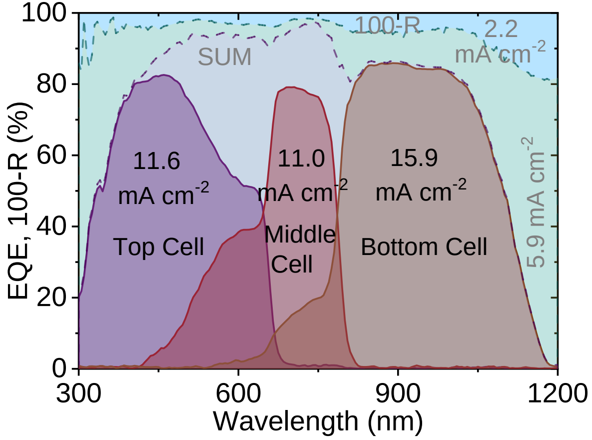
High-Performance Pero/Pero/Si Triple-Junction PVs

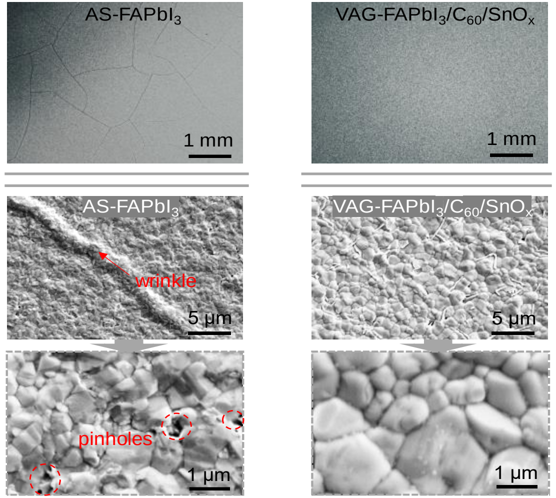
Vacuum-assisted growth: high-quality (free of wrinkles, pinholes, and cracks) perovskite thin films





reference

vacuum-assisted gas quenching



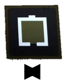
H. Hu, et al., *Energy Environ. Sci.*, 2024, DOI: 10.1039/D3EE03687A.

Scalable Fabrication Methods

Scalability – From Lab to Fab

Developing Scalable, Reliable, and High-Throughput Fabrication Methods for Commercial Scale Solar Modules

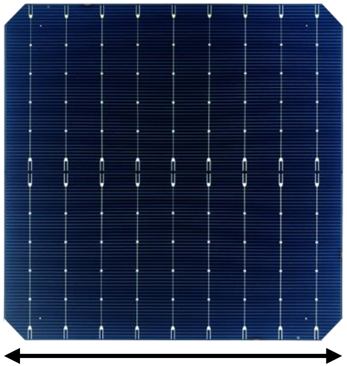
Lab scale: 1cm²



1 cm

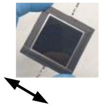
Factor ~ 440

M12: 21 x 21 cm²



21 cm

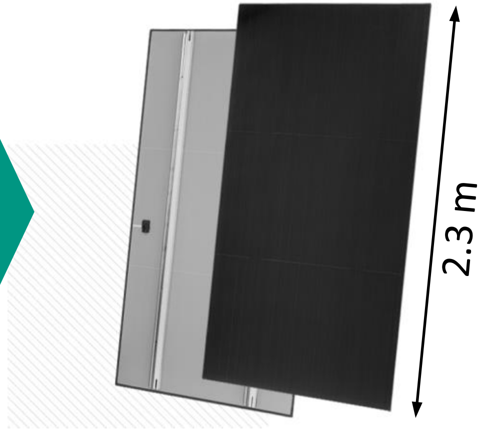
Lab scale perovskite module: ~0.01 m²



0.1 m

Factor > 200

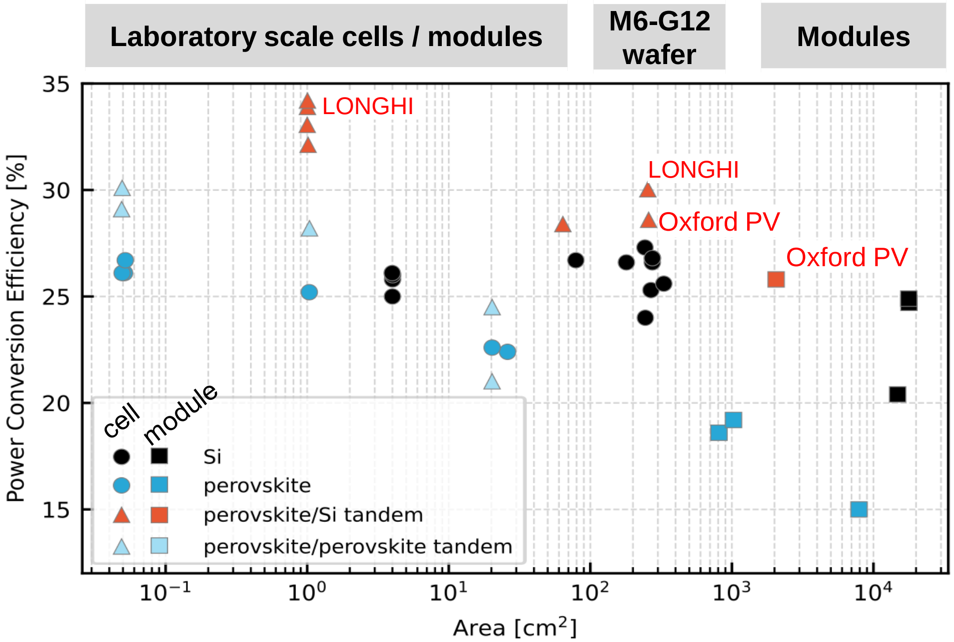
Commercial thin film module > 2 m²



2.3 m

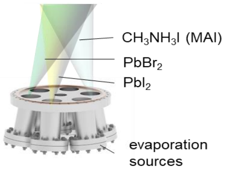
First Solar, Series 7 Thin Film Module
souce: firstsolar.com

Scalability – From Lab to Fab

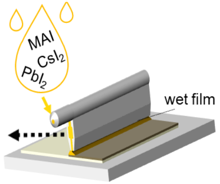


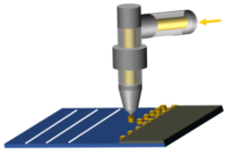
Versatile options for perovskite deposition:

Vapor phase deposition methods in vacuum:



Solution-based deposition methods:





[1] adapted data from: M. A. Green et al., Progress in Photovoltaics 2024 DOI: 10.1002/pip.383
[2] complemented by announcements of Longhi, Oxford PV, ISE Fraunhofer.

Industry Perspective on scalable fabrication of perovskite PV

Energy & Environmental Science

ROYAL SOCIETY OF CHEMISTRY

PERSPECTIVE

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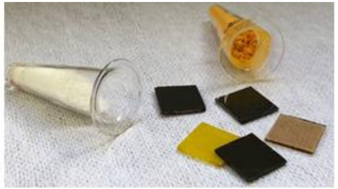
View Journal



Vapor Phase Deposition of Perovskite Photovoltaics: Short Track to Commercialization?

T. Abzieher, D. T. Moore, M. Roß, S. Albrecht, J. Silviac, H. Tan, Q. Jeangros, C. Ballife, M. T. Hoerantner, B. Kim, H. J. Bolink, P. Pistor, J. C. Goldschmid, Y.-H. Chiang, S. D. Stranks, J. Borchert, M. D. McGehee, M. Morales-Masis, J. B. Patel, A. Bruno, and **Ulrich W. Paetzold.**

KIT, HZB Helmholtz Zentrum Berlin, Nanjing University, EPFL, SwiftSolar, Philipps Universität Marburg, University of Cambridge, Albert-Ludwigs-Universität Freiburg, University of Twente The Netherlands, NREL, Bluedot Photonics, csem, KRICT 한국화학연구원, Universitat de València, Martin-Luther-Universität Halle-Wittenberg, Fraunhofer ISE, University of Colorado Boulder, Nanyang Technological University Singapore, King's College London

D. T. Moore

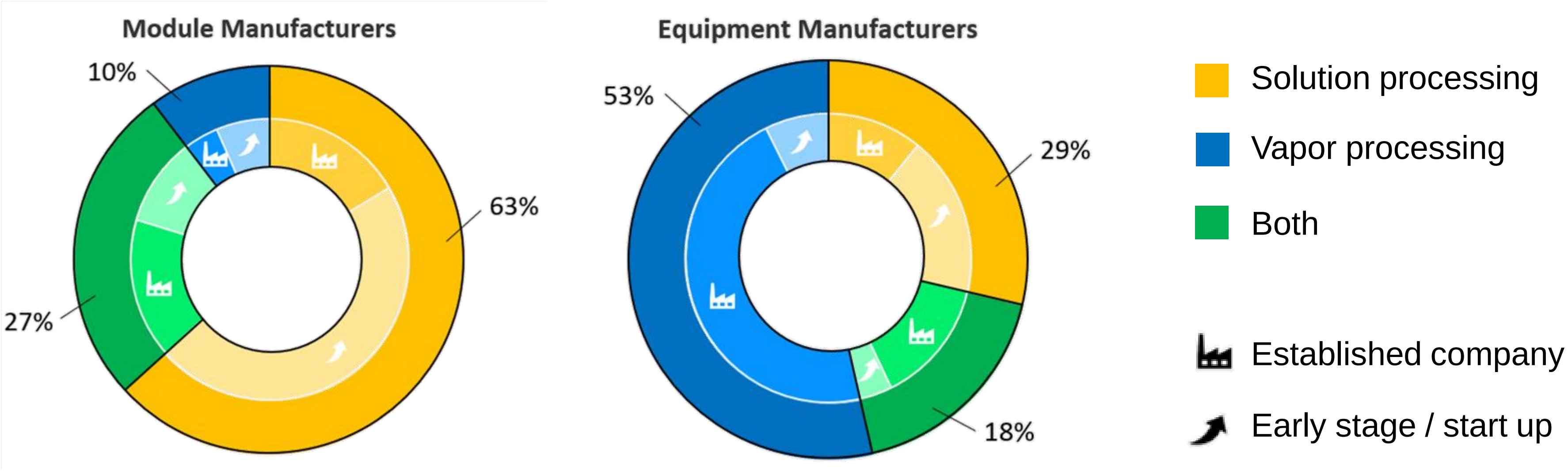
T. Abzieher

- *Why this Perspective?*
  - Vast majority of research studies use solution-processing (> 98% of all articles).
  - BUT vapor phase deposition processes dominate today's established thin-film manufacturing in PV (>99%).“

T. Abzieher et al., *Energy & Environmental Science* **17,** 1645-1663 (2024)

Survey: Industry Perspective for Perovskite PV

Question: What deposition technique is on your technology roadmap? (*180/190 companies replied)

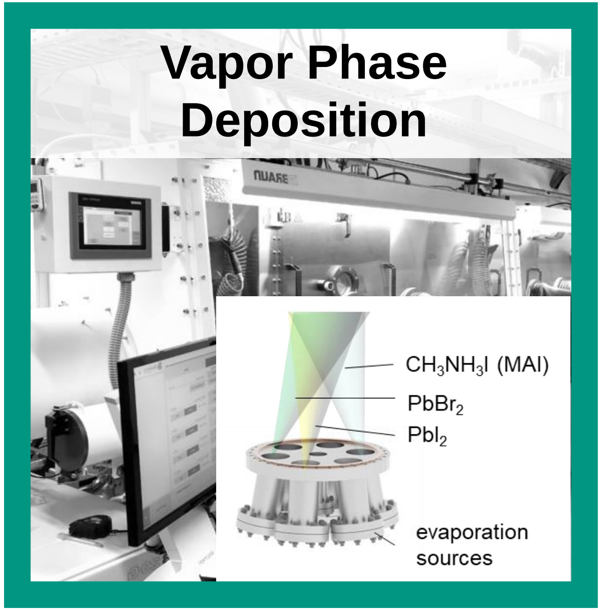


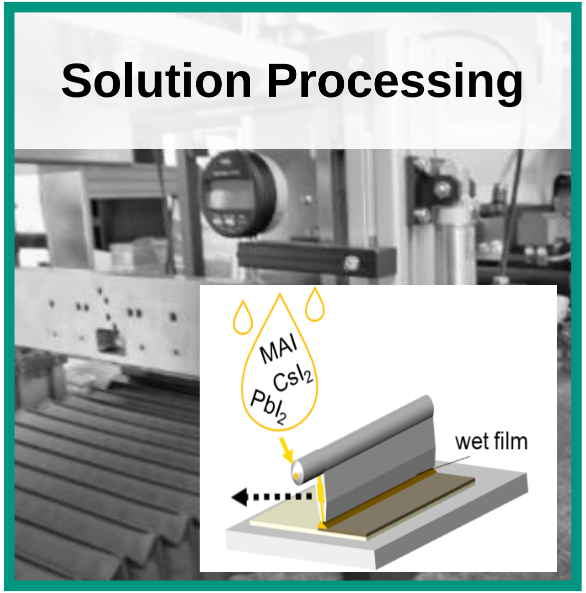
- Mixed viewpoint in industry: Perspectives both for vapor deposition and solution processing

T. Abzieher et al., *Energy & Environmental Science* **17,** 1645-1663 (2024)

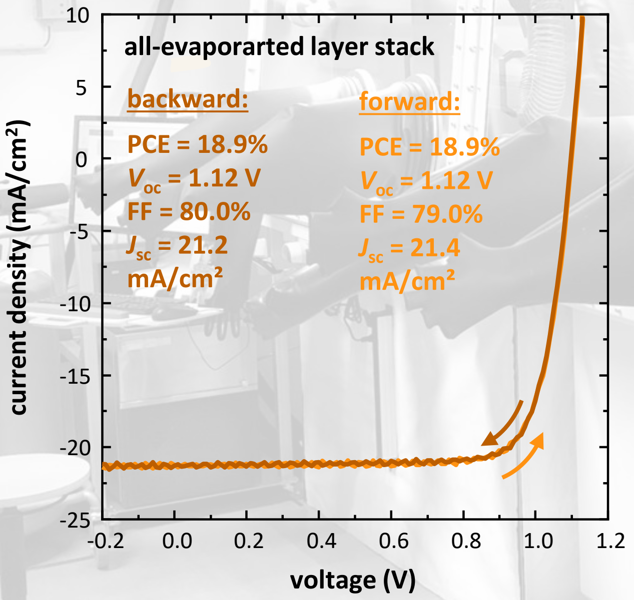
Scalability – From Lab to Fab

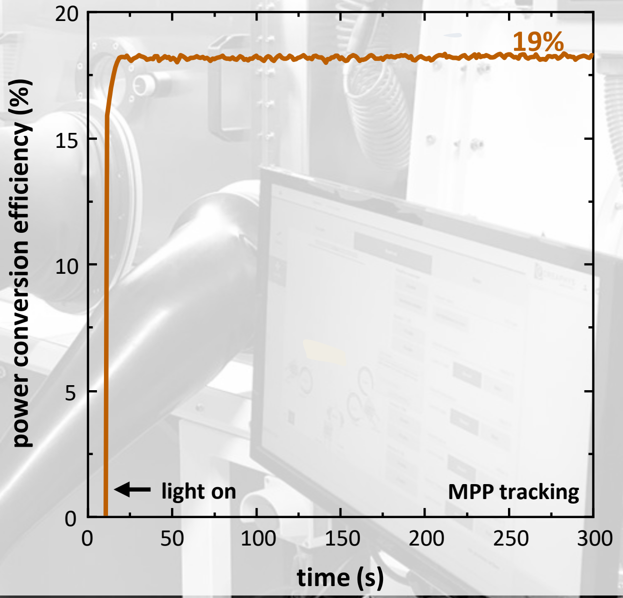
Two process routes: evaporation and solution processing





Highlight: All-evaporated Perovskite Solar Cells

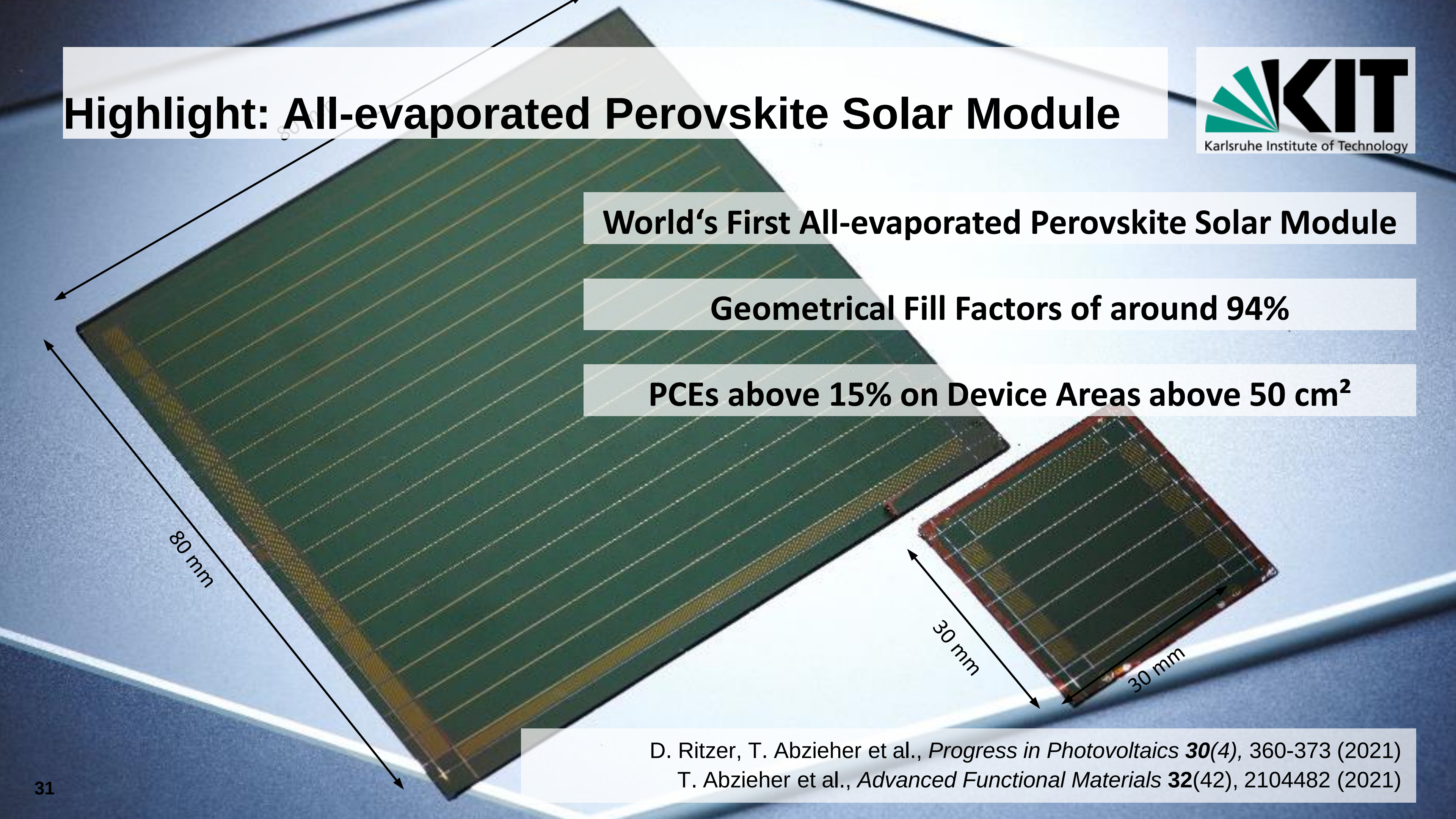




PCEs above 18% can reproducibly be achieved at laboratory scale.

Highlight: All-evaporated Perovskite Solar Module

Karlsruhe Institute of Technology



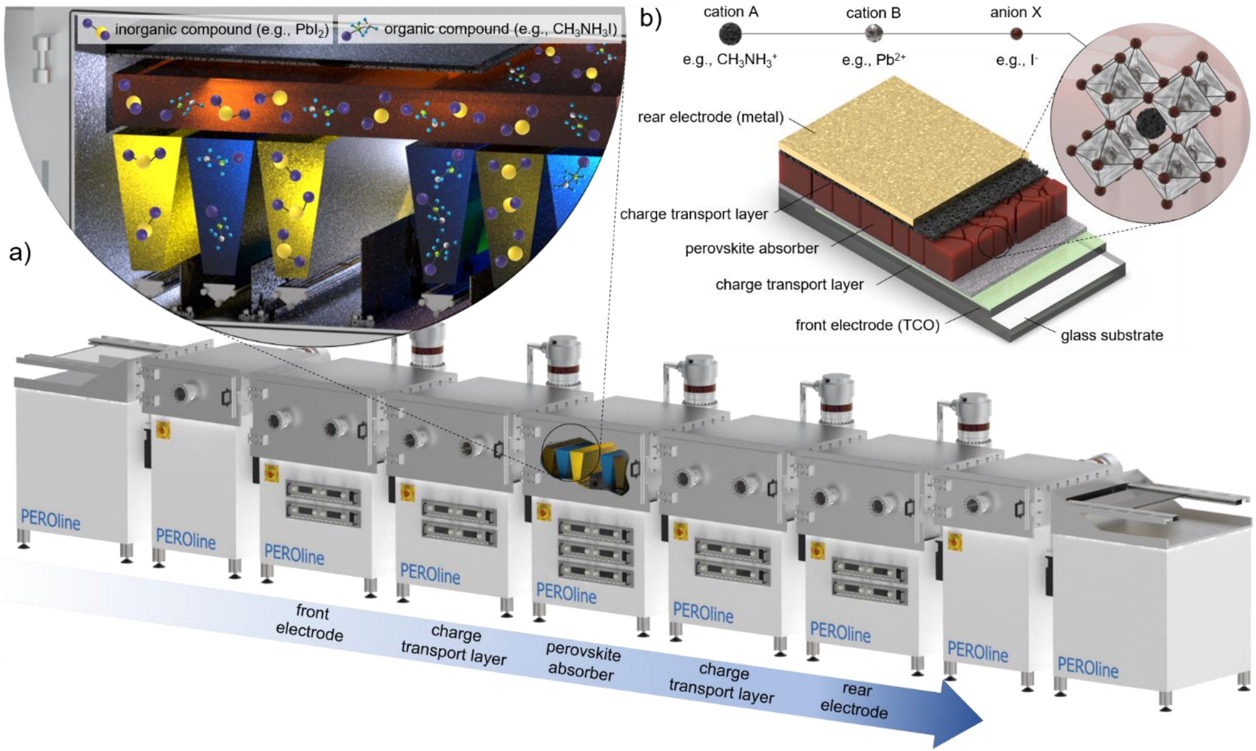
World‘s First All-evaporated Perovskite Solar Module

Geometrical Fill Factors of around 94%

PCEs above 15% on Device Areas above 50 cm²

D. Ritzer, T. Abzieher et al., *Progress in Photovoltaics* ***30****(4),* 360-373 (2021)
T. Abzieher et al., *Advanced Functional Materials* **32**(42), 2104482 (2021)

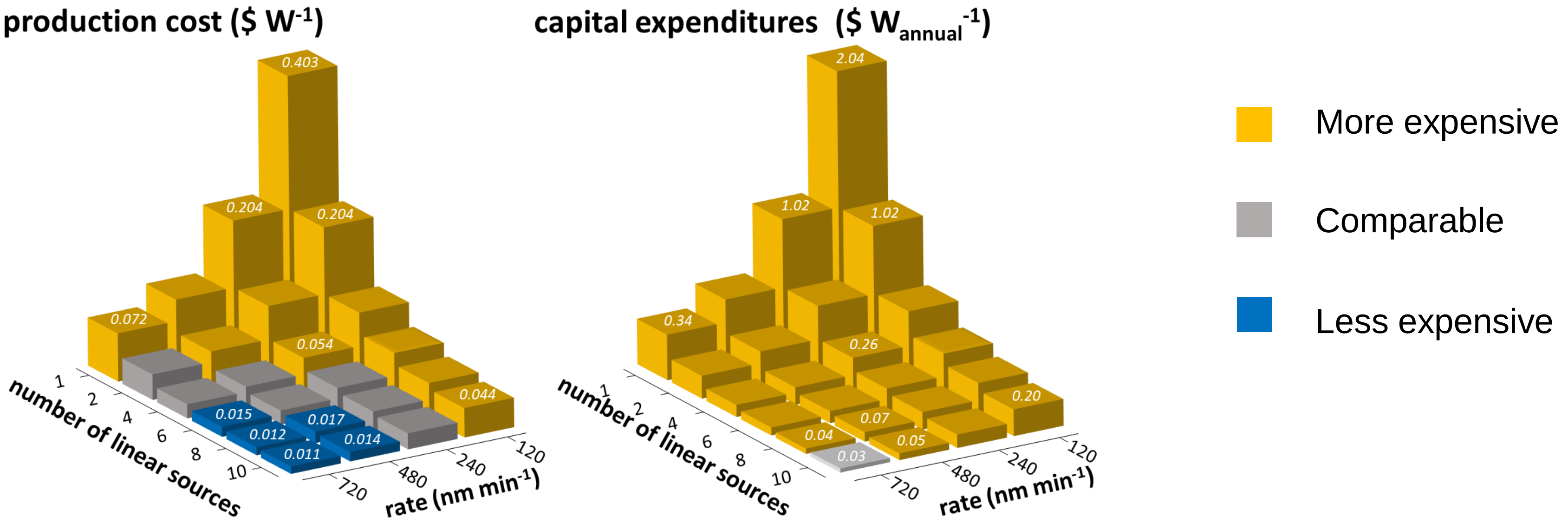
How to scale vapor phase deposition?



T. Abzieher et al., *Energy & Environmental Science* **17,** 1645-1663 (2024)

Basic Technology Assessment

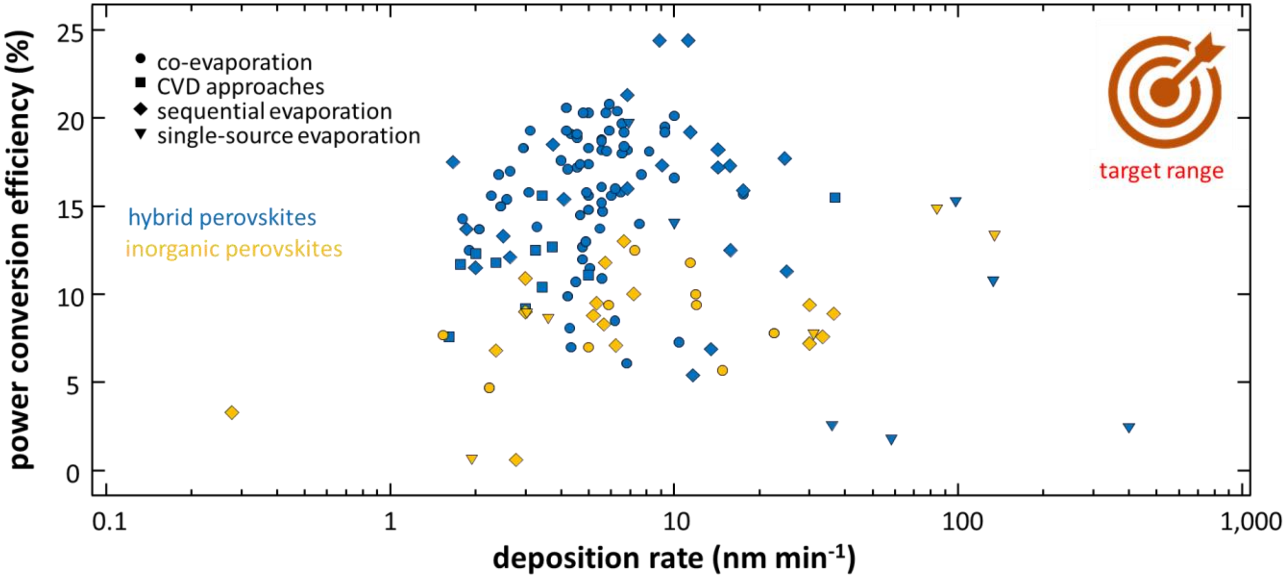
Rate and number of linear sources and deposition rates most important!

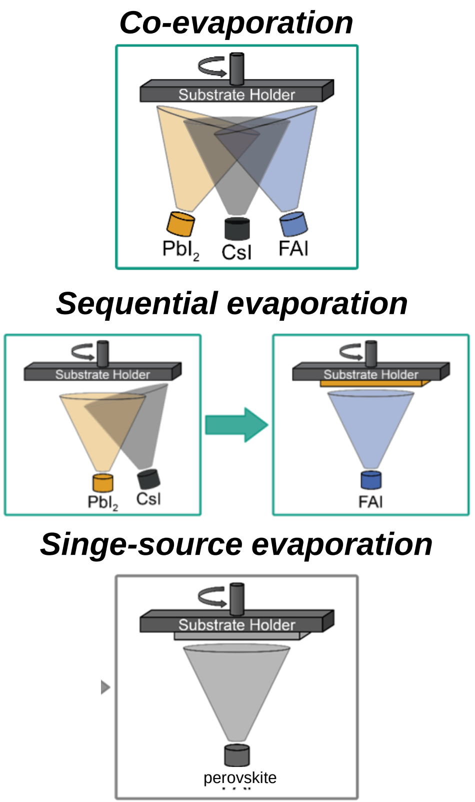


- For high rates (> 700 nm/min), vapor deposition more competitive (in CAPEX and prod. costs)
- Presumable advantages of higher yield and reproducibility not considered

T. Abzieher et al., *Energy & Environmental Science* **17,** 1645-1663 (2024)

Key Challenge: Low deposition rates of vapor-processed perovskite absorbers





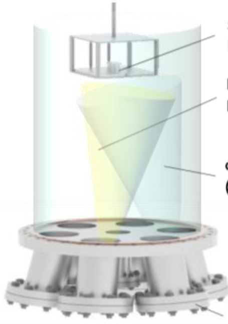
- Today: Deposition rates are around 1-2 order of magnitude too slow
- Urgent need for novel approaches (source designs, material design, close-space sublimation, pulsed laser deposition, etc.)

T. Abzieher et al., *Energy & Environmental Science* **17,** 1645-1663 (2024)

Status and Outlook for Vapor Phase Fabrication Methods: How to Become a Game Changer?

Karlsruhe Institute of Technology

- \+ excellent homogeneity & high yield.
- \+ Performance: closes gap between solution and vapor phase deposition
- \+ established tool manufacturer industry (>99% of thin film PV manufacturing today).
- \- Deposition rates too low (1-2 orderS of magn.)



?

???

How to scale up to > 10.000 wafers per hour?

Industry Survey:

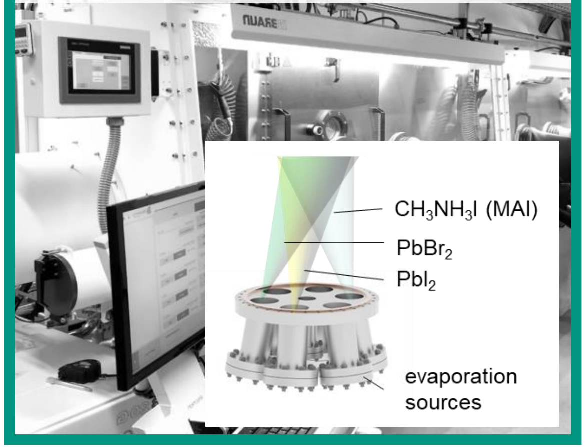
- Importance of vapor phase deposition heavily underrated in academia.
- For high rates (> 700 nm / min), vapor deposition will be competitive (CAPEX and production costs).
- Deposition on textured surfaces, high production yield and reproducibility, simple integration into production lines warrant the use of vapor phase deposition

T. Abzieher et al., *Energy & Environmental Science* **17,** 1645-1663 (2024)

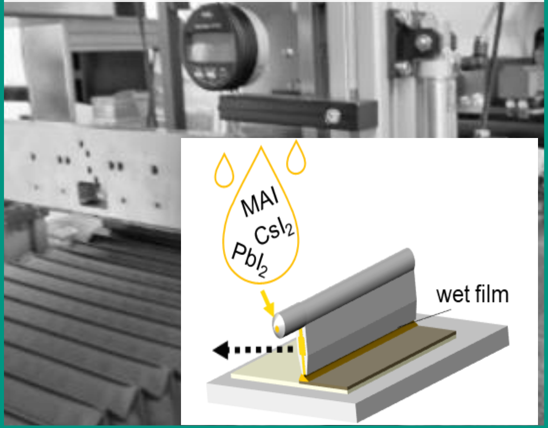
Key Challenge: Scalability – From Lab to Fab

Two process routes: evaporation and solution processing

Vapor Phase Deposition

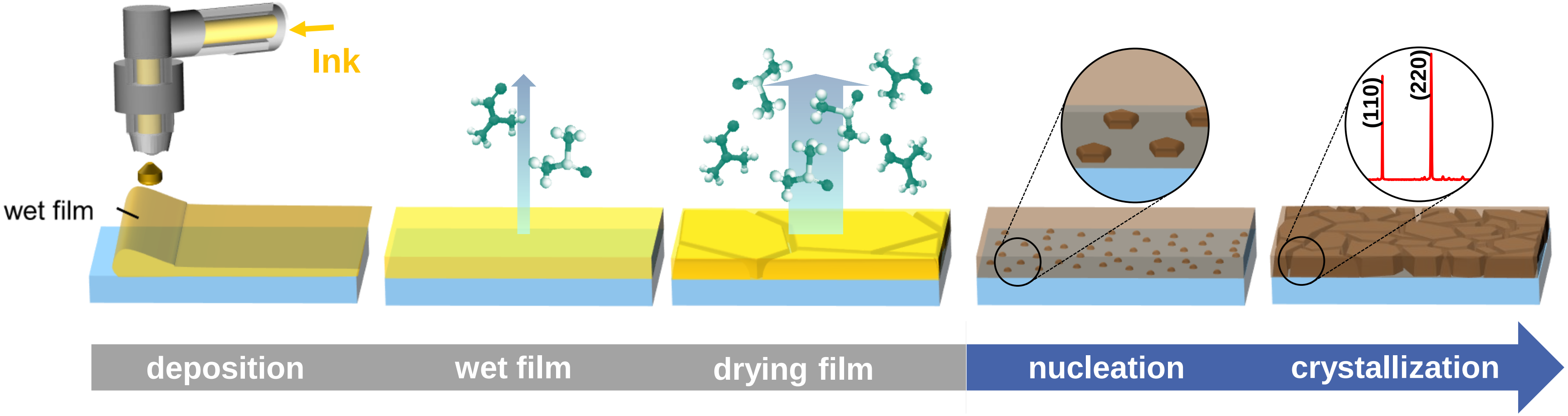


Solution Processing



Solution-Processed Perovskite Thin Film PV

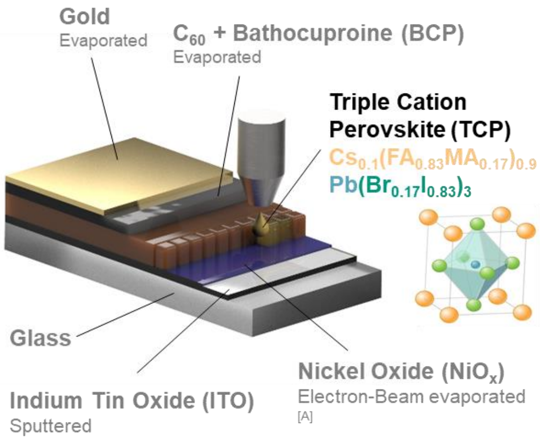
Key Challenge: *Several Entangled Processes Define the Perovskite Thin Film Photovoltaics.*

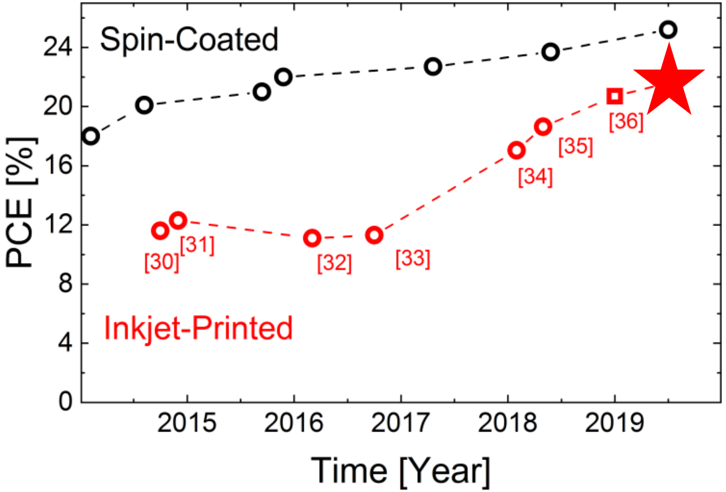


I. A. Howard, T. Abzieher, I. M. Hossain, H. Eggers, F. Schackmar, S. Ternes, B. S. Richards, U. Lemmer, and U. W. Paetzold. *Advanced Materials* **31**(15), 1602807 (2019)

Inkjet-Printed Perovskite Solar Cells

Record performance by printed micrometer-thick perovskite absorber layers





SUNOVATION

Federal Ministry of Education and Research

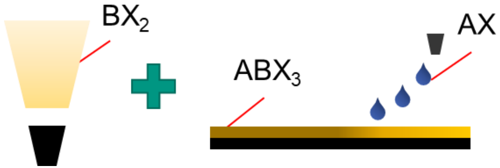
PRINTPERO

INNOVATION LAB thinking works

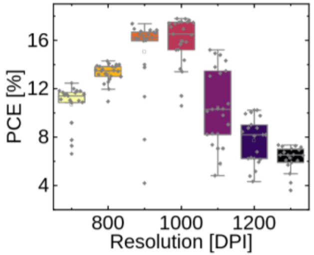
H. Eggers et al. *Advanced Energy Materials* **10**(5), 1903184 (2020)
F. Schackmar et al. *Advanced Materials Technologies* 6(2), 2000271 (2021)
I. Howard et al. *Advanced Materials* **31**(26), 1806702 (2019)
F. Mathies et al. *ACS Applied Energy Materials* **1**(5), 1834-1839 (2018)
R. Pesch et al. *Solar RRL,* 2400165 (2024), doi: 10.5445/IR/1000170051

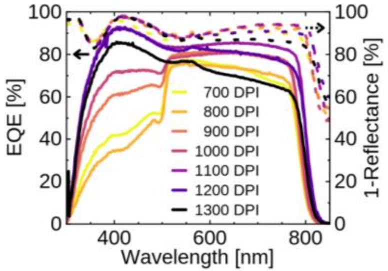
Hybrid Inkjet-Printed Perovskite Top Solar Cells

- Hybrid two-step inkjet-printed perovskite thin films

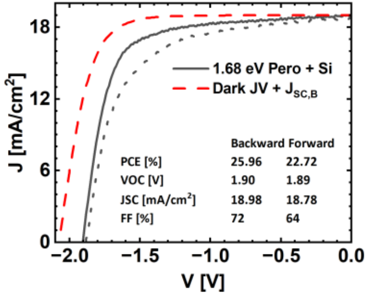


  - Spatially selectable picoliter-precise deposition of organics
  - Drop-on-demand
  - **Drops per inch (DPI)** key parameter

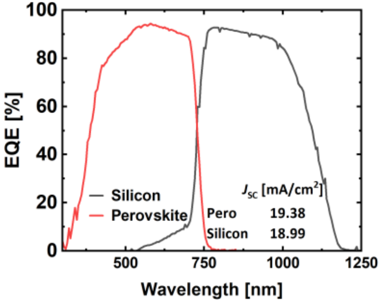




- Perovskite/Si Tandem Solar Cells with Inkjet-Printed Perovskite Top Solar Cells

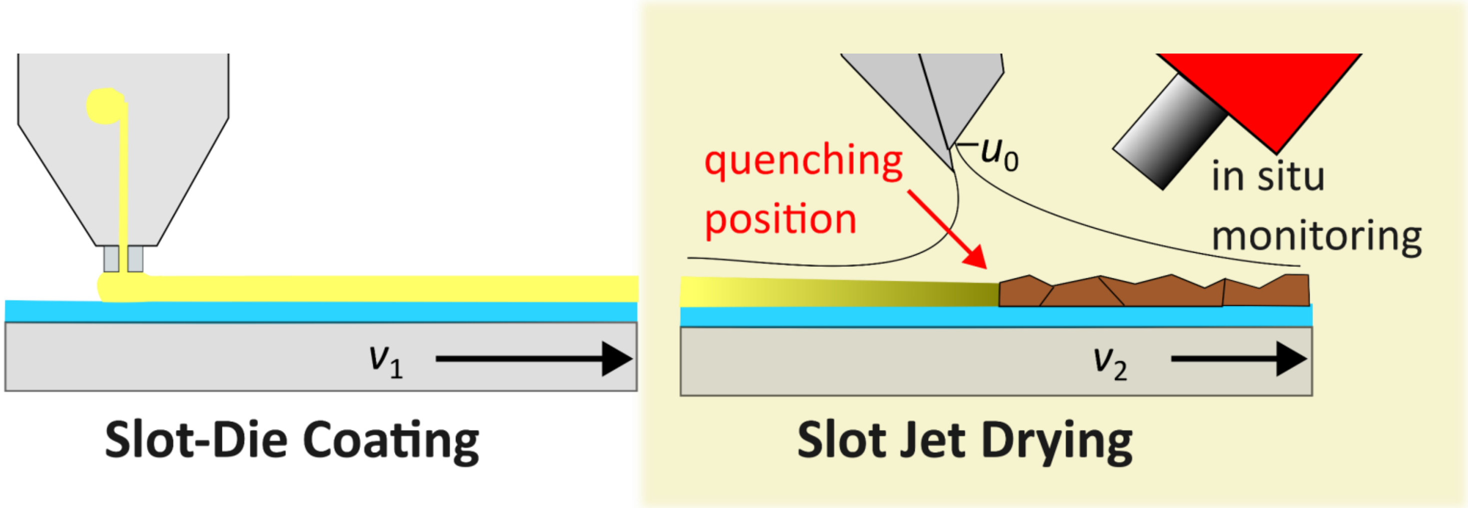


- Next steps:
  - Scaling to full-size wafer
  - Raising efficiency
  - Transfer to industry partners

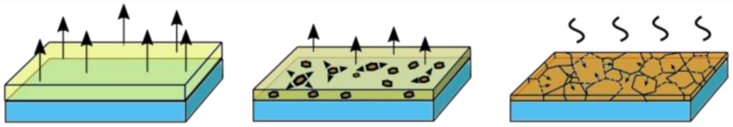


Pesch et al., Solar RRL, 2024, https://doi.org/10.1002/solr.202400165

Slot-die Coated Perovskite Solar Cells



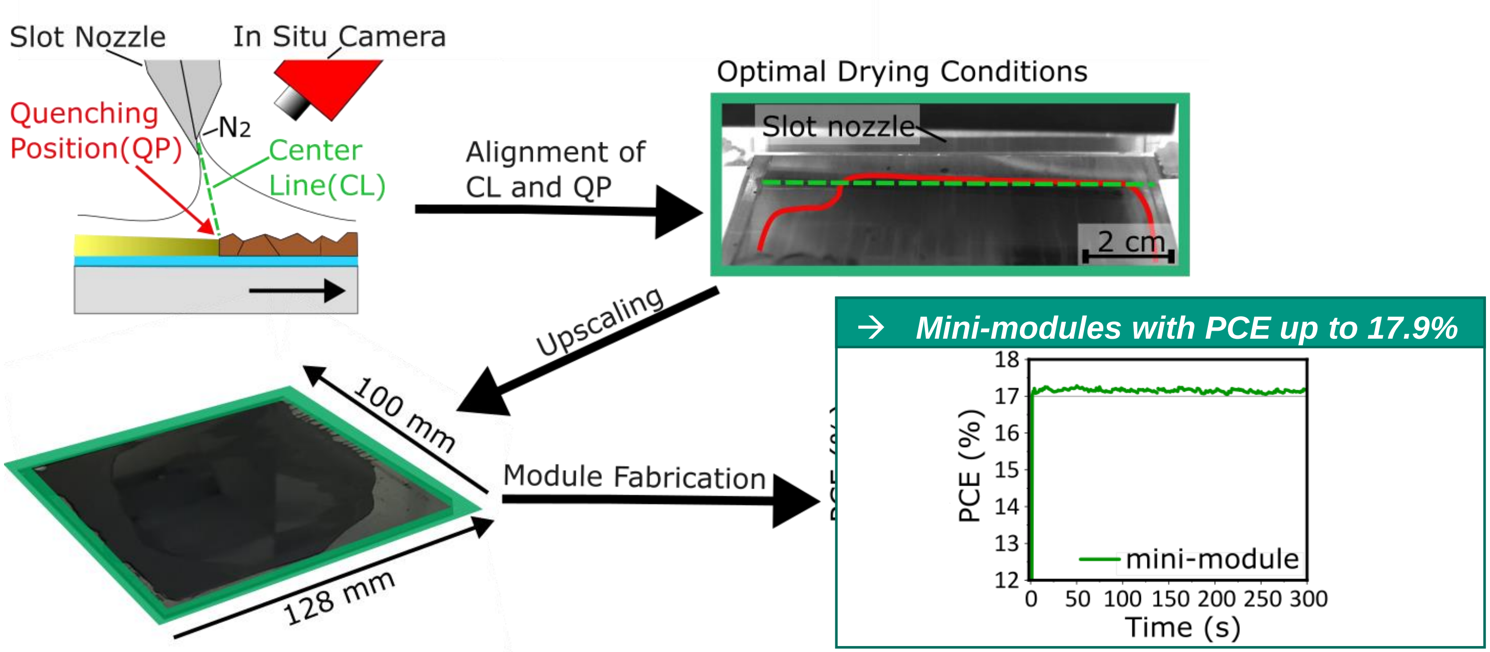
Complex drying dynamics:



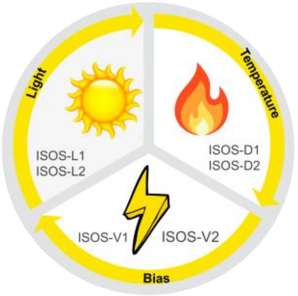
S. Ternes et al., *ACS applied materials & interfaces* **14**(9) 11300-11312 (2022)
S. Ternes et al., *Advanced Science* **11**(14), 2308901 (2024)

Slot-die Coated Perovskite Solar Modules

It is all about drying and controlling the crystallization!



K. Geistert et al., *ACS Applied Materials & Interfaces* 15(45), 52519-52529 (2023)

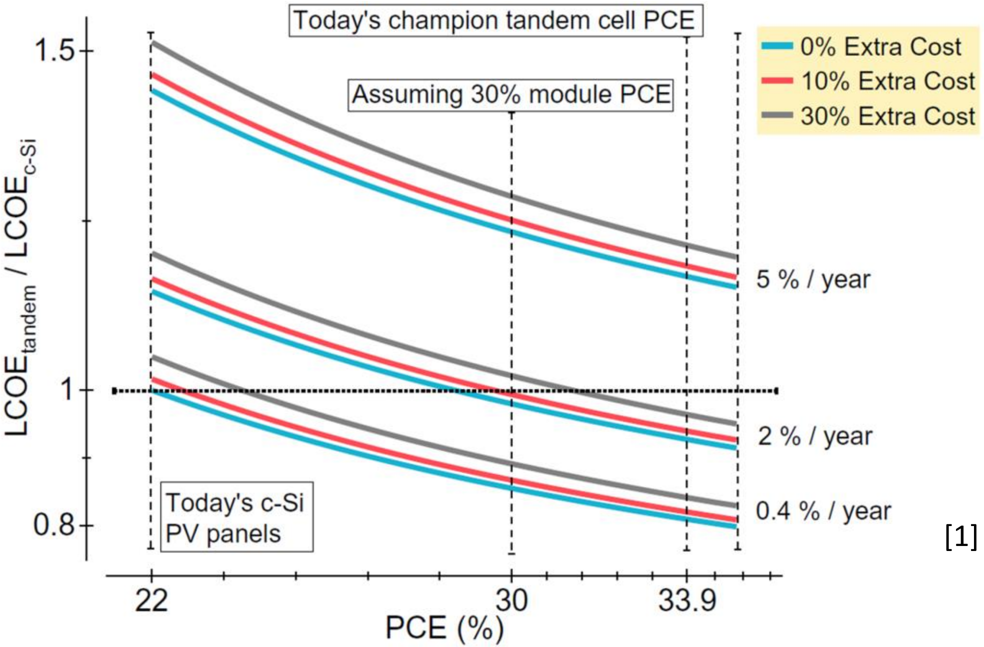

Light
Temperature
Bias
ISOS-L1
ISOS-L2
ISOS-D1
ISOS-D2
ISOS-V1
ISOS-V2

Stability

Stability: Current Major Roadblock for Commercialization

Stability remains the MAJOR CHALLENGE:

- **Identified as the major roadblock. But there needs to be more R&D focused on stability.**
- **To be competitive regarding LCOE and LCA, the degradation rate has to be < 0.5 % p.a.** [1]
- **Very few reports on long-term outdoor data. Best reported degradation rate >17% p.a.** (small-area perovskite/silicon tandems, 1 cm^2, PCE_{init} = 21.4%, encapsulation) [2]



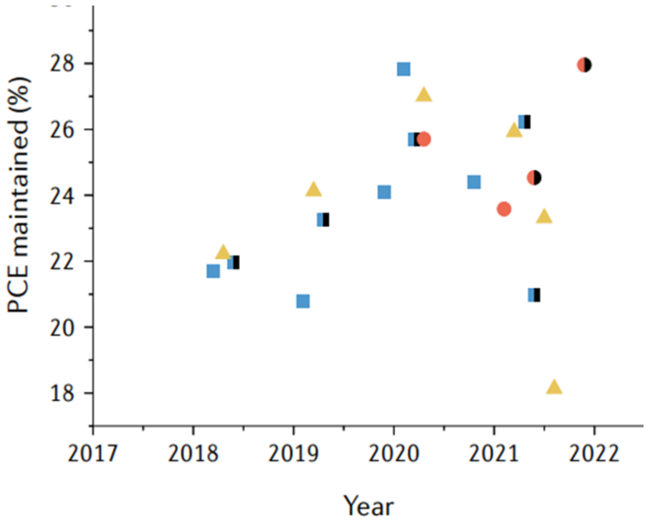
[1]

[1] E.Aydin, et al., Science 2024, DOI: 10.1126/science.adh3849.
[2] M. Babics, et al., Rep. Phys. Sci. 2023, DOI: 10.1016/j.xcrp.2023.101280 .

Stability: Current Major Roadblock for Commercialization

ENCOURAGING PROGRESS:

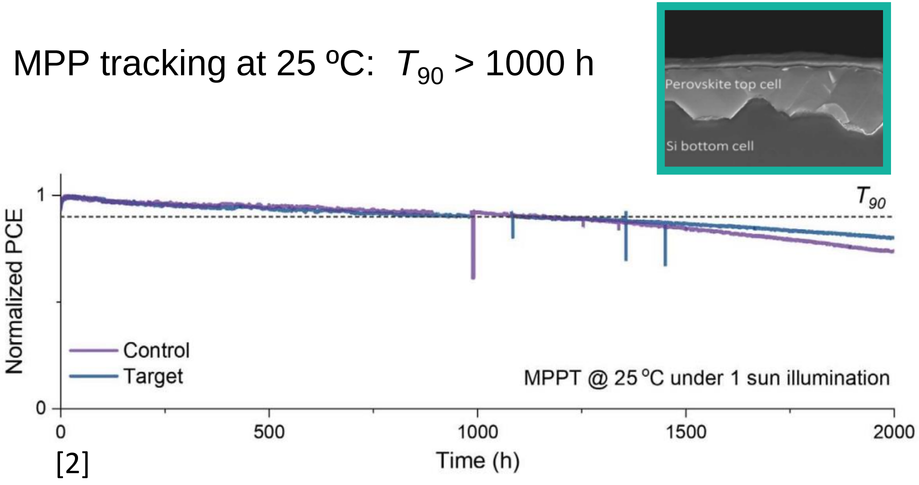
Advances in stability performance of Perovskite/Si tandem soar cells



[1] L. Duan et al., *Nat Rev Mater* 2023, DOI: 10.1038/s41578-022-00521-1.

Stable high-efficiency perovskite/Si tandems with certified PCE of 33.7% achieve T90 > 1000h

MPP tracking at 25 ºC: T_{90} > 1000 h



[1] Ugur et al., *Science* 2024, DOI: .

Prof. Dr. U. W. Paetzold

Stability: Current Major Roadblock for Commercialization

ENCOURAGING PROGRESS:

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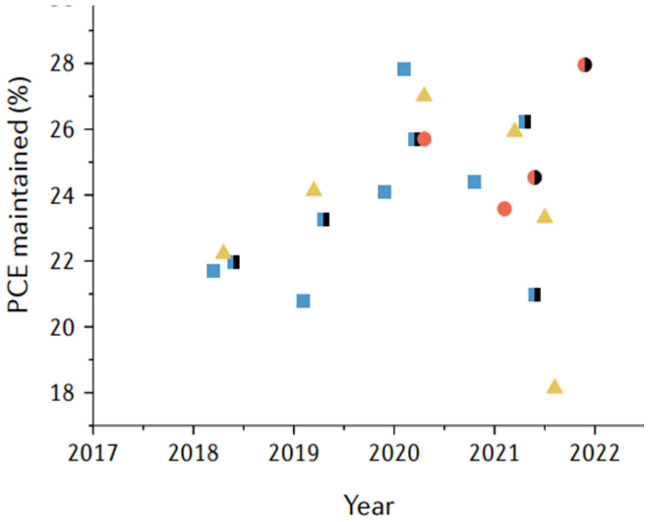
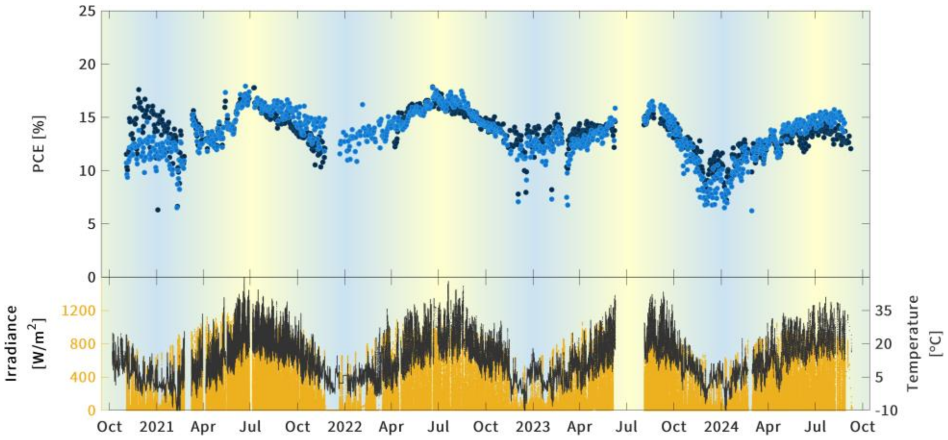


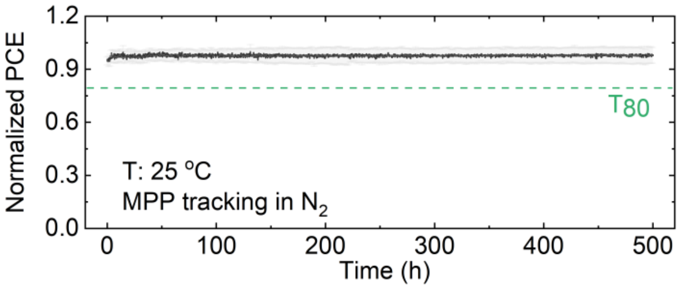


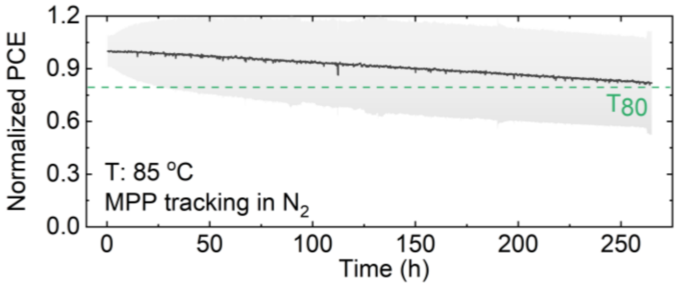
[1] L. Duan et al., *Nat Rev Mater* 2023, DOI: 10.1038/s41578-022-00521-1. Courtesy to C, Ulbrich and M. Khenkin, HZB, 2024.

Stability Research at KIT

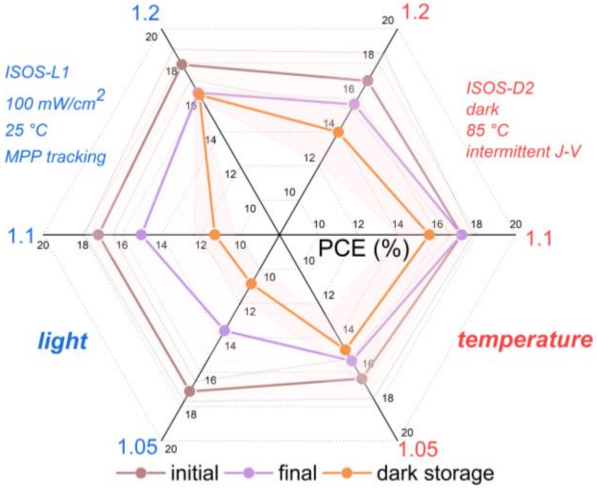
Stability of perovskite solar cells: impact of stoichiometry and morphology

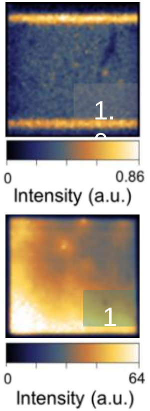
Challenge: stabilize under all conditions





Understand dynamics of simultaneous effects





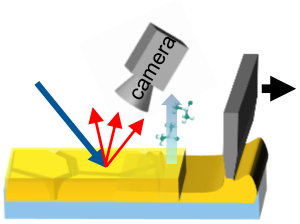
I^- migration under illumination is masked by light-enhanced defect passivation

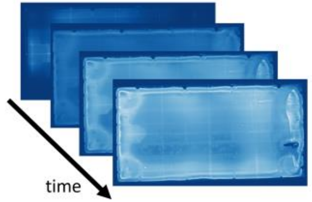
R. Singh et al., *ACS Applied Materials & Interfaces* 16(21), 27450–27462 (2024).

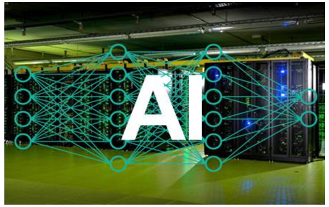
ML Methods

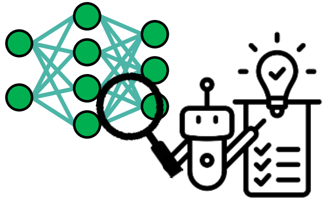
Machine Learning & Scalable Processing @ KIT

Karlsruhe Institute of Technology









process metrology

monitoring data

deep learning

prediction
neural networks predict device performance

explainable AI

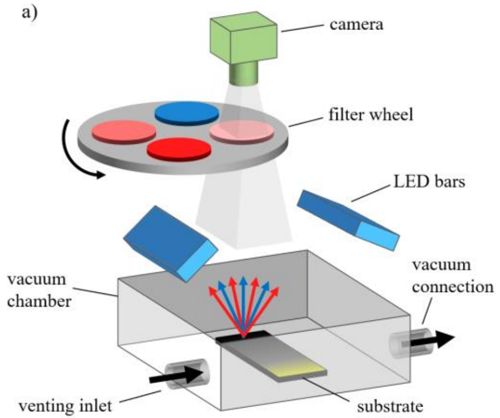
understanding
What is important?
→ **feature importance**
Why? → counterfactuals

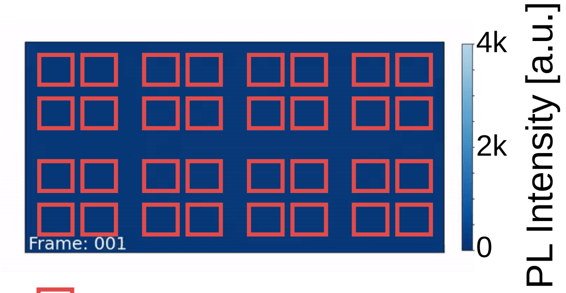
inform, understand, improve, control

HELMHOLTZAI HELMHOLTZ IMAGING KIT Karlsruhe Institute of Technology dkfz.

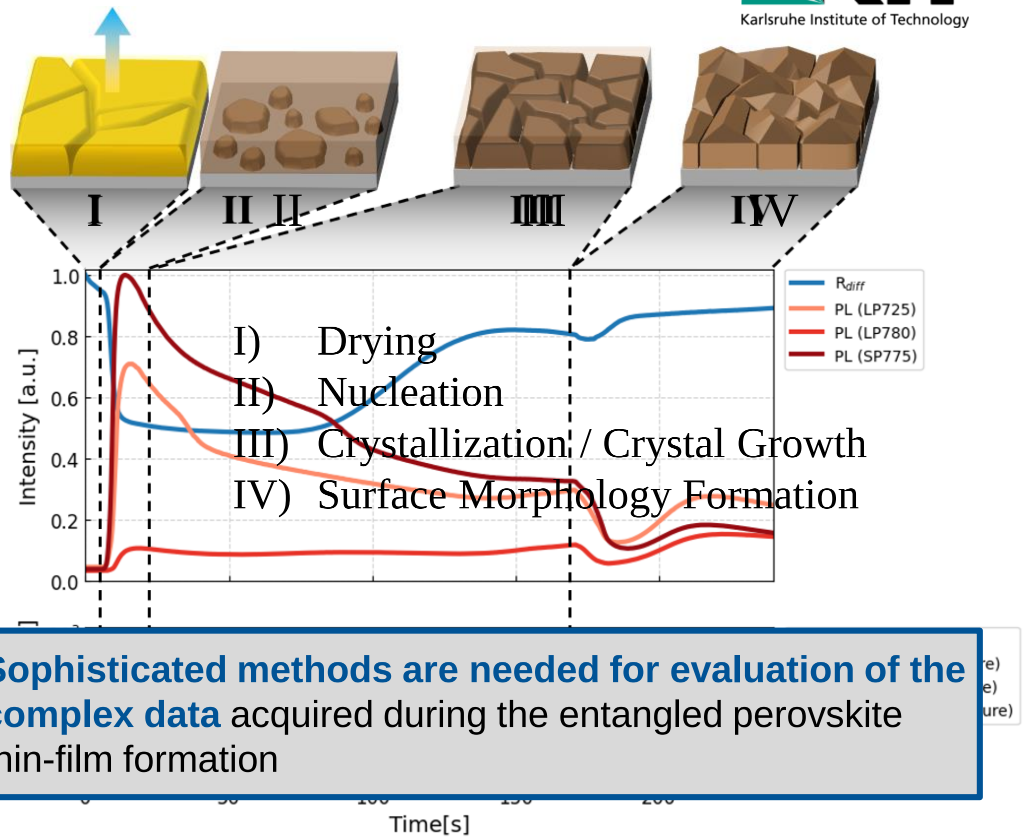
F. Laufer et al., Sol. RRL, 2201114 (2023)
Klein, Ziegler, Laufer et al., Adv. Mater., 2307160 (2023)
Laufer et al., under review (2024)

In situ multi-channel PL imaging





solar cell active area (3x3.5mm^2)

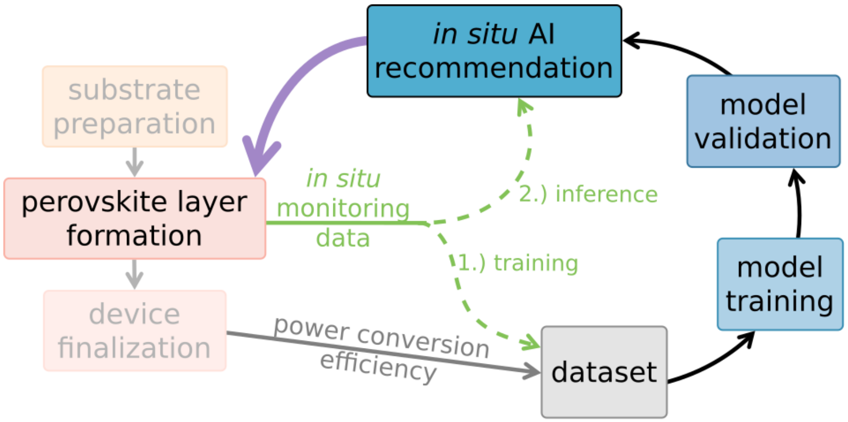


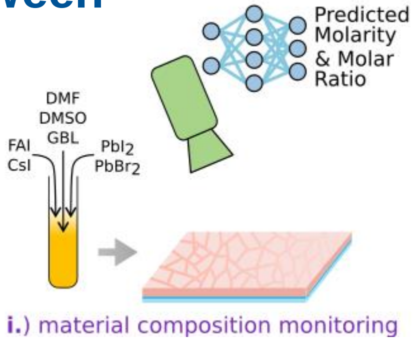
Sophisticated methods are needed for evaluation of the complex data acquired during the entangled perovskite thin-film formation

S. Ternes, F. Laufer et al., Sol. RRL, 2100353 (2021)

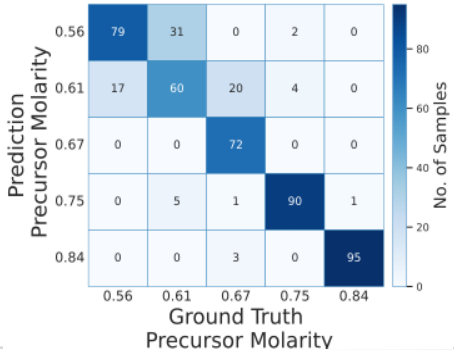
ML-based *in situ* characterization

Machine learning enables learning the **relationship between input data features and the target variables**

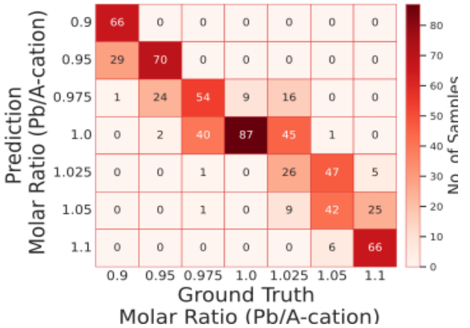




Molarity



Molar ratio

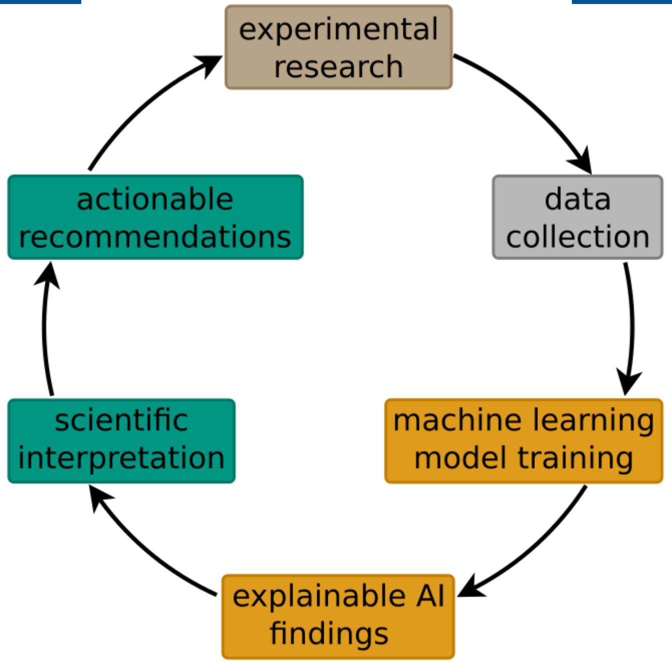


Laufer et al., under review (2024)

Explainable AI Methods

What is important?

Why is it important?



Klein, Ziegler, Laufer et al., Adv. Mater., 2307160 (2023)

Many thanks to…

... the Perovskite Taskforce at KIT.

... all collaboration partners.

... the funding organizations.

partners:

NREL
Oxford
OXFORD PV™ The Perovskite Company
HZB Helmholtz Zentrum Berlin
LayTec
imec
ISFH
JÜLICH
VON ARDENNE
SOLLIANCE
SUNOVATION
MEYER BURGER
cea
IPVF
Q CELLS
Fraunhofer
ZSW
CREAPHYS
Universitat de València
SINGULUS
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funding:

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Federal Ministry for Economic Affairs and Energy
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Gefördert durch DFG Deutsche Forschungsgemeinschaft
Federal Ministry of Education and Research
Niedersachsen
erc European Research Council
NEXUS
Baden-Württemberg Stiftung