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DegradationLab

Field monitoring of perovskite modules: experiences and learning curves

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cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

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Acknowledgements

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Outline

- What are the challenges in PSC monitoring?
  - Hysteresis
  - Impact of I-V conditions and interim loading conditions
  - Degradation
  - Performance Recovery, Diurnal Performance variation
  - Lack of dedicated measurement protocols
- Outdoor monitoring of perovskite mini-modules at UCY
- Summary of Lessons learned

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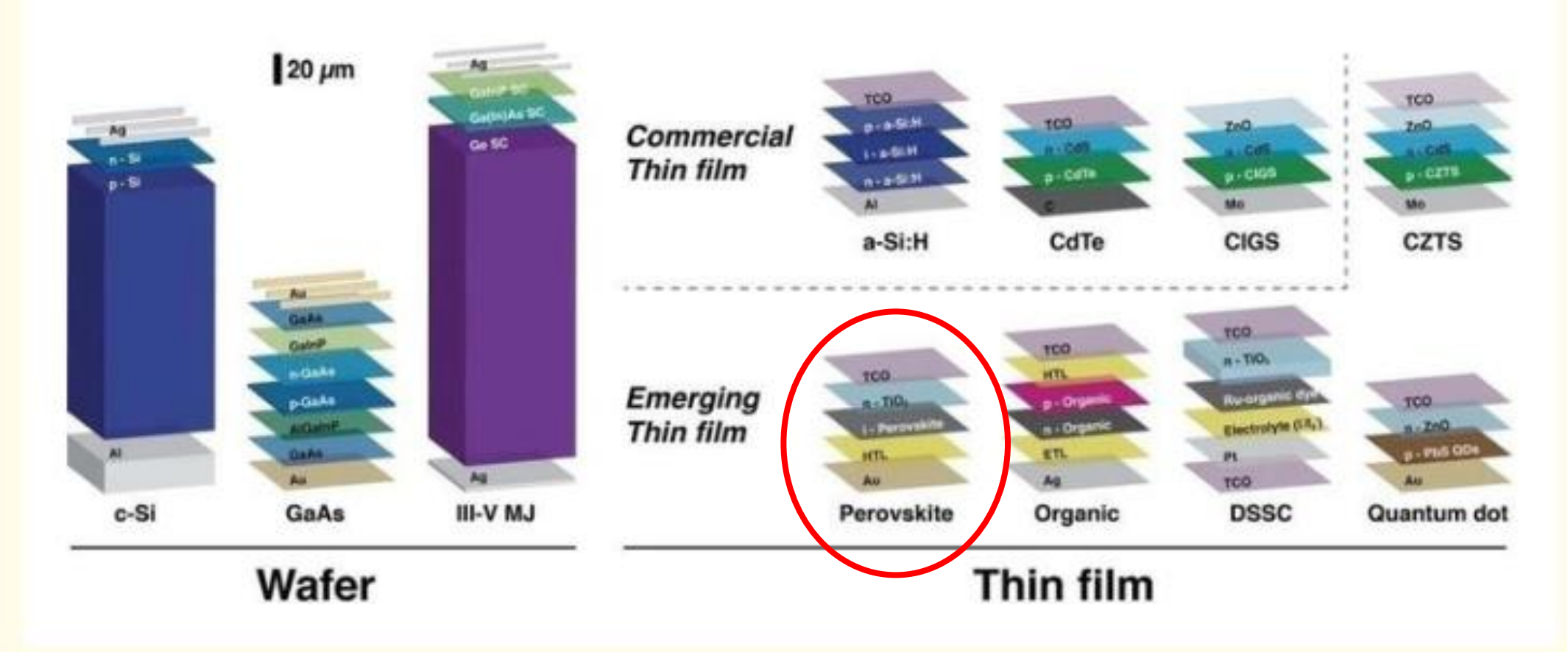
Perovskites in the 'PV arena'



M. Zendehdel, N. Yaghoobi Nia and M. Yaghoubinia, 'Emerging Thin Film Solar Panels', IntechOpen, 2020.

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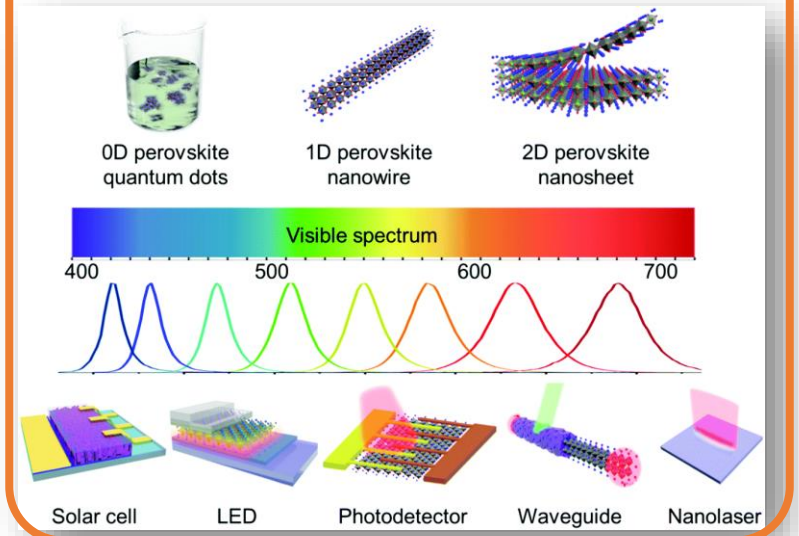
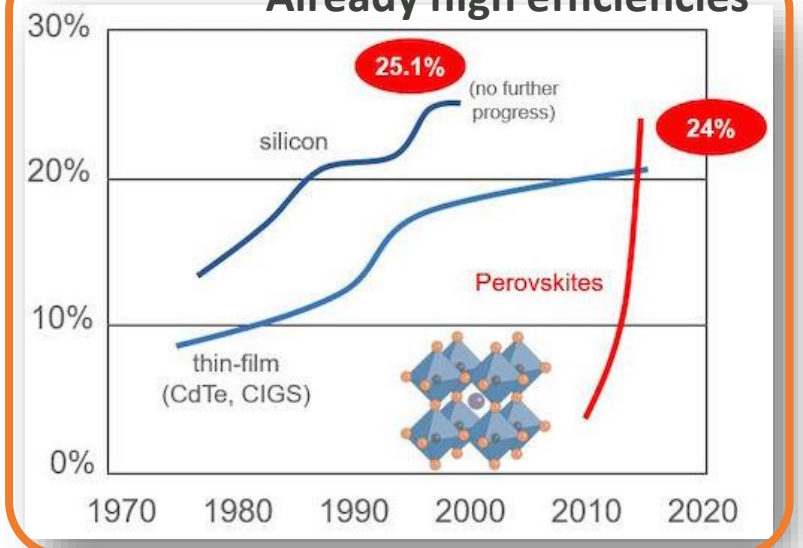
Why perovskites

Desirable & Tunable O/E properties



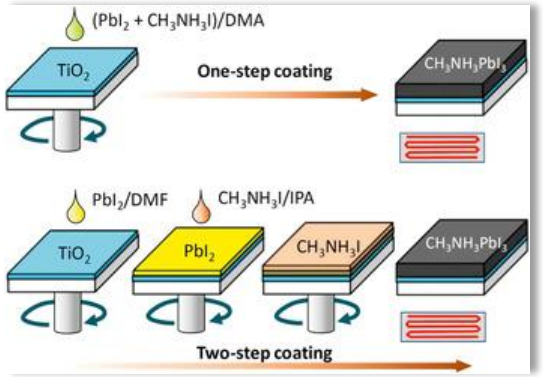
Already high efficiencies



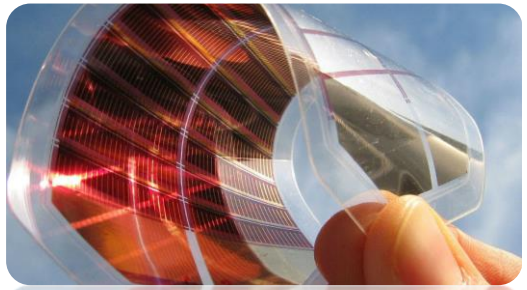
In 2021 (NREL):

- SJ Perov. cell: 25,7% cell
- Mono-Si cell: 26,1%
- Perov. Module: 17,9%

Low cost



Flexible



Scalable: roll2roll, printing, paint!
→ **Integration** prospects

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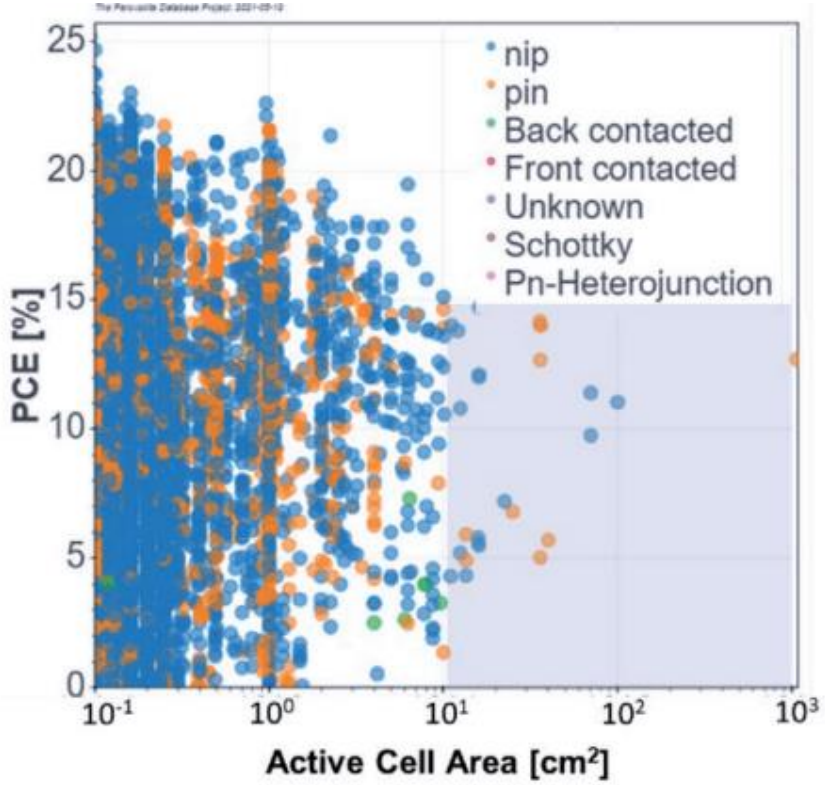
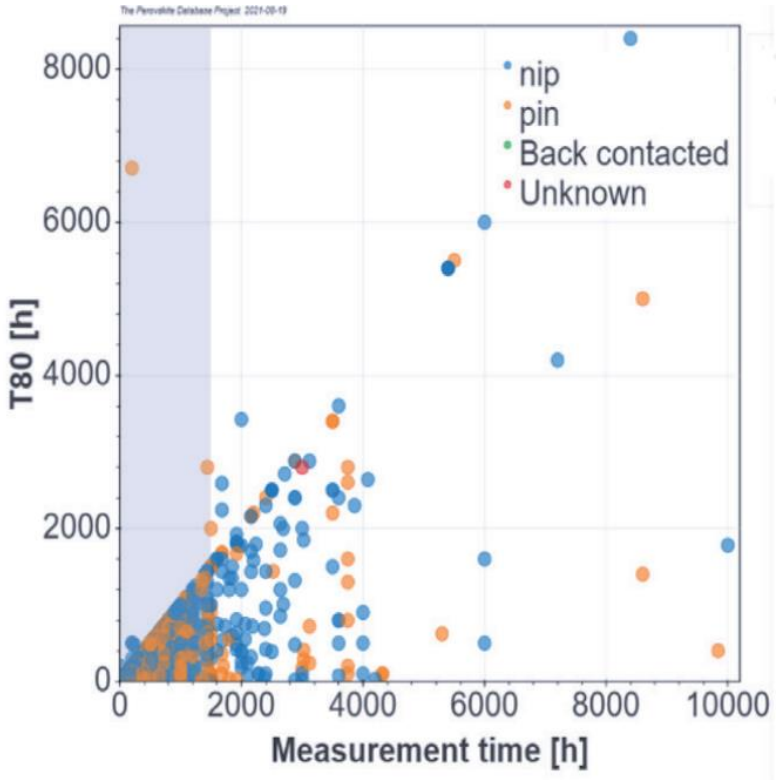
Why ***not yet*** perovskites

Small-area devices (<1cm2)



→ Scalability issue

Stability measurements (<1500h; <0.1% devices tested outdoors)



→long-term stability issue

→Field reliability

Ref: Thin Film Photovoltaics (Edited by B. Zaidi), Chapter 'Outdoor performance of perovskite Technology', 2022

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Guidelines on perovskite testing- Status

nature energy
CONSENSUS STATEMENT
https://doi.org/10.1038/s41560-019-0529-5
OPEN

Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures

Mark V. Khenkin[1,2], Eugene A. Katz[1,3*], Antonio Abate[4], Giorgio Bardizza[5], Joseph J. Berry[6], Christoph Brabec[7,8], Francesca Brunetti[9], Vladimir Bulović[10], Quinn Burlingame[11], Aldo Di Carlo[9], Rongrong Cheacharoen[12], Yi-Bing Cheng[13], Alexander Colsmann[14], Stephane Cros[15], Konrad Domanski[16], Michał Dusza[17], Christopher J. Fell[18], Stephen R. Forrest[19,20,21], Yulia Galagan[22], Diego Di Girolamo[9,23], Michael Grätzel[24], Anders Hagfeldt[25], Elizabeth von Hauff[26], Harald Hoppe[27], Jeff Kettle[28], Hans Köbler[4], Marina S. Leite[29,30], Shengzhong (Frank) Liu[31,32], Yueh-Lin Loo[11,33], Joseph M. Luther[6], Chang-Qi Ma[34], Morten Madsen[35], Matthieu Manceau[15], Muriel Matheron[15], Michael McGehee[6,36], Rico Meitzner[27], Mohammad Khaja Nazeeruddin[37], Ana Flavia Nogueira[38], Çağla Odabaşı[39], Anna Osherov[10], Nam-Gyu Park[40], Matthew O. Reese[6], Francesca De Rossi[9,41], Michael Saliba[42,43], Ulrich S. Schubert[27,44], Henry J. Snaith[45], Samuel D. Stranks[46], Wolfgang Tress[25], Pavel A. Troshin[47,48], Vida Turkovic[35], Sjoerd Veenstra[22], Iris Visoly-Fisher[1,3], Aron Walsh[49,50], Trystan Watson[41], Haibing Xie[51], Ramazan Yıldırım[39], Shaik Mohammed Zakeeruddin[24], Kai Zhu[6] and Monica Lira-Cantu[51*]

Table 1 | Overview of existing ISOS protocols and suggested additional protocols that account for the properties of perovskite materials and devices

Test ID	Light source	Temperature	Rel. humidity	Environment/Set-up	Characterization light source	Load
Outdoor stability (ISOS-O)						
ISOS-O-1	Sunlight	Ambient	Ambient	Outdoor	Solar simulator	MPP or OC
ISOS-O-2	Sunlight	Ambient	Ambient	Outdoor	Sunlight	MPP or OC
ISOS-O-3	Sunlight	Ambient	Ambient	Outdoor	Sunlight and Solar simulator	MPP

IEC TR 63228
Edition 1.0 2019-07

TECHNICAL REPORT

Measurement protocols for photovoltaic devices based on organic, dye-sensitized or perovskite materials

*'..overview **of current best practices** for measuring the performance of [emerging] PV devices .. It seeks to **highlight where the existing standards fail to accommodate the requirements of these technologies**, to identify what additional measures may be needed for accurate determination of the device efficiency, and how these measures might be standardised in the future.'*

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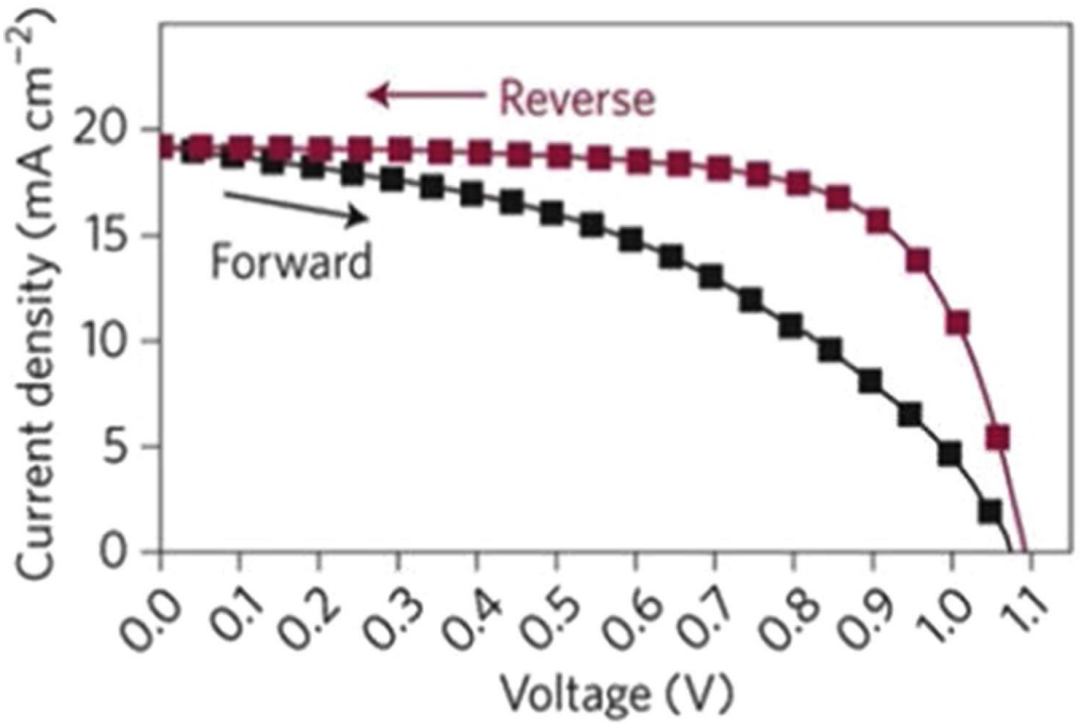
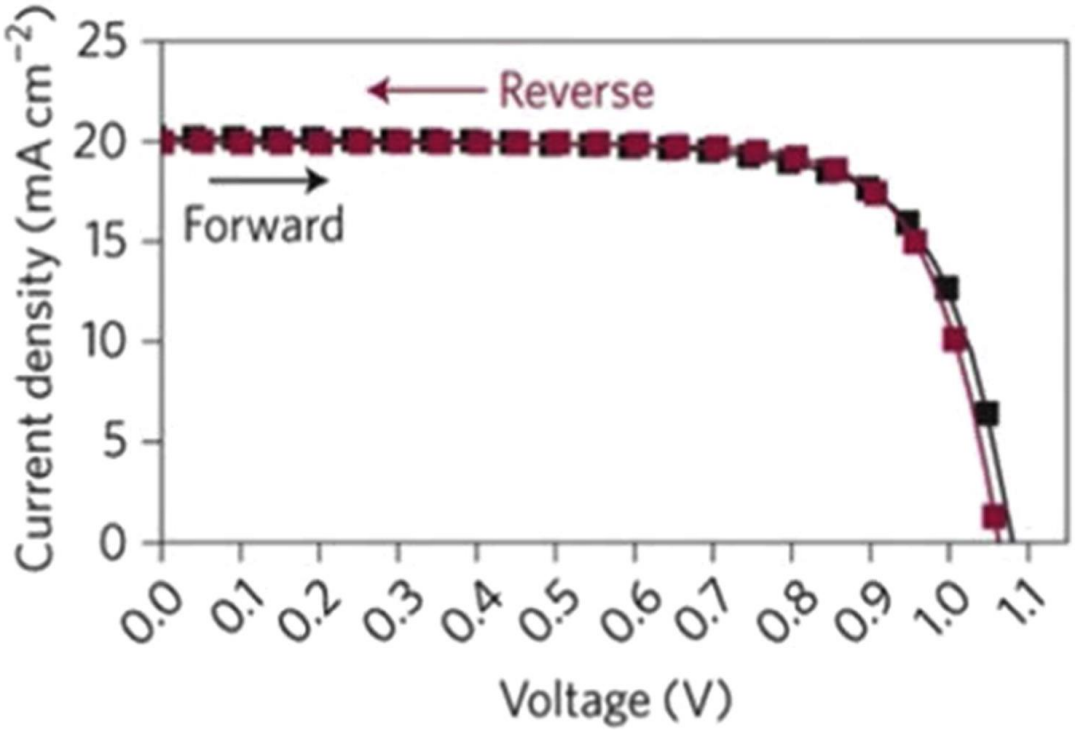
Challenges in perovskite testing: Hysteresis

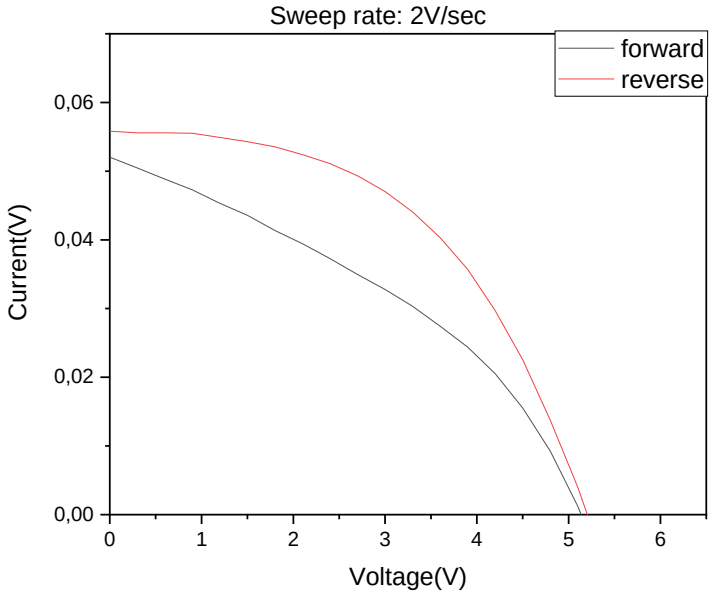


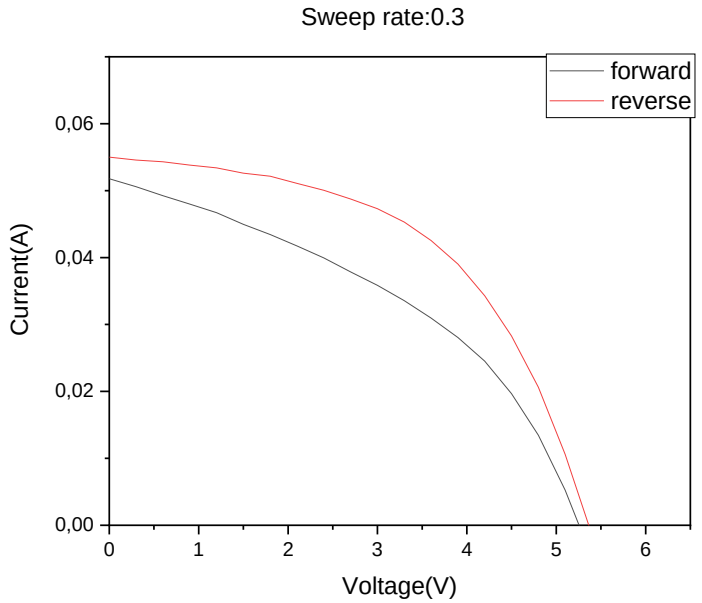


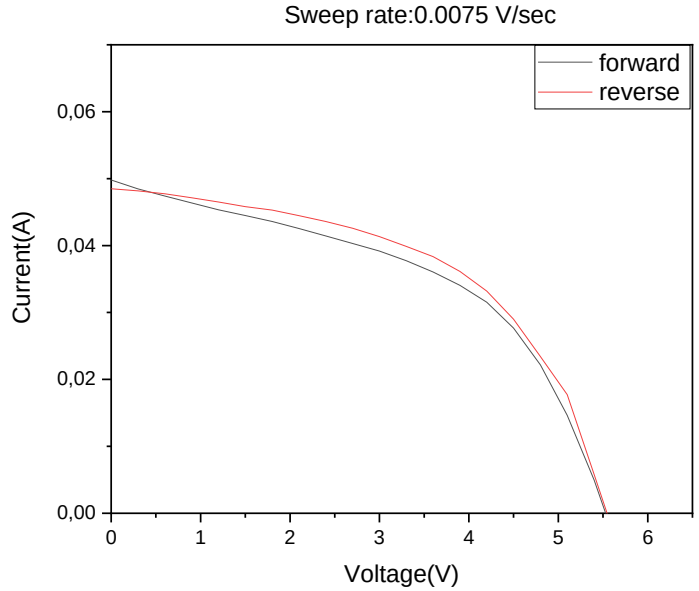
Ref: N. K. Elumalai et. al, Solar Energy Materials and Solar Cells, Vol. 157, 2016, pp. 476-509

Challenges in perovskite testing: Hysteresis & impact of I-V conditions

- Impact of voltage sweep rate







Forward first measurements

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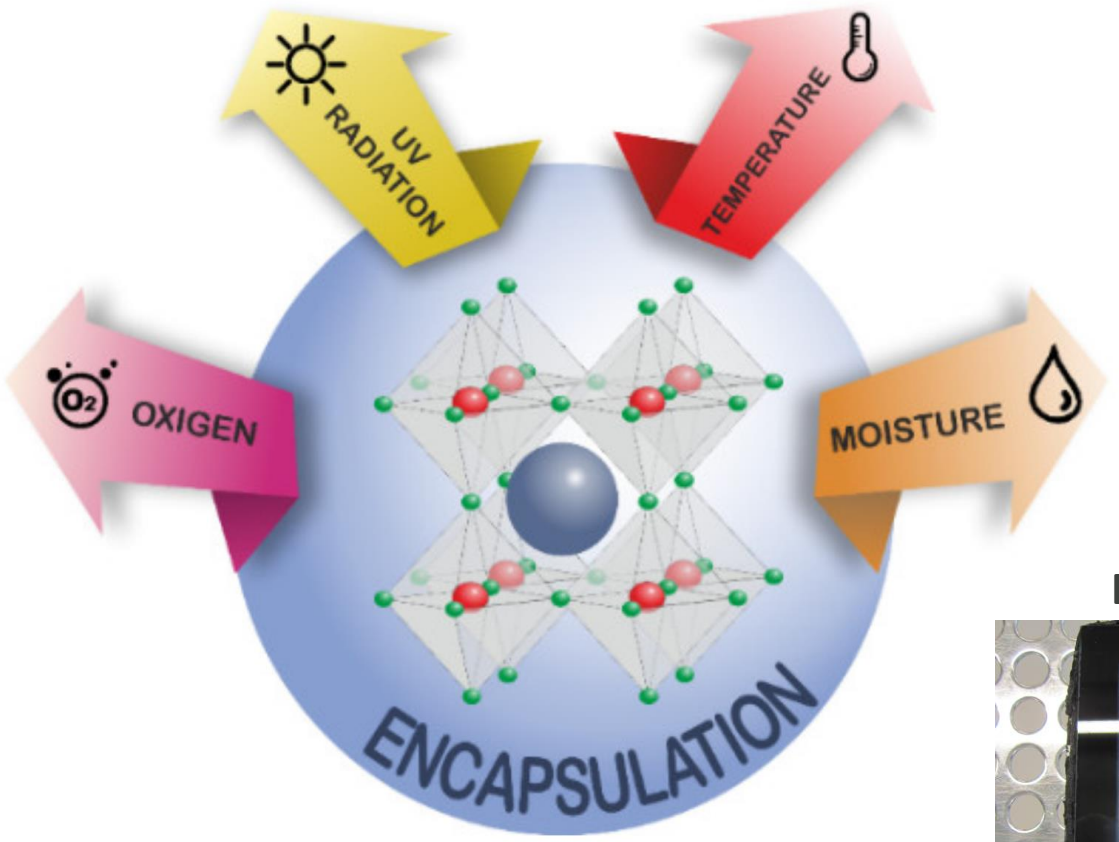
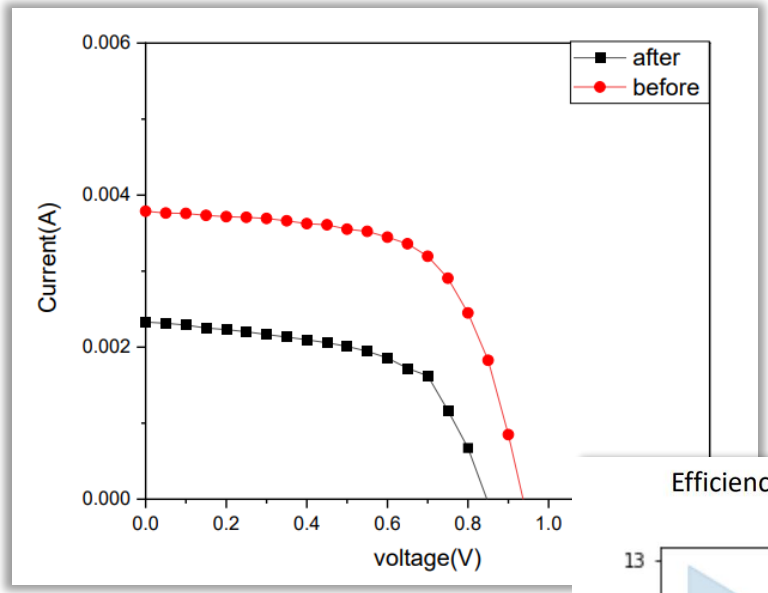
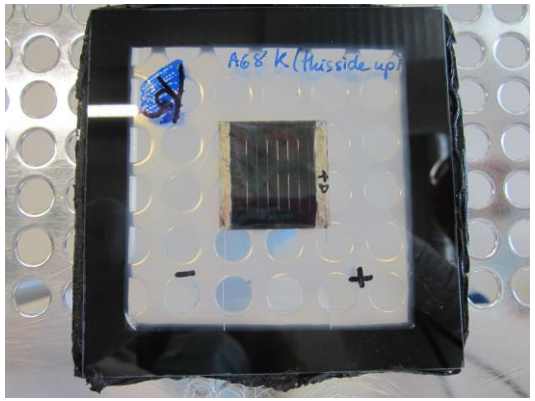
Challenges in perovskite testing: Performance Degradation

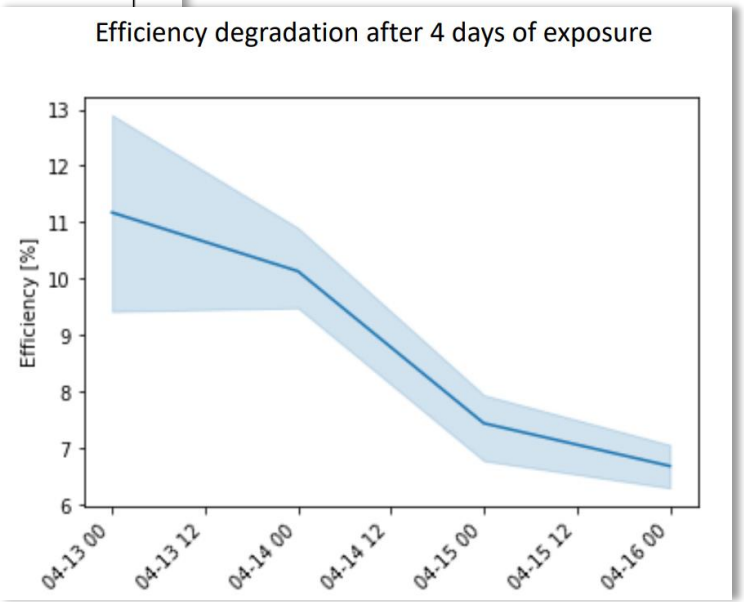




Drop in performance after outdoor aging

Encapsulation





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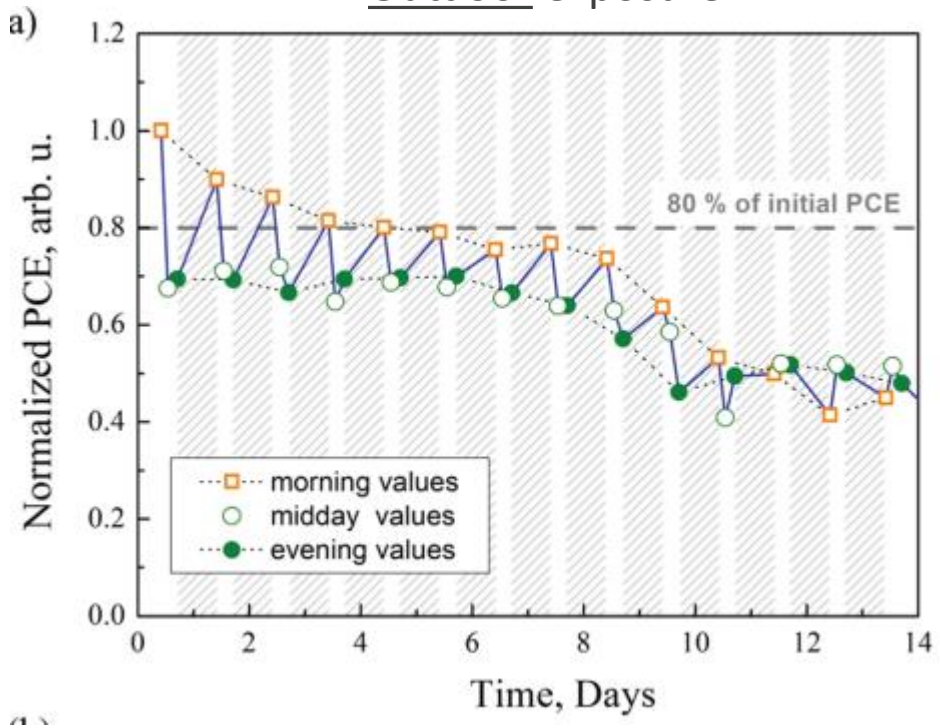
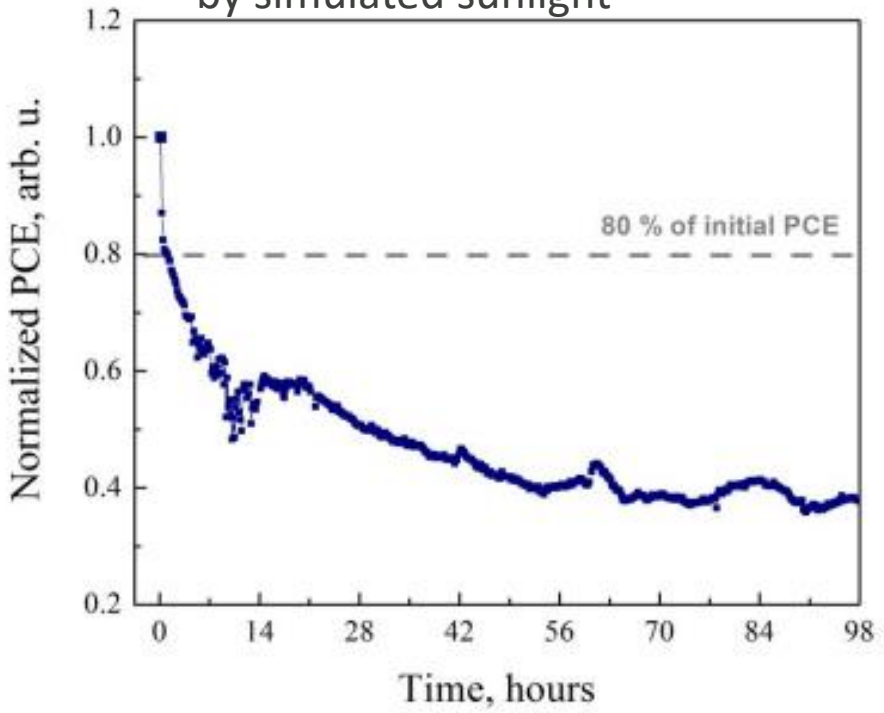
Challenges in perovskite testing: Diurnal performance variation (overnight recovery)

Outdoor exposure



Indoors continuous illumination by simulated sunlight



Ref: M. Khenkin et. Al, ***Energy Environ. Sci.***, 2018,**11**, 739-743

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Outdoor monitoring – Measurement conditions

Electrical measurements taken:

- **I-V curves (forward and reverse voltage sweeps)**

Electrical measurement **frequency:**

- I-V data logged **every 5 minutes**

Electrical measurement **technique:**

- **Sweep rate**: 1V/sec, **hold time**: 0sec, forward/reverse sweep **(forward-first measurements**).

Environmental measurements:

- Solar irradiance (POA), ambient & device temperatures, wind velocity, humidity & precipitation levels.

Reference measurements

- Use of control modules indoors
- Collection of regular I-V measurements indoors

Visual checks / records

- Frequent inspection of the modules

Module condition between measurements: Voc

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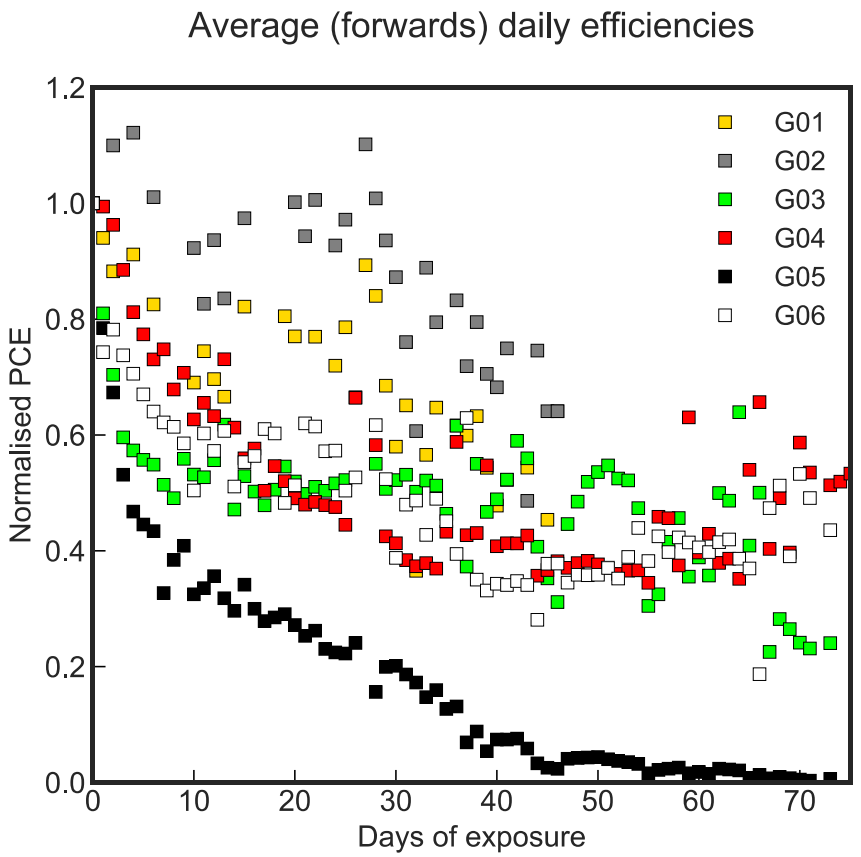
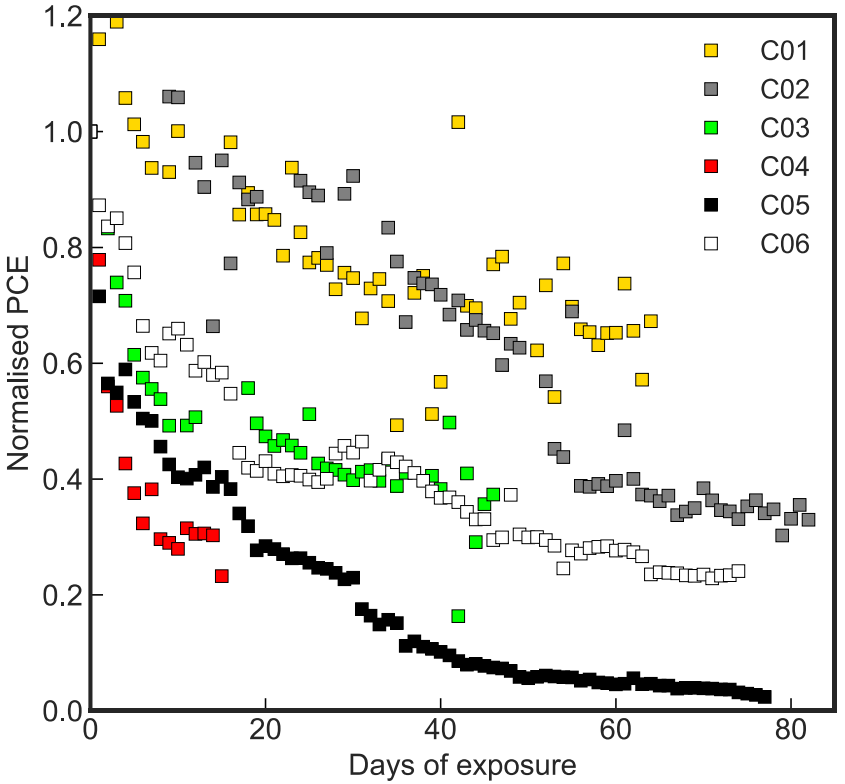
Preliminary field measurements

Fraunhofer ISE



UCY FOSS



Ref: M. Norton et. al, *37th EUPVSEC, 2020, 3BO.10.4*

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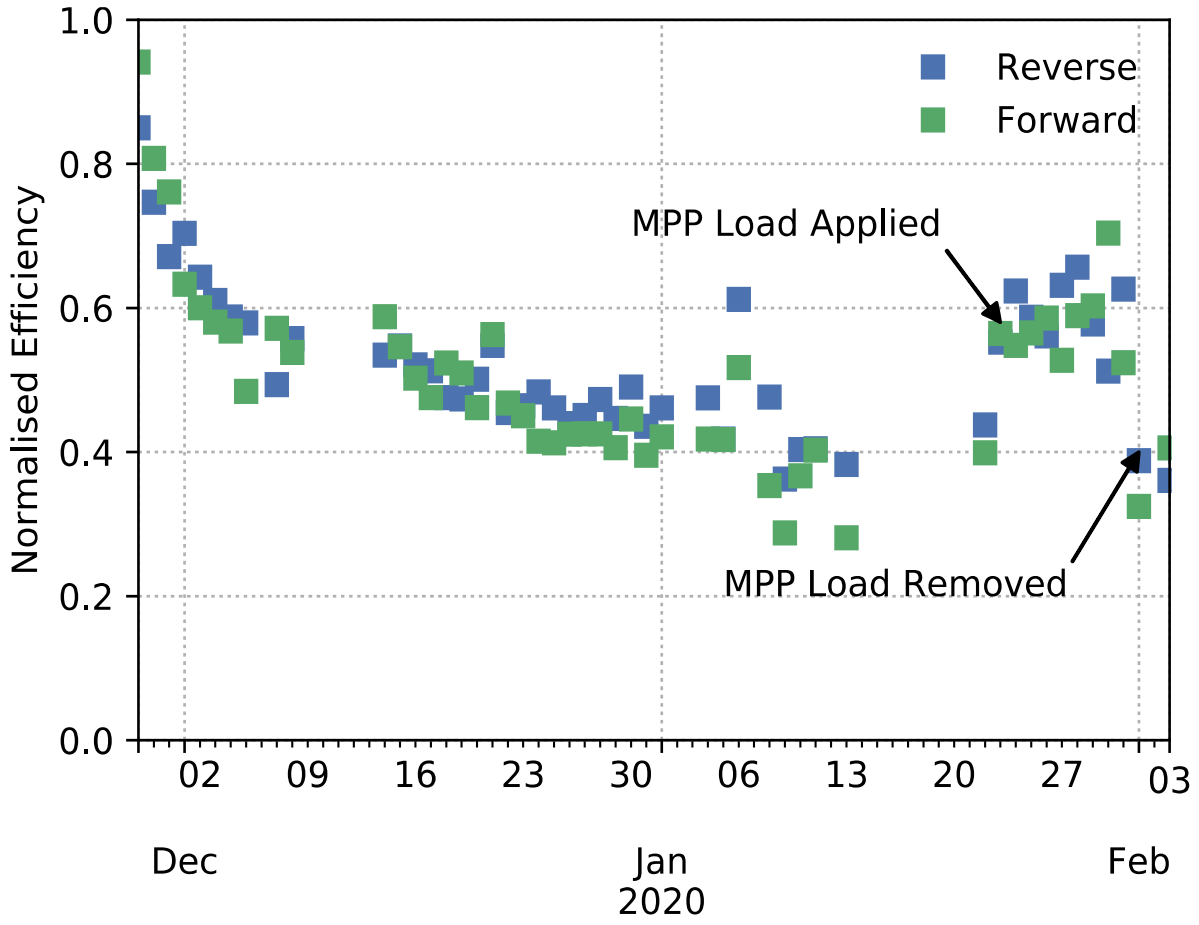
Observations - Interim loading effect

- Use of MPP loading improved performance (from 40% of initial power to 65%)
- However, using MPP loading does not prevent eventual progression of performance degradation



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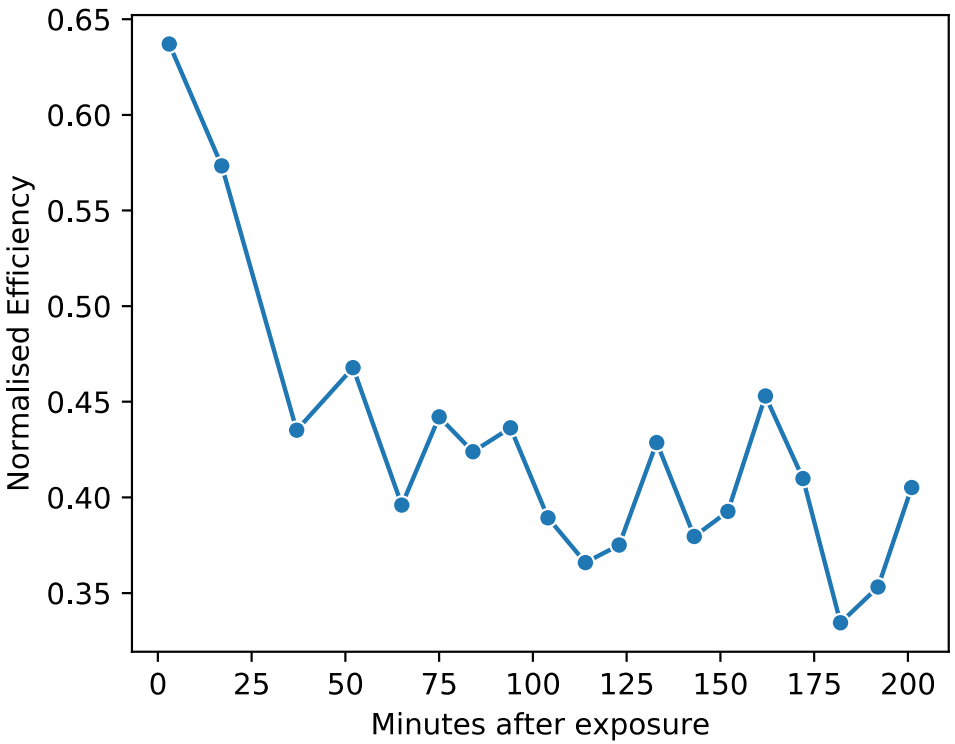
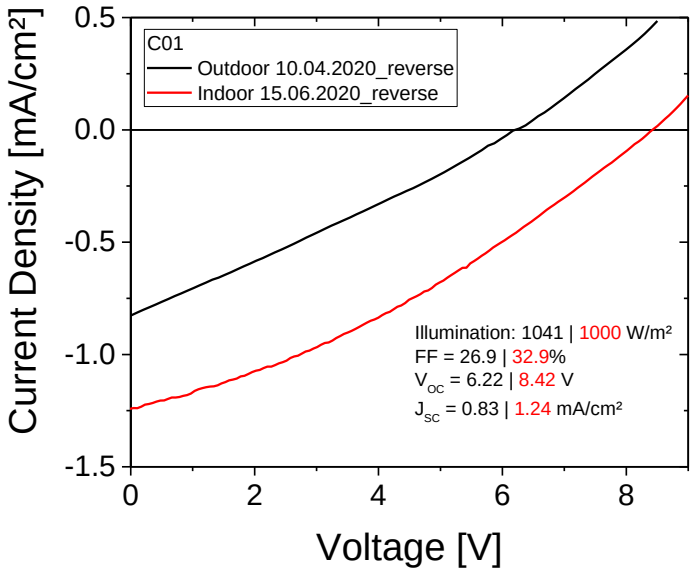
Observations - Recovery



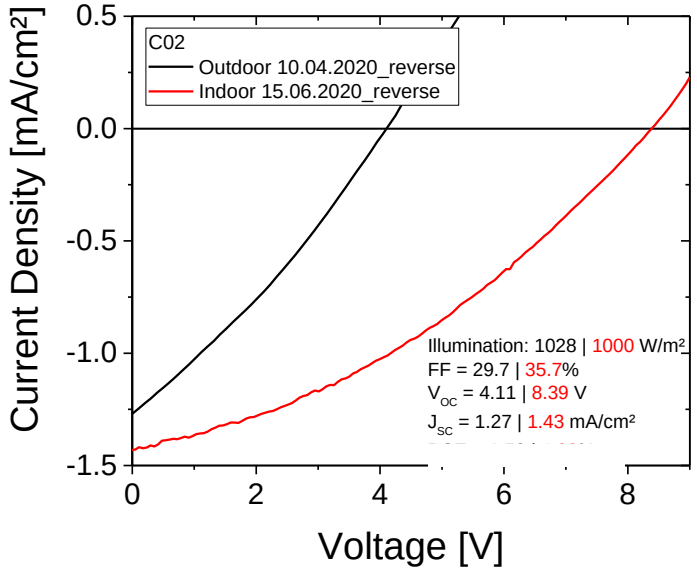
- Reverse scans showed some overnight recovery
- To investigate possible performance recovery, module was:
  - removed from outdoor setup
  - kept in dark, uncontrolled conditions
  - replaced outdoors after 2 weeks
  - kept at Voc between scans
- Immediate improvement over last outdoor measurements.
- Within 2 hours, efficiency had returned to roughly prior performance.

Observations: Performance Recovery

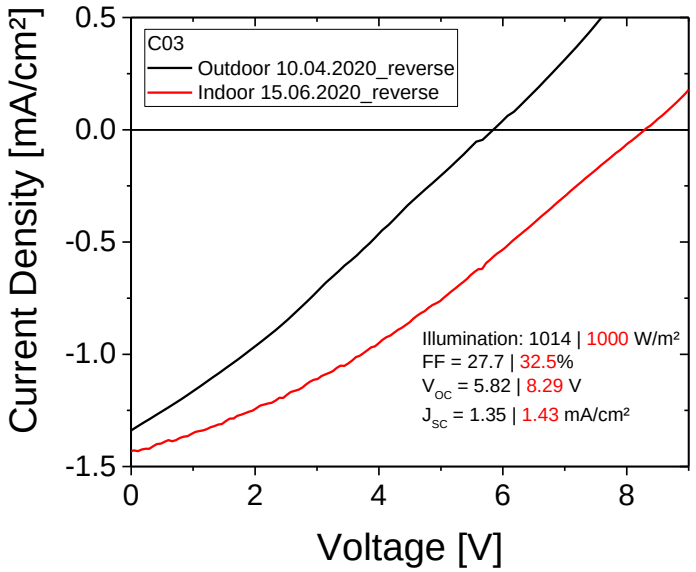
- reversible degradation (after weeks in dark storage conditions)



Initial Efficiency	1.00
After 7 weeks exposure	0.32
After 2 months recovery	0.81



Initial Efficiency	1.00
After 12 weeks exposure	0.35
After 2 months recovery	0.99

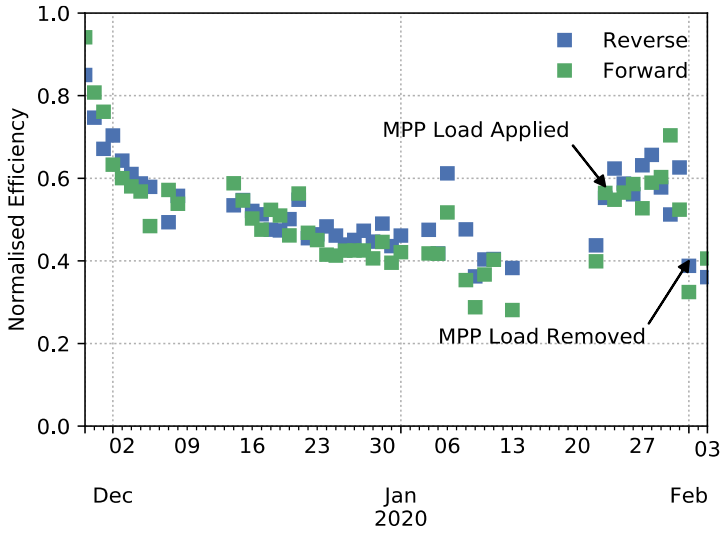


Initial Efficiency	1.00
After 9 weeks exposure	0.50
After 2 months recovery	0.89

Ref: M. Norton et. al, *37th EUPVSEC, 2020, 3BO.10.4*

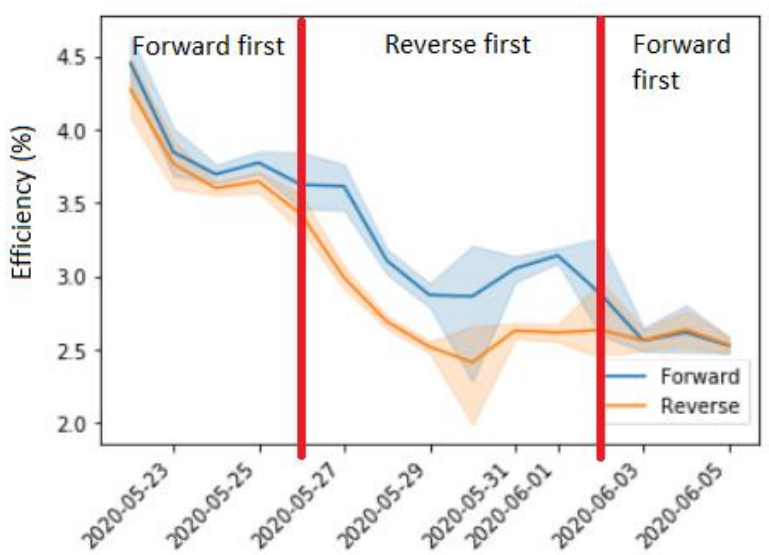
Impact of I-V sweep conditions

- Development of ‘perovskite-appropriate’ test protocols: Impact of IV sweep conditions

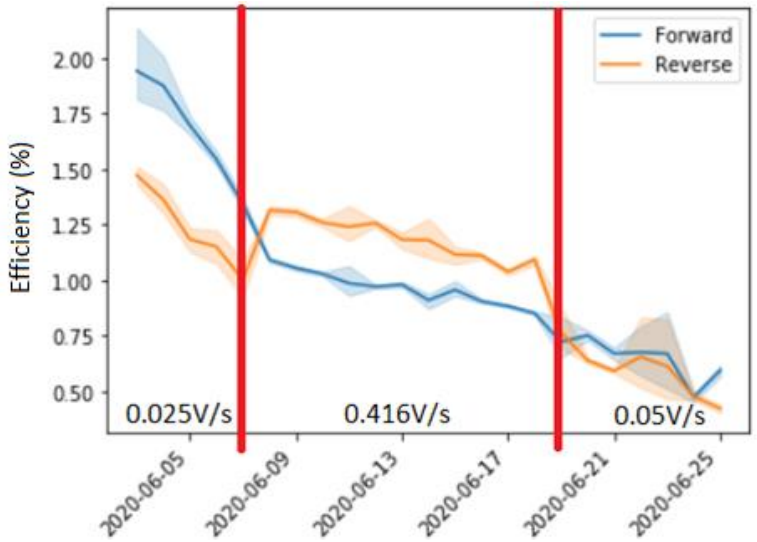


Interim loading (from Voc to MPP)

Apparent recovery of performance (by 60%)



V scan direction priority (forward/reverse first)
[only for Voc load conditions]



V scan sweep rate
[for both Voc, MPP load conditions]

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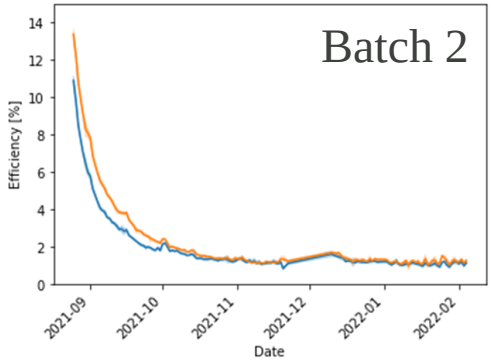
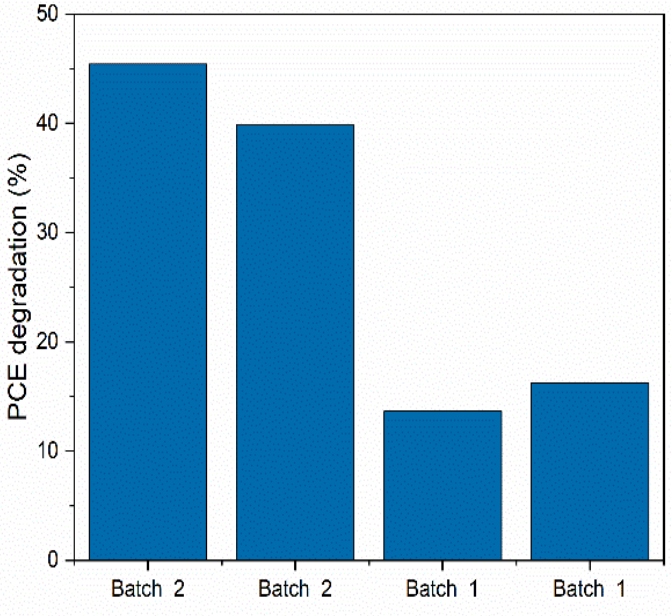
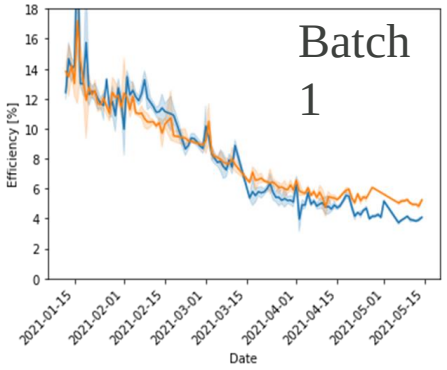
Effect of environmental conditions on performance

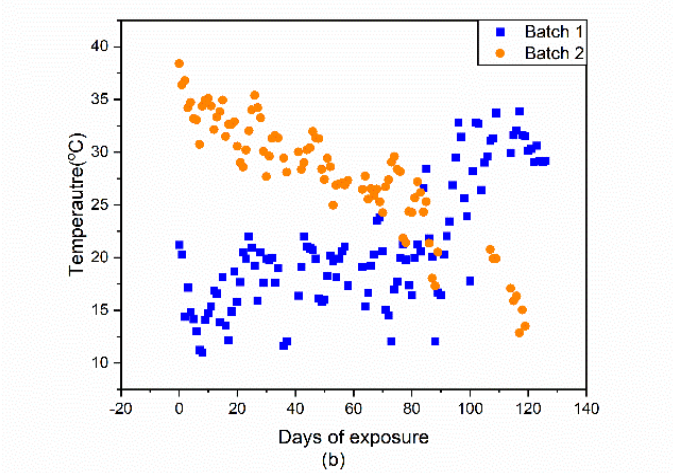


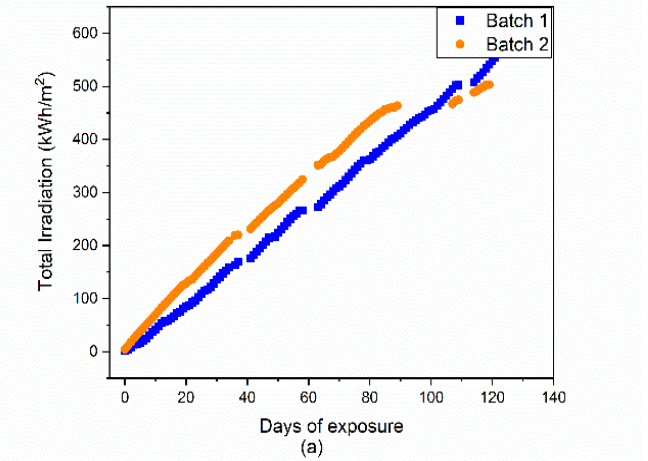


- 4 identical modules tested in different seasons
- Monitoring: electr. Parameters, $T_{ambient}$, irradiation
- Efficiency degradation → mostly current losses
- Batch1:
  - mean T_{module} =28°C,
  - total weekly solar irradiation = 20.22 kWh/m^2
- Batch2:
  - mean T_{module} = 49.6°C
  - total weekly solar irradiation = 41.25 kWh/m^2
- For same total irradiance applied: higher degradation in higher temperatures → **<u>temperature major stressor outdoors</u>**



*Efficiency degradation **<u>after 1 week</u>** outdoors.*





Ref: V. Paraskeva et. al, Seasonal dependence of diurnal efficiency degradation and recovery in perovskite mini-modules during outdoor testing, IEEE PVSC 2022

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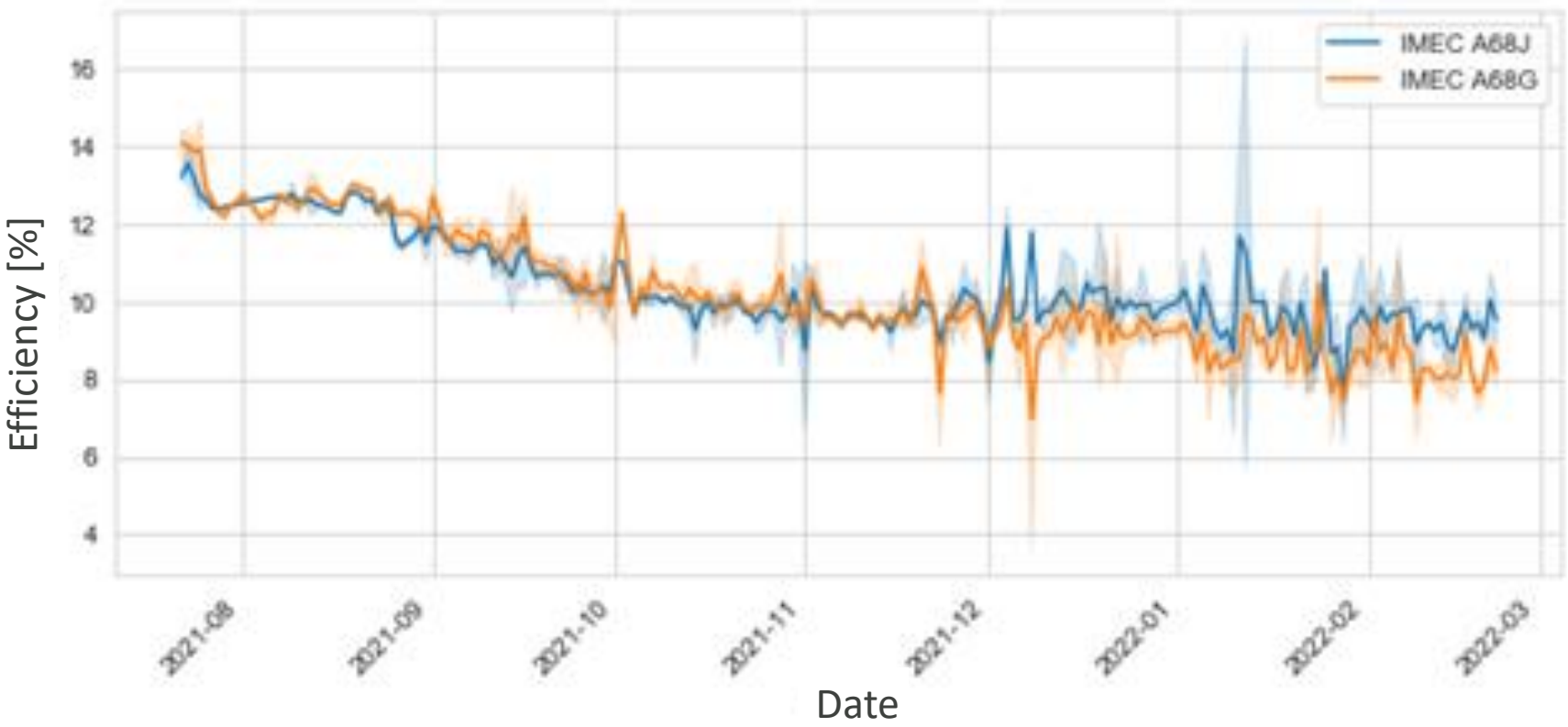
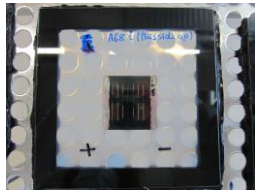
Long term monitoring





- 8+ months continuous monitoring
- **Performance degradation (28%) over first 3 months**
- **Current losses are significant**

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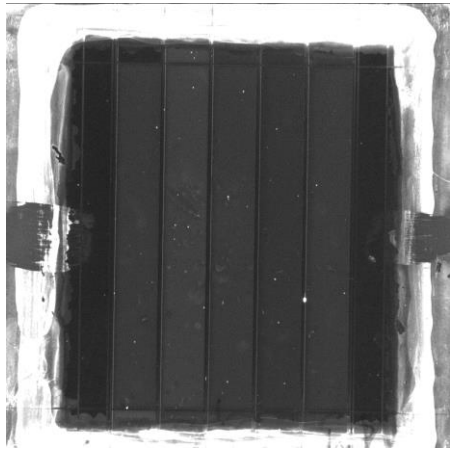
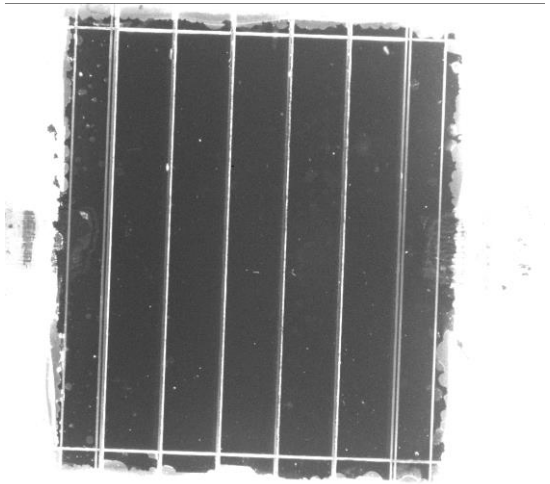
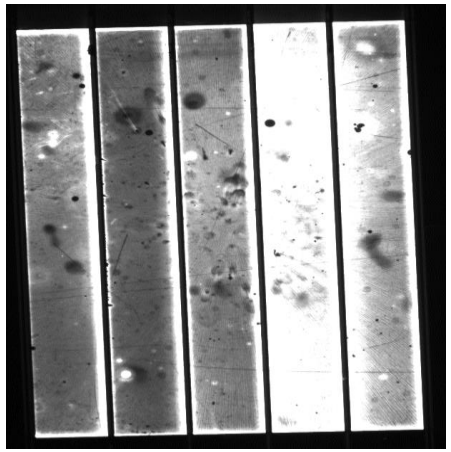
Monitoring failure development and evolution

PL

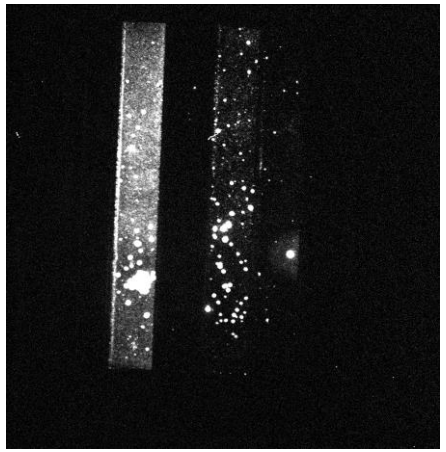




EL



BEFORE



AFTER

After 3 months in the dark (recovery)

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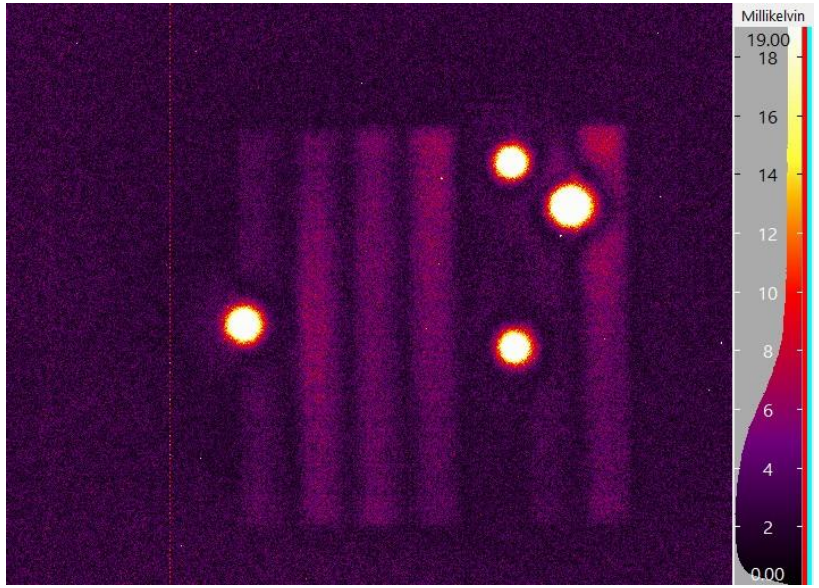
DLIT images of perovskite mini-modules before outdoor testing

Dark Lock-In Thermography images



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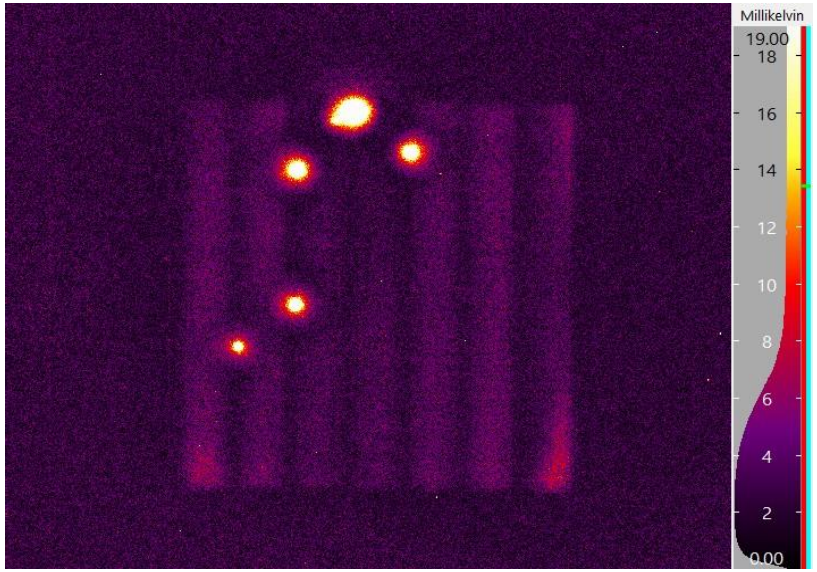
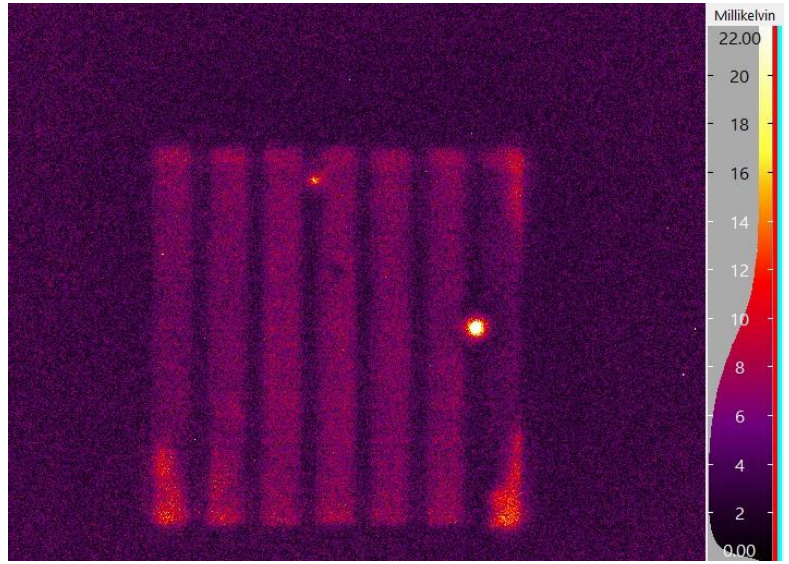


A68J



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Learning curves

- Encapsulation
- Hysteresis in I-V scans → I-V conditions critical

  → both FW&REV scans @ optimal scan rate
- Degradation → permanent vs reversible

  → nature, origin, evolution, recovery mechanisms??
- MPP loading → more representative result of instantaneous PCE
- Imperative to monitor environmental conditions in PSC field monitoring
- Standardized outdoor monitoring protocols for PSC
- Long-term outdoor studies to build experiences on monitoring of PSC
  - → large scale database of perovskite PV plant outdoor performance → PR, performance loss rates, climate, and other stress-factor dependency → development of field reliability algorithms & models
  - → development of field diagnostics for PSC in future

Thank you for your attention

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