Measurement challenges of PSK devices and their mitigation

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Context

- Characterisation requirements, resources and capabilities vary widely
- Perspective from a calibration laboratory
- Focus on P_{MAX}
- What is different for reliability studies?

What is the goal?

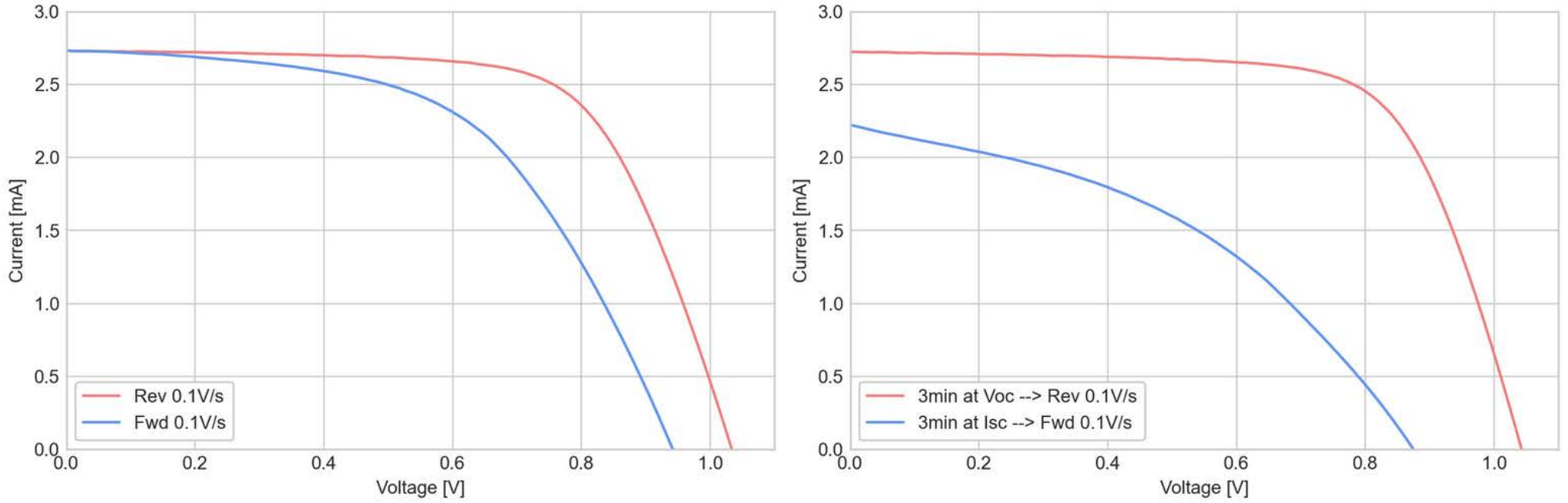
Wishlist

1. A fool proof procedure
2. Cheap, fast and easy to implement
3. Agnostic to the material
4. Reproducible and representative of outdoor performance
5. No need to understand what is going on inside the device (black box)

- The goal is reproducible P_{MAX} measurements.
- Reproducibility and equivalence have not yet been demonstrated.
- Work is ongoing.
- Other methods can be validated against a reference.

Why are perovskites ‘tricky’? – meta-stability

- There is a coupling of meta-stability (reversible change in performance) on different timescales:
  - Fast (seconds to minutes) Responsible for Hysteresis (attributed to halide migration)



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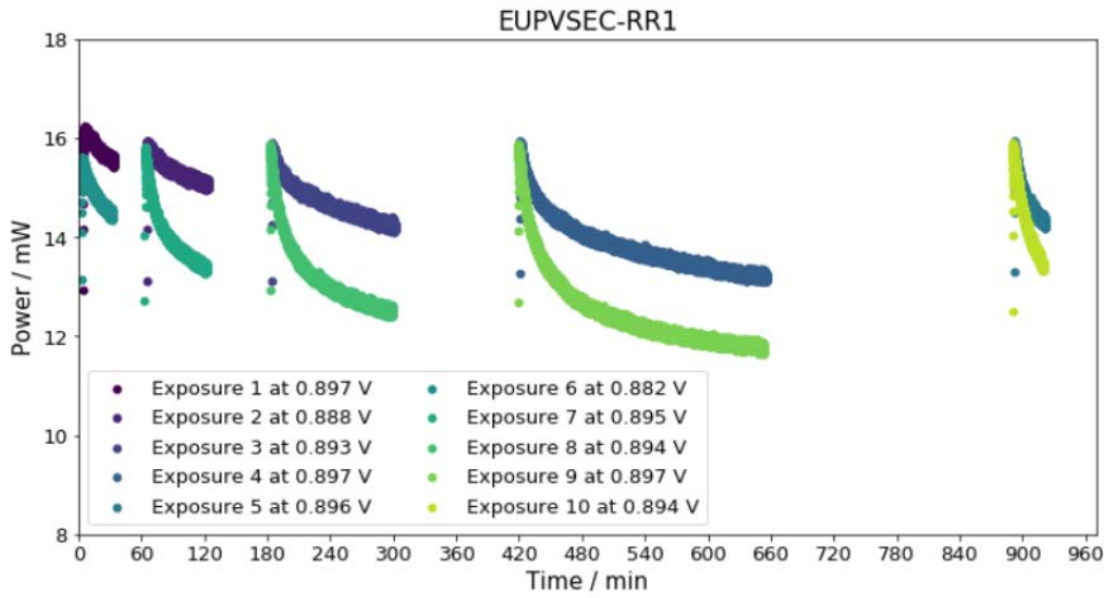

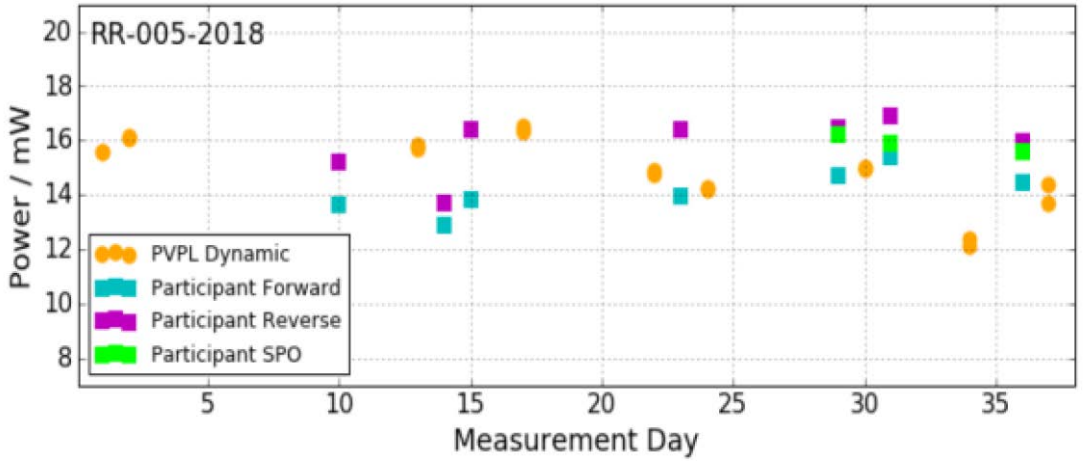

B. Mihaylov et al ‘Perovskite Meta-Stability Effects in Hysteresis-Free Measurements‘, EUPVSEC 2019 3CO.6.1

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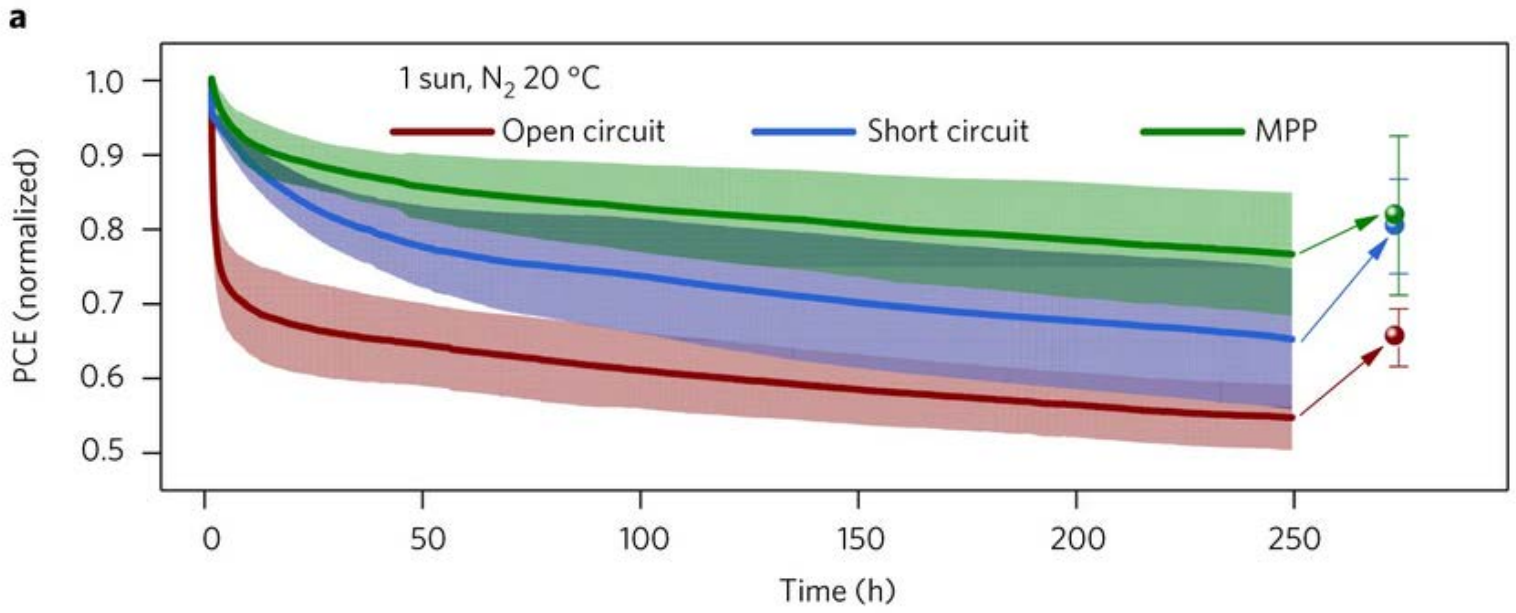
  - Fast (seconds to minutes) Responsible for Hysteresis (attributed to halide migration)
  - Medium to Slow (15 min to hours) Affects Reproducibility. (attributed to cation migration)
- Different meta-stabilities for different:
  - device stacks
  - PSK recipes
  - processing methods

→ hard to generalize

Why are perovskites ‘tricky’? – degradation

- Intrinsic and/or extrinsic degradation (irreversible change in performance) on short timescales
- The degradation rate under STC can be a function of the voltage bias conditions



Domanski, K. et al. ‘Systematic investigation of the impact of operation conditions on the degradation behaviour of perovskite solar cells.’ Nat Energy 3, 61–67 (2018). https://doi.org/10.1038/s41560-017-0060-5

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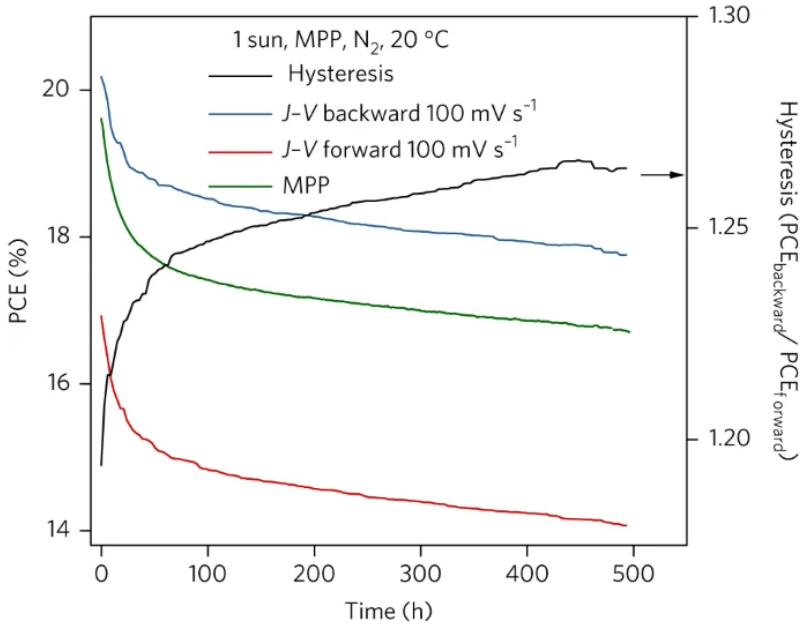
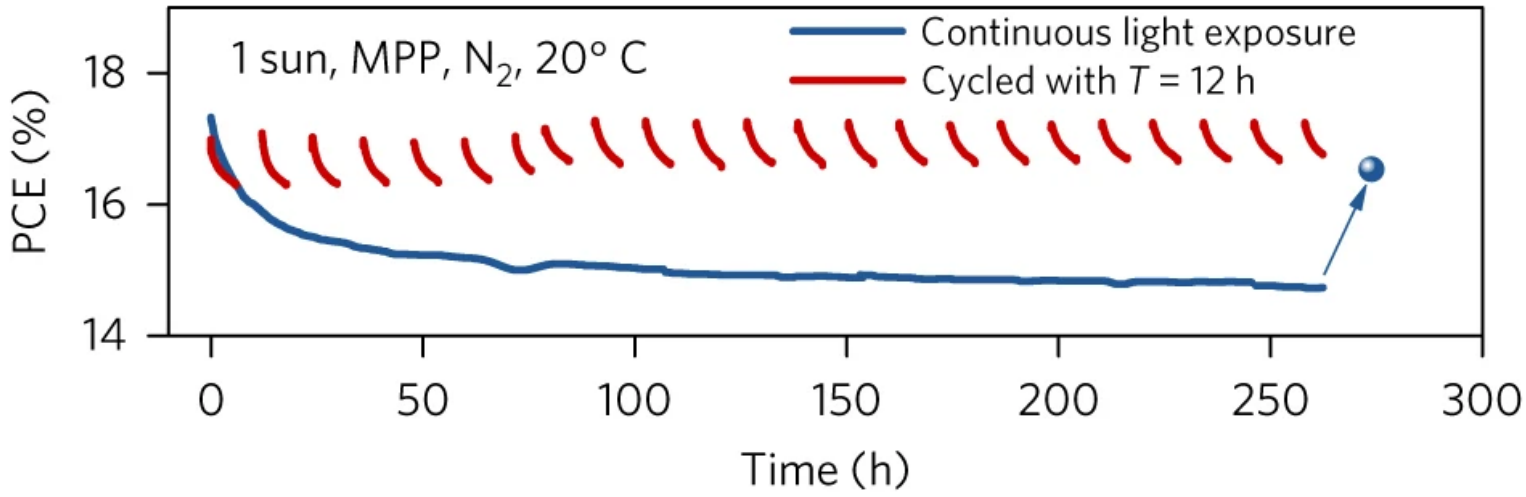
- The degradation rate under STC can be a function of the voltage bias conditions
- Degradation affects meta-stability and meta-stability affects degradation





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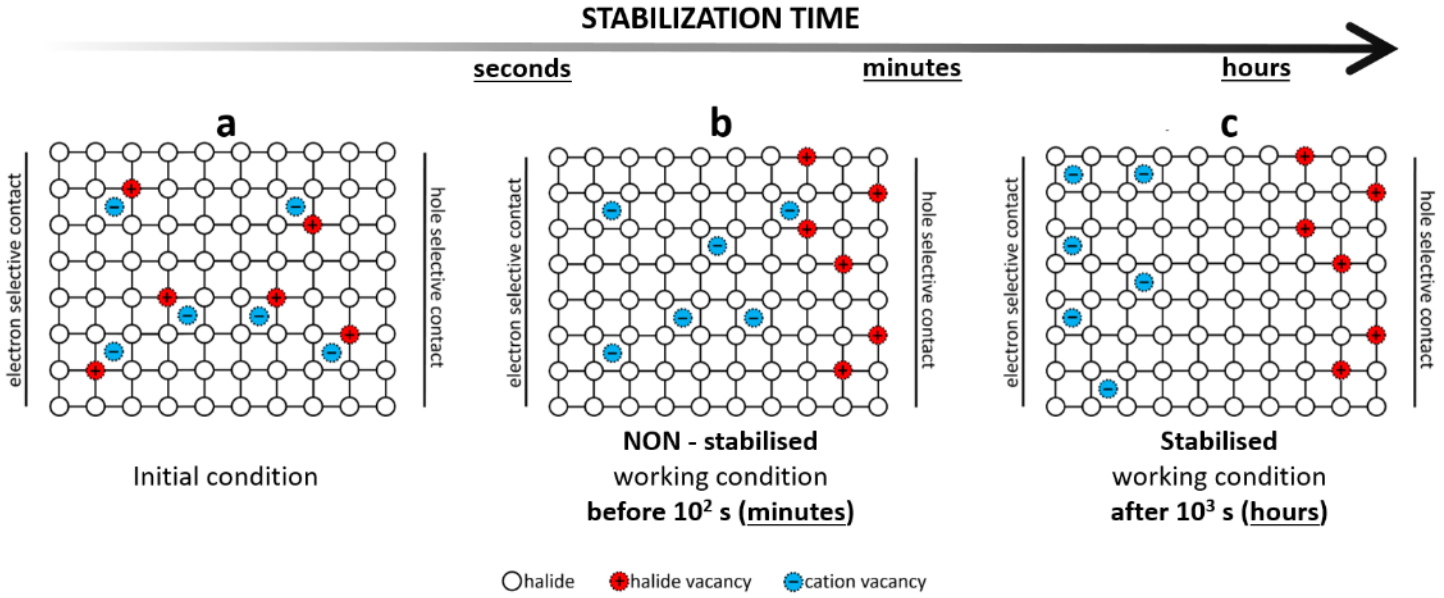
Useful mental model – ionic motion

- Broad consensus: motion of ionic species responsible for meta-stabilities
- P_{max} depends on distribution of ionic species within the bulk and accumulated at the interfaces
- (Quasi) steady-state: this distribution has reached (near) equilibrium conditions at a given external voltage bias



Domanski, K et al. 'Migration of cations induces reversible performance losses over day/night cycling in perovskite solar cells'. Energy & Environmental Science 2017, 10, 604–613

Solving fast meta-stability (Hysteresis)

Hysteresis can be ‘solved’ with (quasi) steady-state/settled measurements:

Single point measurements (1-15 min):

- SPO/SCFV (may not be at Vmpp)
- MPPT (the algorithm my affect the end result)

Partial or full I-V curves (based on some settling and time criteria):

- Dynamic I-V
- Asymptotic I-V
- Time-resolved I-V
- Real-Time One Sweep
- Manual I-V (ESTI)

The equivalency of these methods is not yet proven. All practically ‘remove’ hysteresis for some devices.

Solving slow meta-stability (Reproducibility)

Problem:

Settled state is a function of the device history (voltage bias and light exposure).

Solution:

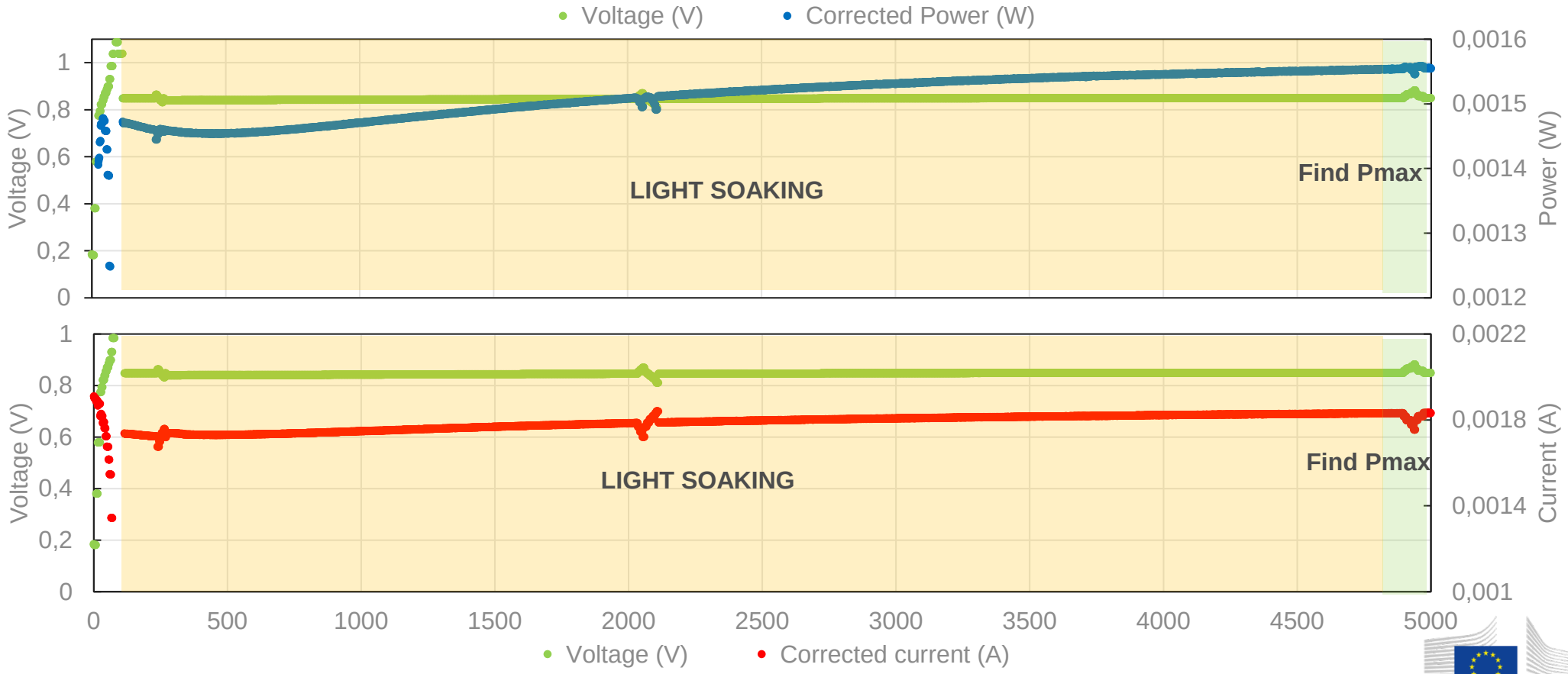
Define the measurand better, i.e. define the pre-conditioning so that the same state is measured.

But:

- How do you ‘reset’ the device state ?
- The function that maps performance to history is unknown a priori.
- Practical limitations of comprehensively investigating this on a case-by-case basis.
- Limitation on maximum measurement times.
- Even when results are reproducible: Do they reflect outdoor performance correctly ?

I-V measurements @ ESTI

- STEP 1: Quick fast I-V to *estimate* V_{mp}
- STEP 2: STC light soaking @ V≅Vmpp for 15 min to 1 h. This is device dependent.
- STEP 3: Find P_{max} and keep until settling criteria is met (e.g. 0.05%/min), but at least 5 min.



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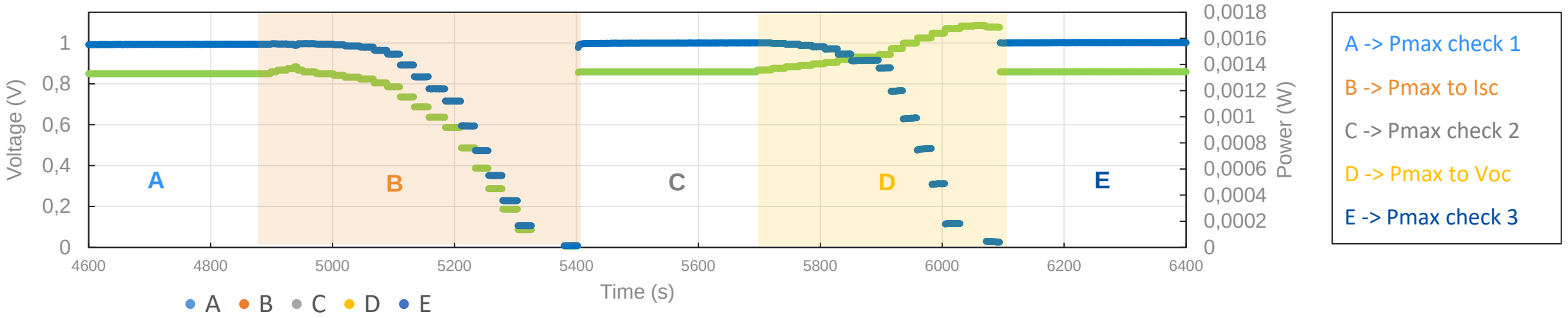
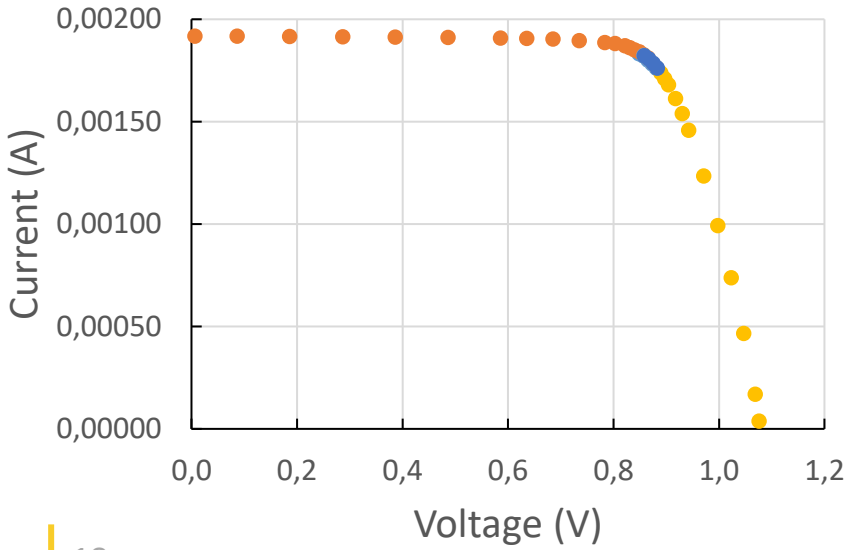
I-V measurements @ ESTI





- STEP 4: Complete the I-V (min of 60 sec per point) and check P_{max} after 0 V and V_{oc} bias. (The order can be device specific)
- STEP 5: (Optional) Repeat Step 3 and 4 (Second manual I-V)
- STEP 6: (Optional) After resting in the dark for a few days repeat Step 1 to 4.

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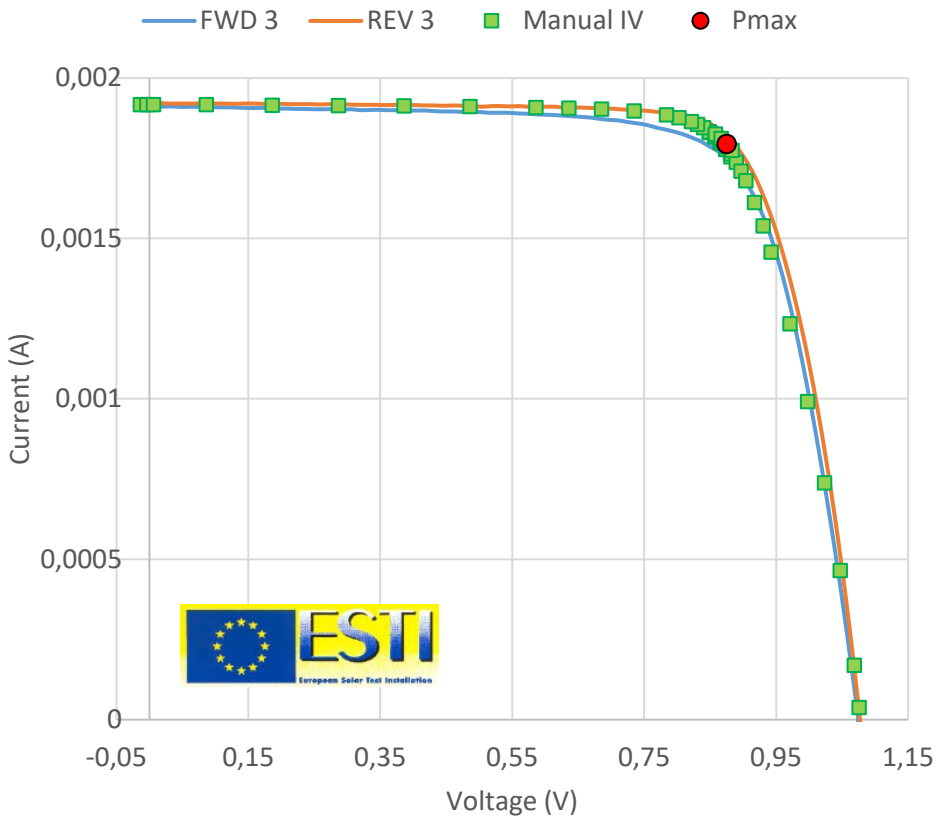
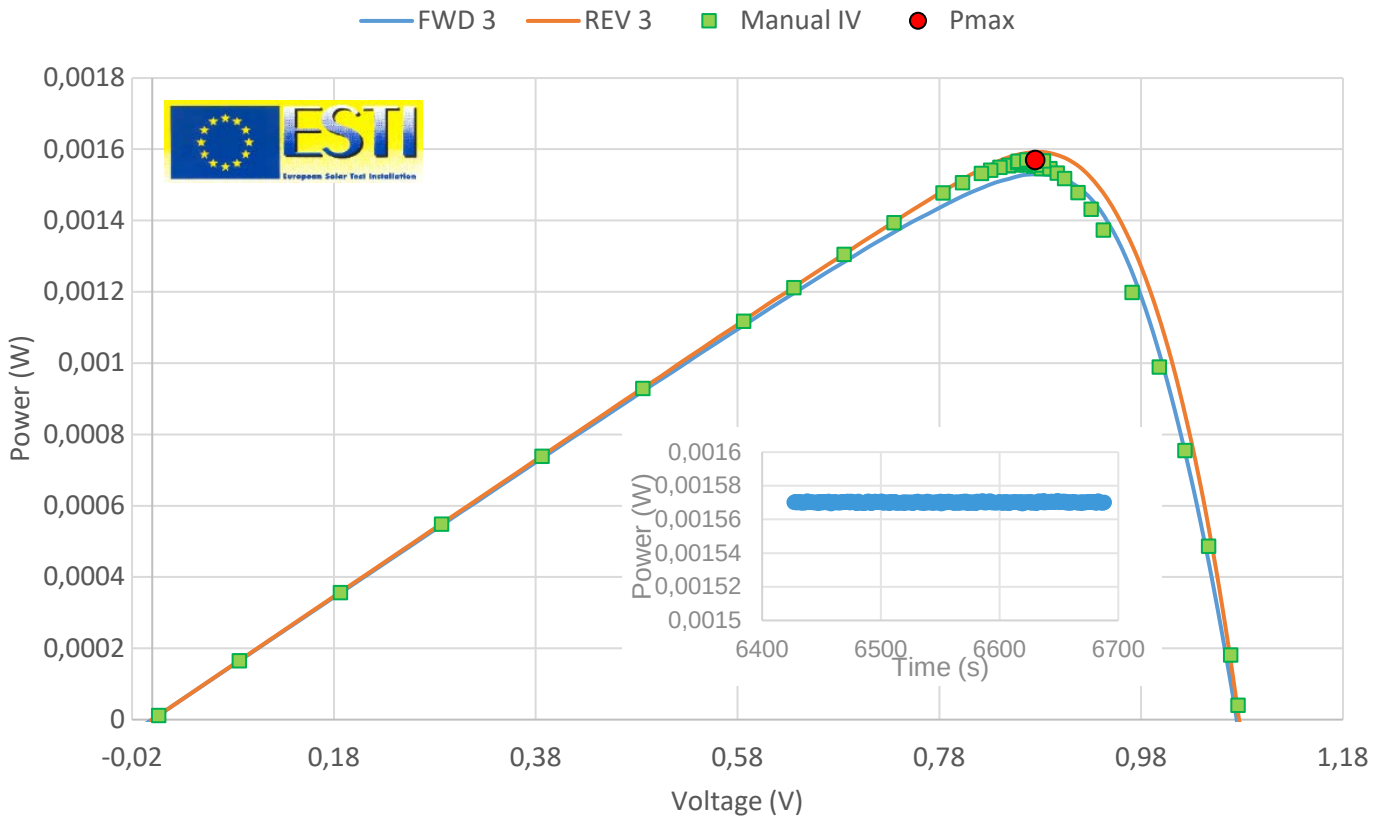
I-V measurements @ ESTI

CASE 1: Device is stable under illumination during the measurement





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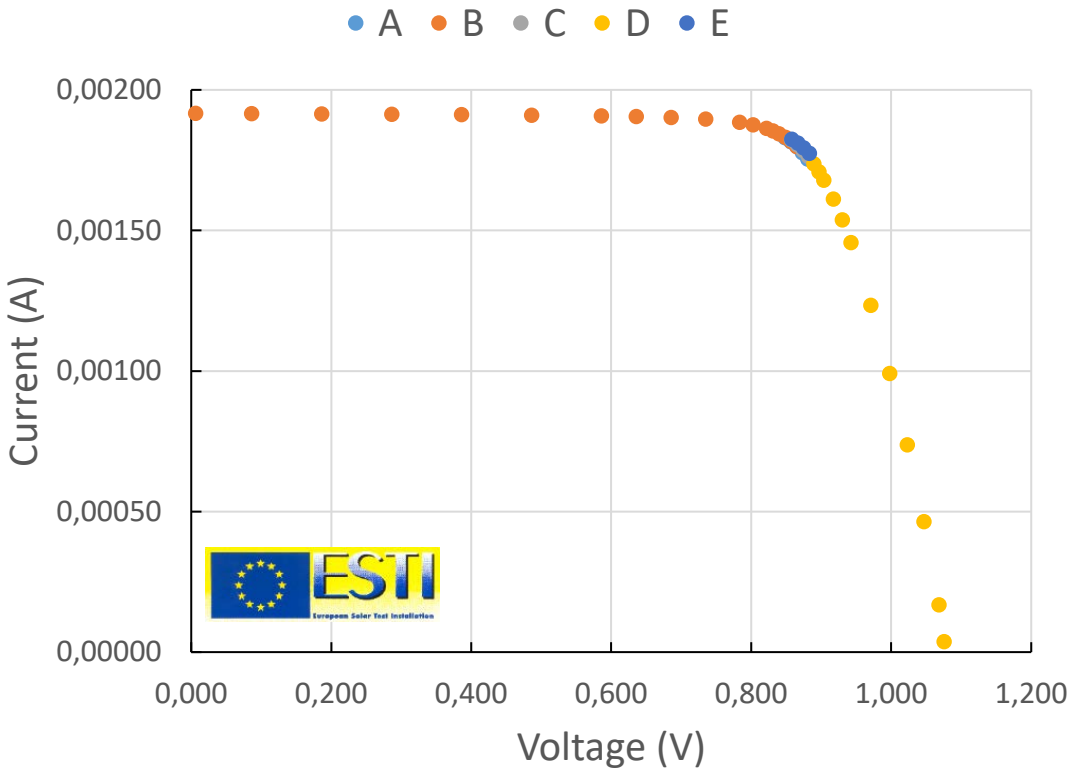
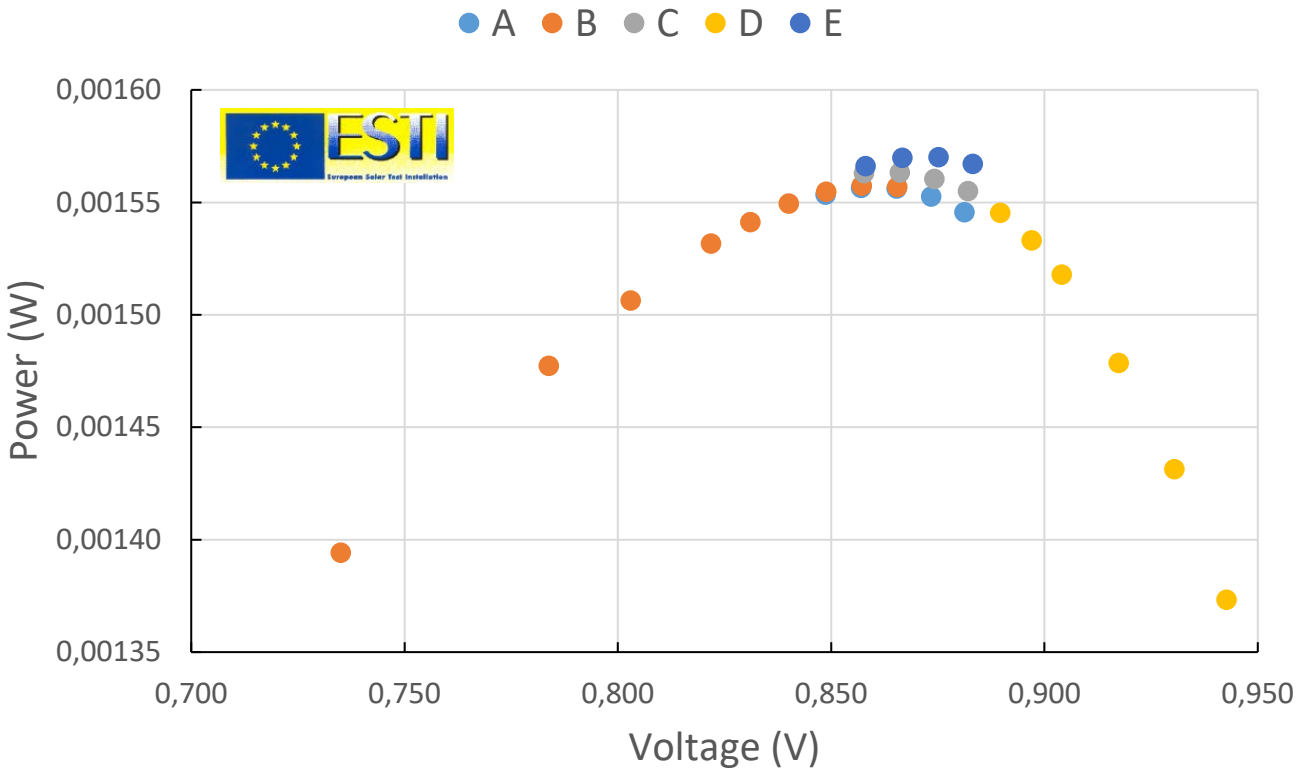
I-V measurements @ ESTI

CASE 2: Device improves under illumination (light soaking effect)





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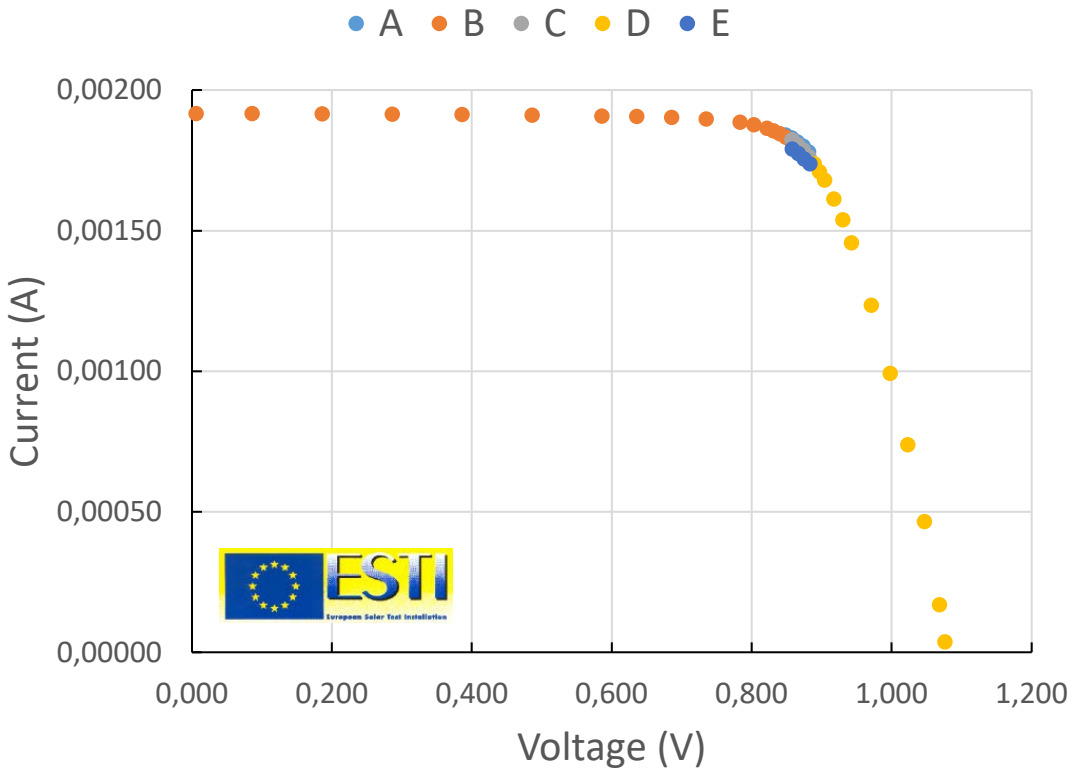
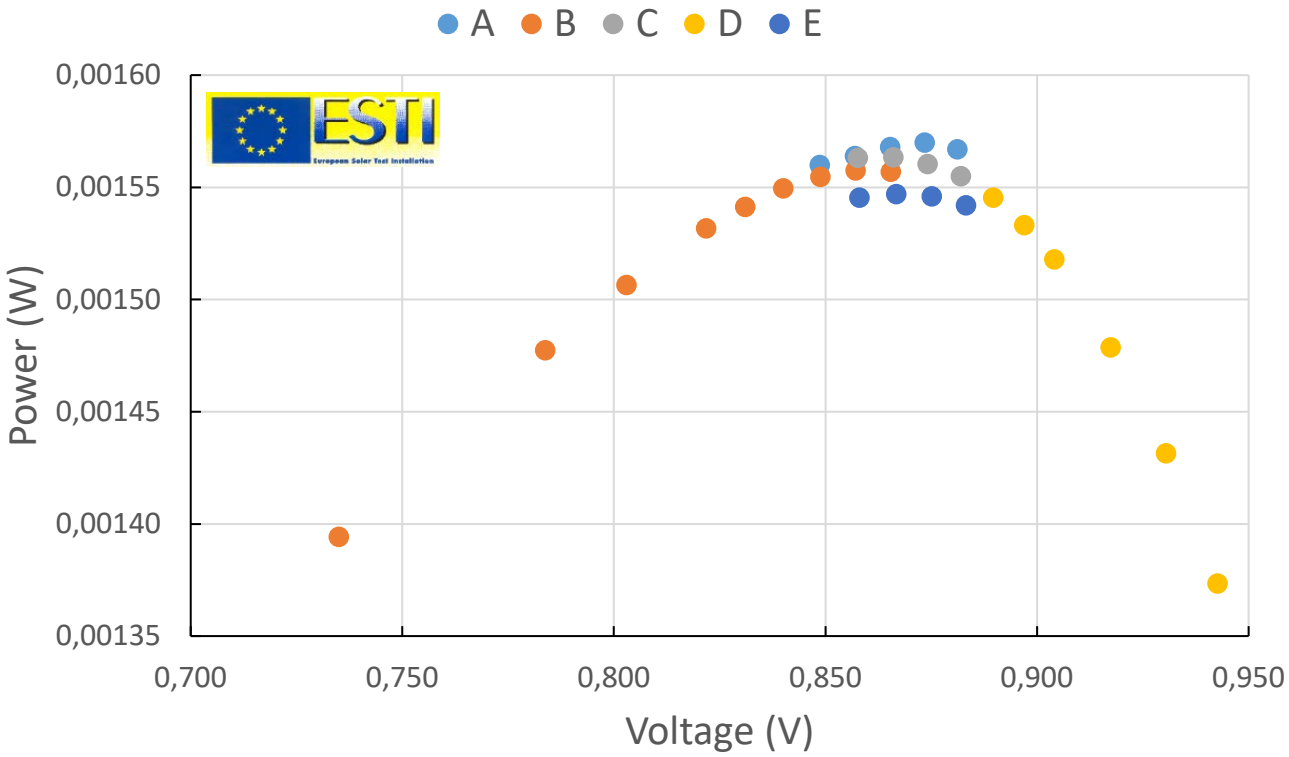
I-V measurements @ ESTI

CASE 3: Device gets worse under illumination (degradation)





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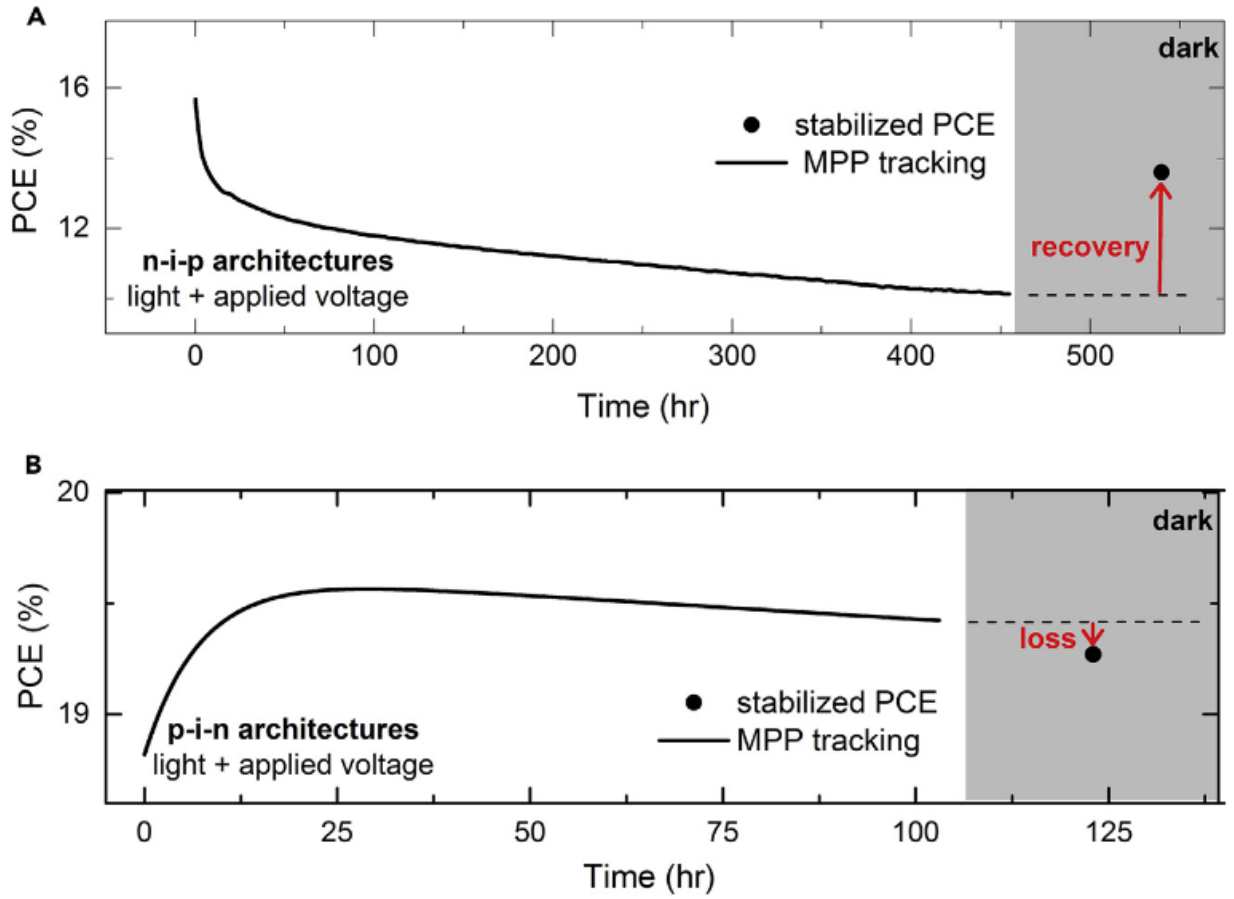
The longer timescale context



Michael Saliba et al. 'Measuring Aging Stability of Perovskite Solar Cells', https://doi.org/10.1016/j.joule.2018.05.005.

Optimum settled efficiency

- Which efficiency do we certify? → The highest measured settled efficiency
- All are conservative and ‘real’ measurements:
  - Tracked for more than 5 minutes
  - No unrealistic pre-conditioning (voltage or light bias)
- The highest is a local maximum.
- If it is a global maximum it can be ‘found’/reproduced by other methods in other laboratories.
- 1ST Reproducible → 2ND Representative

What about reliability studies ?

- Performing the full protocol at ESTI takes 2-3h.
- In the context of days of aging it may be acceptable.
- It allows to compare all 3 settled P_{max} measurements
- Helps to investigate the connection between meta-stability and degradation.
- Shortcut protocol could be validated against it.

Thank you

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References for graphs and imaged from external sources are on each individual slide.

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