ISOS (International Summit on Organic PV Stability) protocols in action

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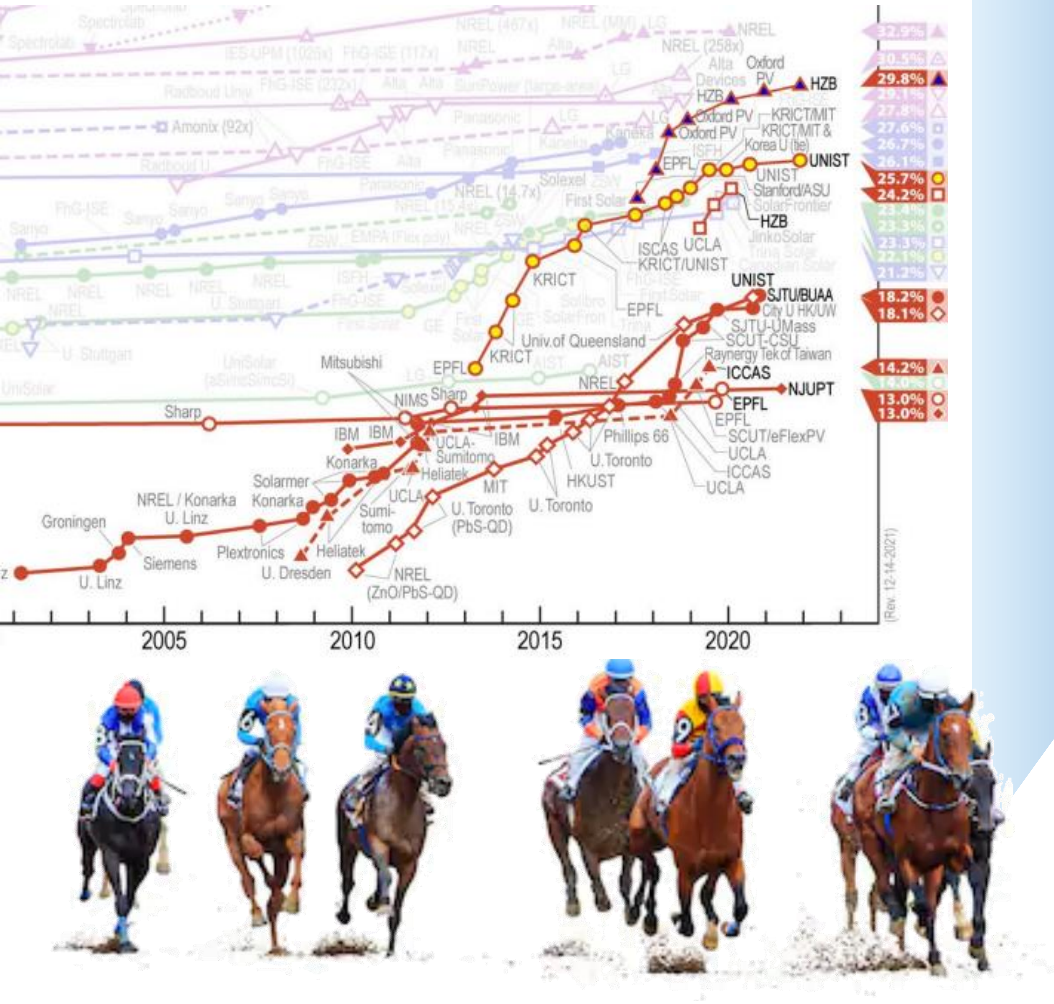
“Since reaching 20% efficiency, research in perovskite photovoltaics has shifted from *a race for efficiency* to *a race for stability*.” ©

W. Tress et al. Nature energy 4, 568 (2019)

RACE FOR EFFICIENCY

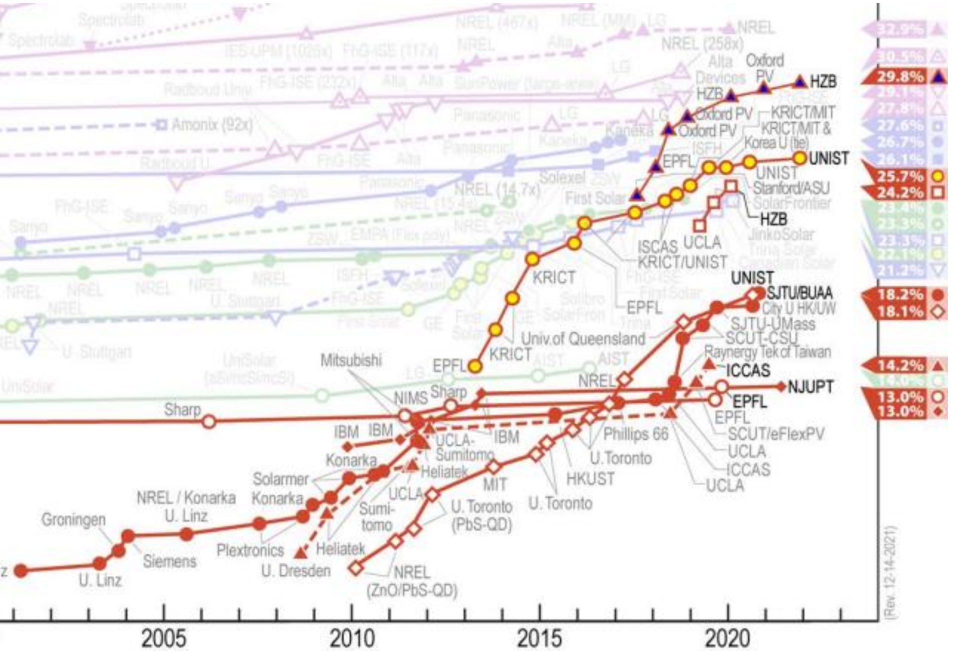


RACE FOR STABILITY

"Since reaching 20% efficiency, research in perovskite photovoltaics has shifted from *a race for efficiency* to *a race for stability*." ©

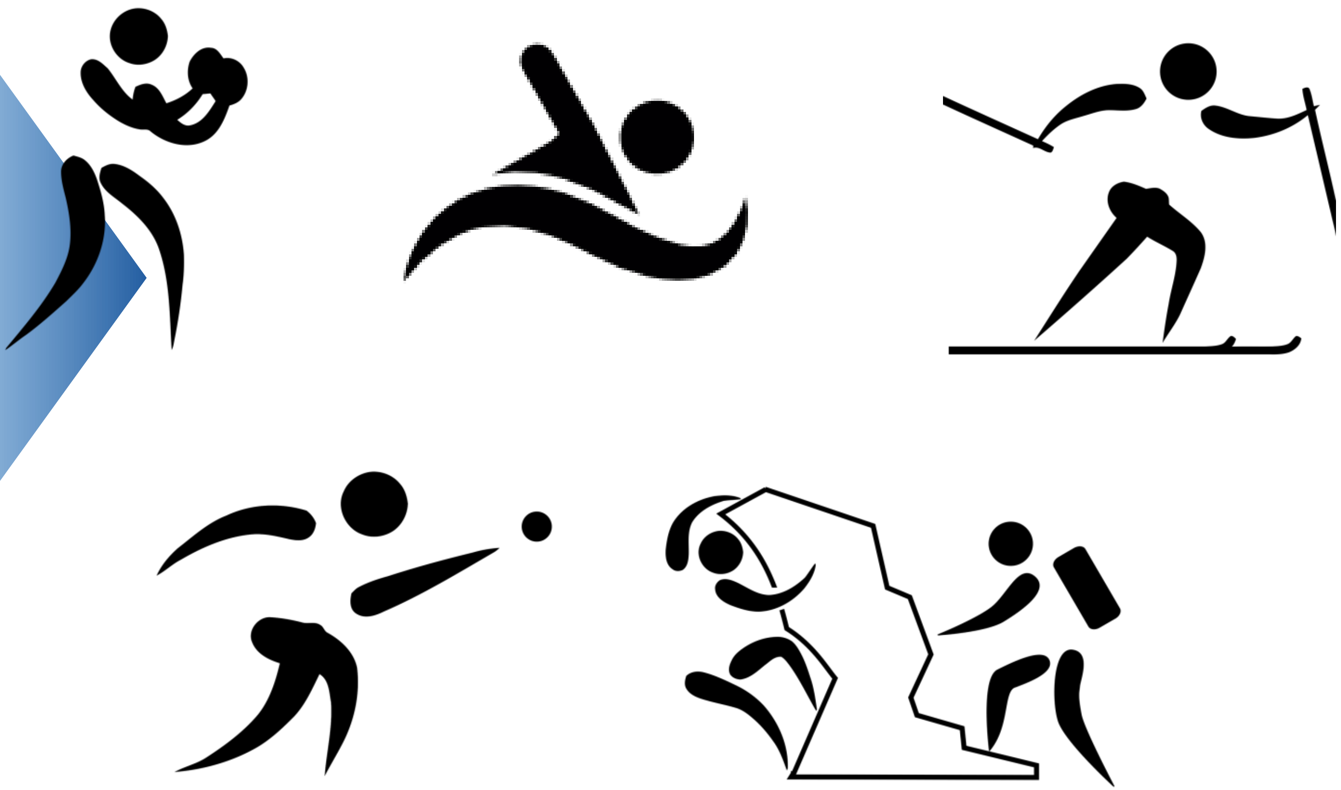
W. Tress et al. Nature energy 4, 568 (2019)

RACE FOR EFFICIENCY



OLYMPICS

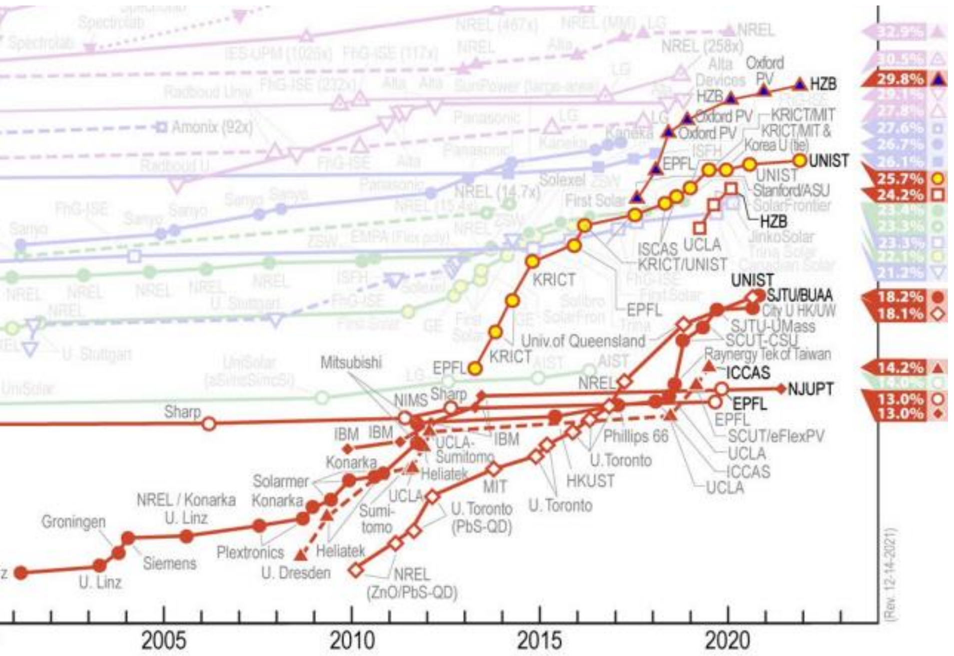
~~RACE~~ FOR STABILITY



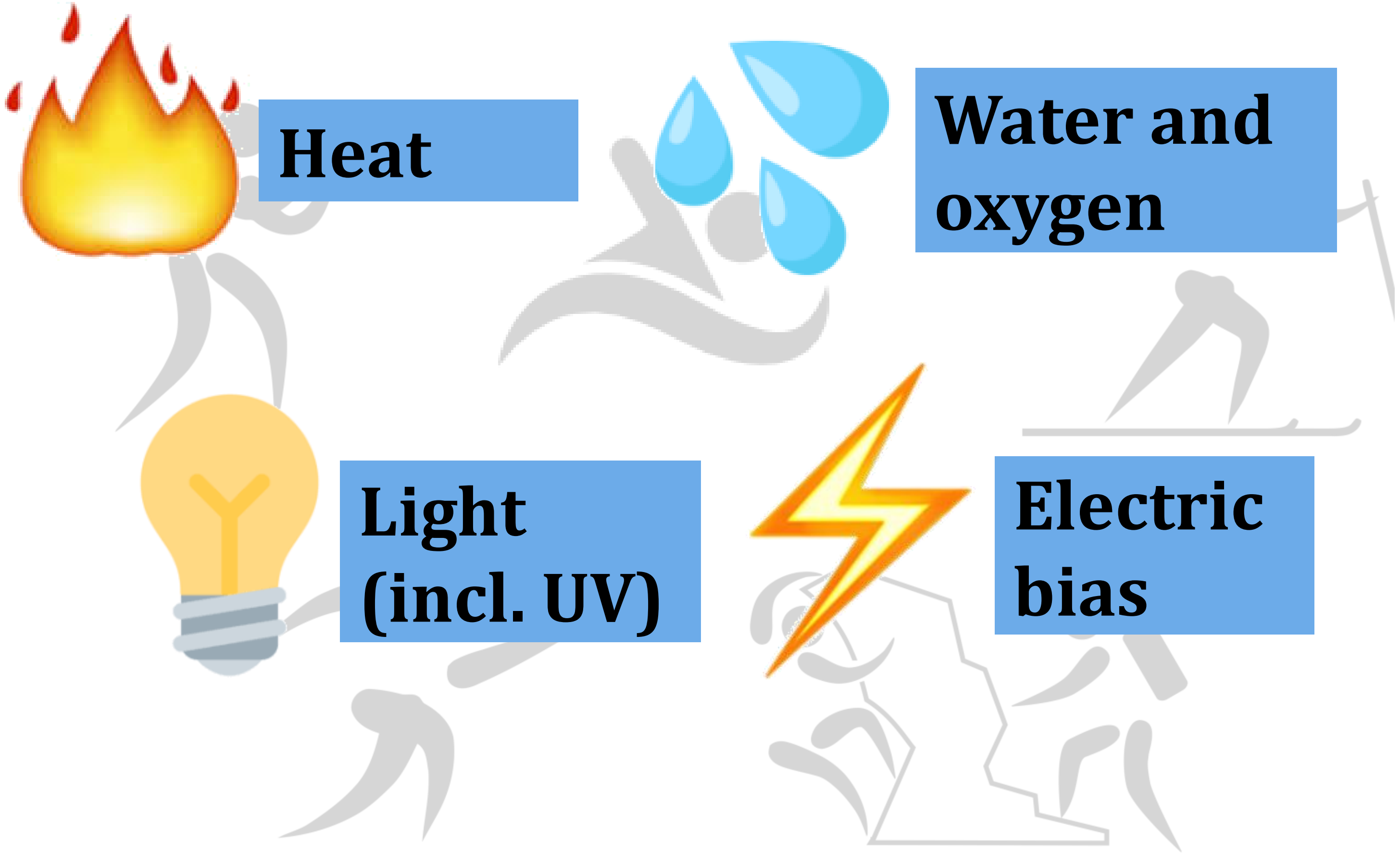
“Since reaching 20% efficiency, research in perovskite photovoltaics has shifted from *a race for efficiency* to *a race for stability*.” ©

W. Tress et al. Nature energy 4, 568 (2019)

RACE FOR EFFICIENCY



OLYMPICS ~~RACE~~ FOR STABILITY



Protocols for Organic and Hybrid PVs (since 2008)

International Summits on Organic and Perovskite Photovoltaics (ISOS)

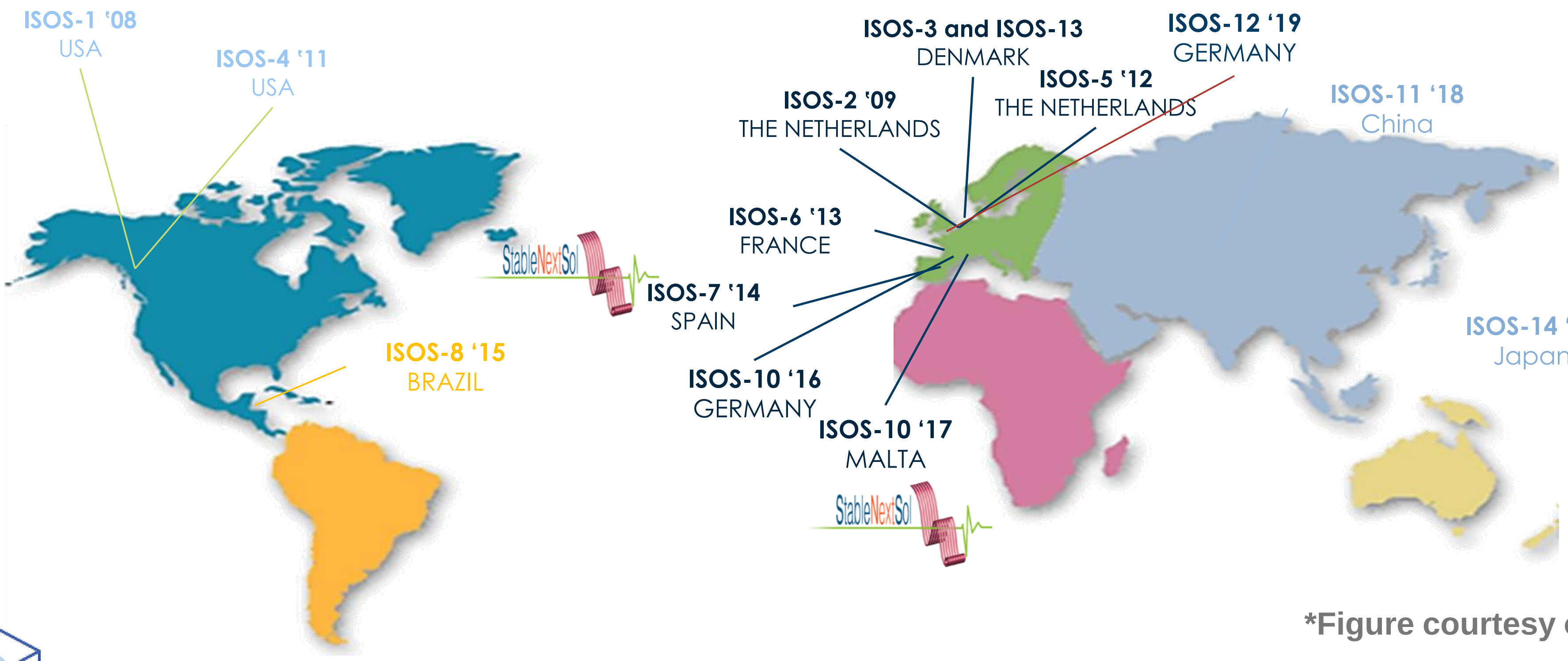


*Figure courtesy of M. Lira Cantu, ICN2

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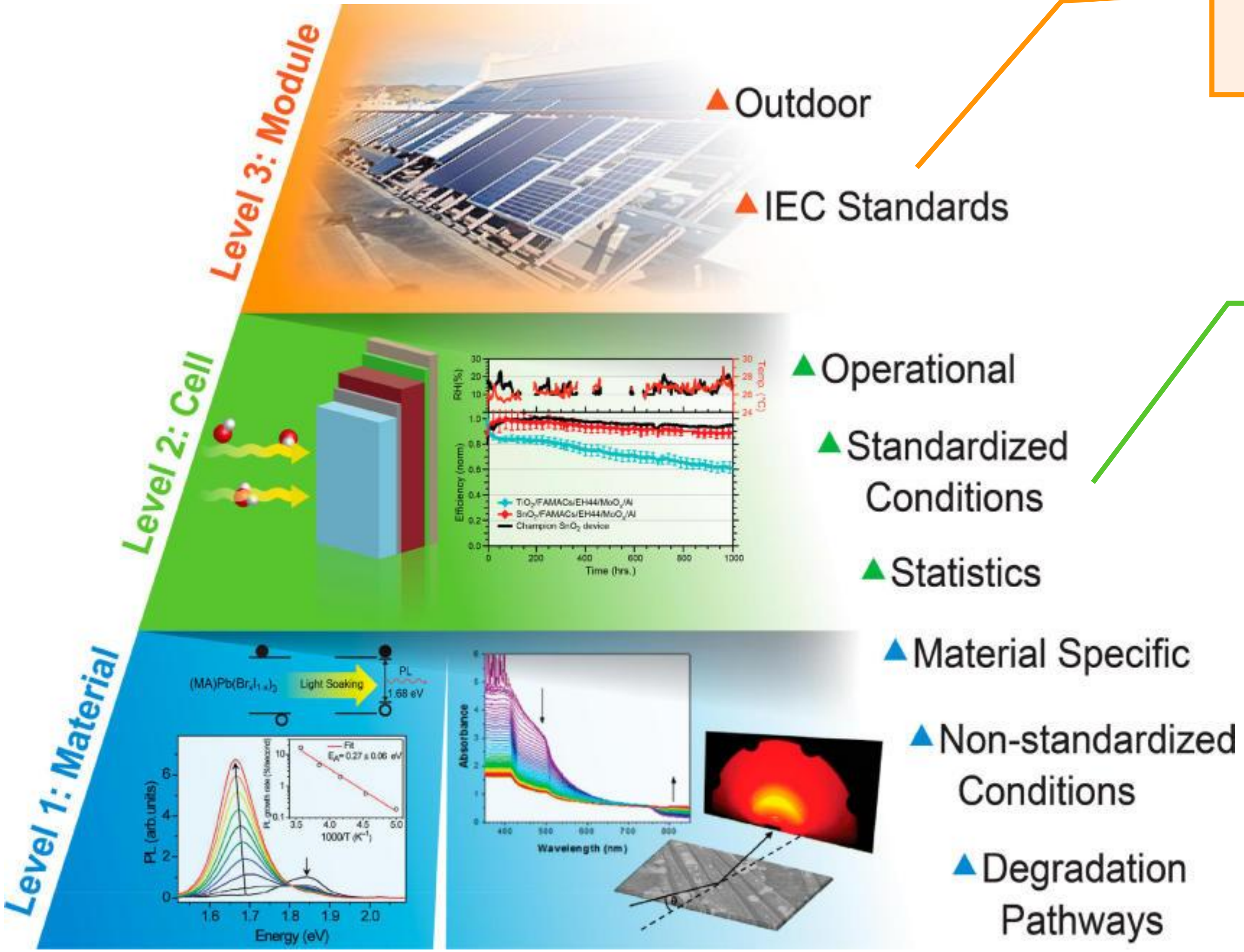
Next one is in Berlin, Germany in September 30 – October 2, 2024

IEC Qualification testing serves **for rapid detection of <u>known</u> failure or degradation modes** in the intended environment

ISOS protocols are meant to assist in unifying the procedures of PSCs stability studies, improve **comparability** between data from different laboratories and device architectures. It is intended as an intermediate stage in PSC technology maturing, aimed at the **identification of degradation pathways and** the prospects for **their mitigation**.



Christians et al. ACS Energy Lett. 2018, 3, 2136−2143

OUTLINE

1. What are ISOS protocols? What was added for Perovskite Solar Cells?

2. How does it work? Examples of researches following ISOS protocols.

3. Which activities are ongoing now in the community? And how to join it :)

M.O. Reese et al. Solar Energy Materials & Solar Cells 95 (2011) 1253–1267

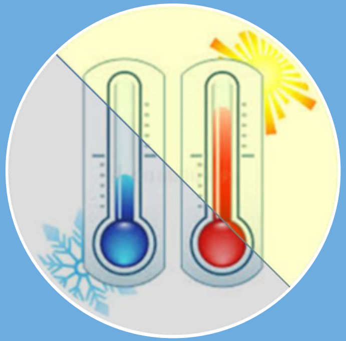
ISOS RESEARCH AGING PROTOCOLS

ISOS-D
Dark storage

ISOS-L
Light soaking

ISOS-O
Outdoor

ISOS-T
Thermal cycling



ISOS-LT
Light-humidity-thermal cycling

ORIGINAL ISOS PROTOCOLS

Test type	Dark (ISOS-D)			Outdoor (ISOS-O)		
Test ID	ISOS-D-1 Shelf	ISOS-D-2 High temp. storage	ISOS-D-3 Damp heat	ISOS-O-1 Outdoor	ISOS-O-2 Outdoor	ISOS-O-3 Outdoor
Light source	None	None	None	Sunlight	Sunlight	Sunlight
Temp.[a]	Ambient	65/85 °C	65/85 °C	Ambient	Ambient	Ambient
Relative humidity (R.H.)[a]	Ambient	Ambient (low)	85%	Ambient	Ambient	Ambient
Environment[a]	Ambient	Oven	Env. chamber	Outdoor	Outdoor	Outdoor
Characterization light source	Solar simulator or sunlight	Solar simulator	Solar simulator	Solar simulator	Sunlight	Sunlight and solar simulator
Load[b]	Open circuit	Open circuit	Open circuit	MPP or open circuit	MPP or open circuit	MPP

Test type	Light-soaking (ISOS-L)			Thermal cycling (ISOS-T)		
Test ID	ISOS-L-1 Laboratory weathering	ISOS-L-2 Laboratory weathering	ISOS-L-3 Laboratory weathering	ISOS-T-1 Thermal cycling	ISOS-T-2 Thermal cycling	ISOS- T-3 Thermal cycling
Light source	Simulator	Simulator	Simulator	None	None	None
Temp.[a]	Ambient	65/85 °C	65/85 °C	Between room temp. and 65/85 °C	Between room temp. and 65/85 °C	−40 to +85 °C
Relative humidity (R.H.)[a]	Ambient	Ambient	Near 50%	Ambient	Ambient	Near 55%
Environment/setup	Light only	Light & Temp.	Light, Temp. and R.H.	Hot plate/oven	Oven/env. chamb.	Env. chamb.
Characterization light source	Solar simulator	Solar simulator	Solar simulator	Solar simulator or sunlight	Solar simulator	Solar simulator
Load[b]	MPP or open circuit	MPP or open circuit	MPP	Open circuit	Open circuit	Open circuit

Test type	Solar-thermal-humidity cycling (ISOS-LT)		
Test ID	ISOS-LT-1 solar-thermal cycling	ISOS-LT-2 solar-thermal-humidity cycling	ISOS-LT-3 solar-thermal-humidity-freeze cycling
Light source	Simulator	Simulator	Simulator
Temp.	Linear or step ramping between room temp. and 65 °C	Linear ramping between 5 and 65 °C	Linear ramping between −25 and 65 °C
Relative humidity (R.H.)	Monitored, uncontrolled	Monitored, controlled at 50% beyond 40 °C	Monitored, controlled at 50% beyond 40 °C
Environment/setup	Weathering chamber	Env. chamb. with sun simulation	Env. chamb. with sun simulation and freezing
Characterization light source	Solar simulator	Solar simulator	Solar simulator
Load[b]	MPP or open circuit	MPP or open circuit	MPP or open circuit

M.O. Reese et al. Solar Energy Materials & Solar Cells 95 (2011) 1253–1267

ORIGINAL ISOS PROTOCOLS

Test type	Dark (ISOS-D)			Outdoor (ISOS-O)		
Test ID	ISOS-D-1 Shelf	ISOS-D-2 High temp.	ISOS-D-3 Damp	ISOS-O-1 Outdoor	ISOS-O-2 Outdoor	ISOS-O-3 Outdoor
Light source				Sunlight	Sunlight	Sunlight
Temp.[a]				Ambient	Ambient	Ambient
Relative humidity (R.H.)				Ambient	Ambient	Ambient
Environment[a]				Outdoor	Outdoor	Outdoor
Characterization light source				Solar simulator	Sunlight	Sunlight and solar simulator
Load[b]				MPP or open	MPP or open	MPP

Test type	Light-soaking (ISOS-L)			Thermal cycling (ISOS-T)		
Test ID	ISOS-L-1 Laboratory weathering	ISOS-L-2 Laboratory weathering	ISOS-L-3 Laboratory weathering	ISOS-T-1 Thermal cycling	ISOS-T-2 Thermal cycling	ISOS- T-3 Thermal cycling
Light source	Simulator	Simulator	Simulator	None	None	None
Temp.[a]	Ambient	65/85 °C	65/85 °C	Between room temp. and 65/85 °C	Between room temp. and 65/85 °C	−40 to +85 °C
Relative humidity (R.H.)[a]	Ambient	Ambient	Near 50%	Ambient	Ambient	Near 55%
Environment/setup	Light only	Light & Temp.	Light, Temp. and R.H.	Hot plate/oven	Oven/env. chamb.	Env. chamb.
Characterization light source	Solar simulator	Solar simulator	Solar simulator	Solar simulator or sunlight	Solar simulator	Solar simulator
Load[b]	MPP or open circuit	MPP or open circuit	MPP	Open circuit	Open circuit	Open circuit

Test type	Solar-thermal-humidity cycling (ISOS-LT)		
Test ID	ISOS-LT-1 solar-thermal cycling	ISOS-LT-2 solar-thermal-humidity cycling	ISOS-LT-3 solar-thermal-humidity-freeze cycling
Light source	Simulator	Simulator	Simulator
Temp.	Linear or step ramping between room temp. and 65 °C	Linear ramping between 5 and 65 °C	Linear ramping between −25 and 65 °C
Relative humidity (R.H.)	Monitored, uncontrolled	Monitored, controlled at 50% beyond 40 °C	Monitored, controlled at 50% beyond 40 °C
Environment/setup	Weathering chamber	Env. chamb. with sun simulation	Env. chamb. with sun simulation and freezing
Characterization light source	Solar simulator	Solar simulator	Solar simulator
Load[b]	MPP or open circuit	MPP or open circuit	MPP or open circuit

M.O. Reese et al. Solar Energy Materials & Solar Cells 95 (2011) 1253–1267

ORIGINAL ISOS PROTOCOLS

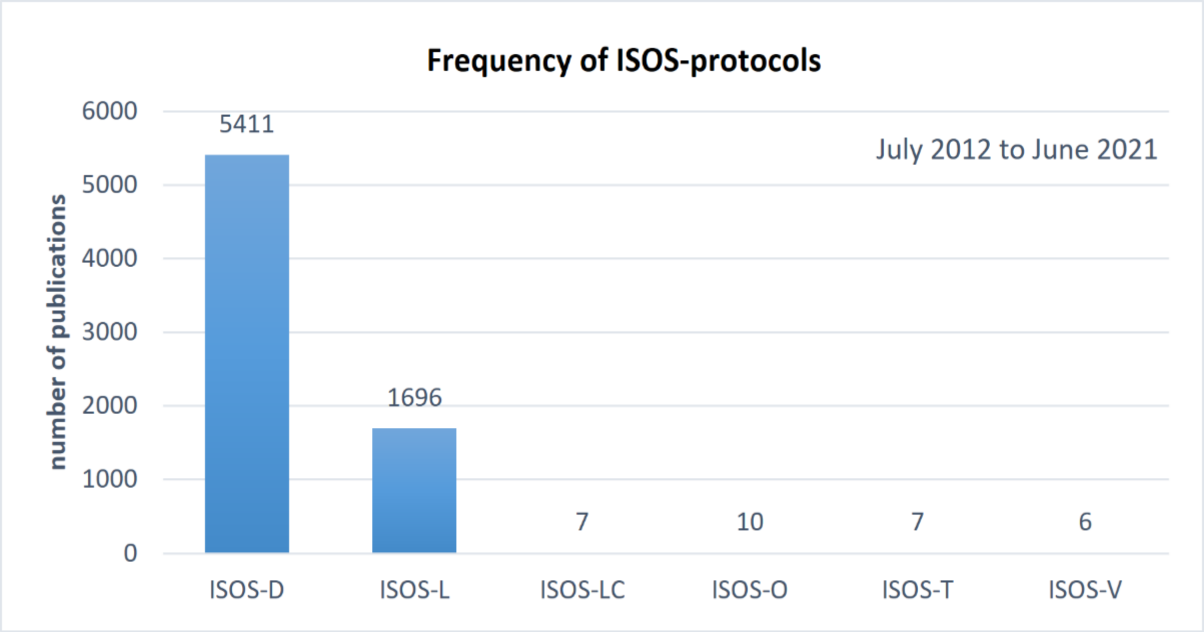
Test type	Dark (ISOS-D)			Outdoor (ISOS-O)		
Test ID	ISOS-D-1 Shelf	ISOS-D-2 High temp.	ISOS-D-3 Damp	ISOS-O-1 Outdoor	ISOS-O-2 Outdoor	ISOS-O-3 Outdoor
Light source				Sunlight	Sunlight	Sunlight
Temp.[a]				Ambient	Ambient	Ambient
Relative humidity (R.H.)				Ambient	Ambient	Ambient
Environment[a]				Outdoor	Outdoor	Outdoor
Characterization light source				Solar simulator	Sunlight	Sunlight and solar simulator
Load[b]				MPP or open	MPP or open	MPP

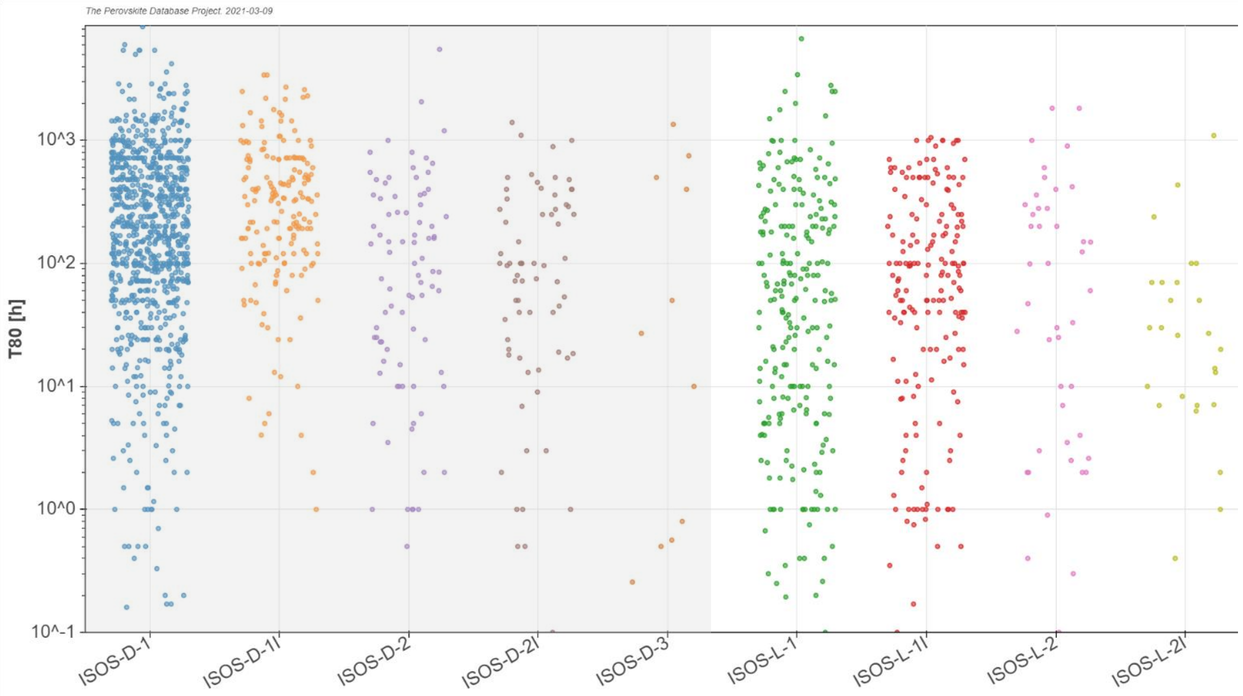
Test type	Light-soaking (ISOS-L)			Thermal cycling (ISOS-T)		
Test ID	ISOS-L-1 Laboratory	ISOS-L-2 Laboratory	ISOS-L-3 Laboratory	ISOS-T-1 Thermal cycling	ISOS-T-2 Thermal cycling	ISOS- T-3 Thermal cycling
Light source				None	None	None
Temp.[a]				Between room temp. and 65/85 °C	Between room temp. and 65/85 °C	−40 to +85 °C
Relative humidity (R.H.)[a]				Ambient	Ambient	Near 55%
Environment/setup				Hot plate/oven	Oven/env. chamb.	Env. chamb.
Characterization light source				Solar simulator or sunlight	Solar simulator	Solar simulator
Load[b]				Open circuit	Open circuit	Open circuit

Test type	Solar-thermal-humidity cycling (ISOS-LT)		
Test ID	ISOS-LT-1 solar-thermal cycling	ISOS-LT-2 solar-thermal-humidity cycling	ISOS-LT-3 solar-thermal-humidity-freeze cycling
Light source	Simulator	Simulator	Simulator
Temp.	Linear or step ramping between room temp. and 65 °C	Linear ramping between 5 and 65 °C	Linear ramping between −25 and 65 °C
Relative humidity (R.H.)	Monitored, uncontrolled	Monitored, controlled at 50% beyond 40 °C	Monitored, controlled at 50% beyond 40 °C
Environment/setup	Weathering chamber	Env. chamb. with sun simulation	Env. chamb. with sun simulation and freezing
Characterization light source	Solar simulator	Solar simulator	Solar simulator
Load[b]	MPP or open circuit	MPP or open circuit	MPP or open circuit

M.O. Reese et al. Solar Energy Materials & Solar Cells 95 (2011) 1253–1267

WHAT WAS AVAILABLE AT THE TIME OF PROTOCOLS INTRODUCTION?

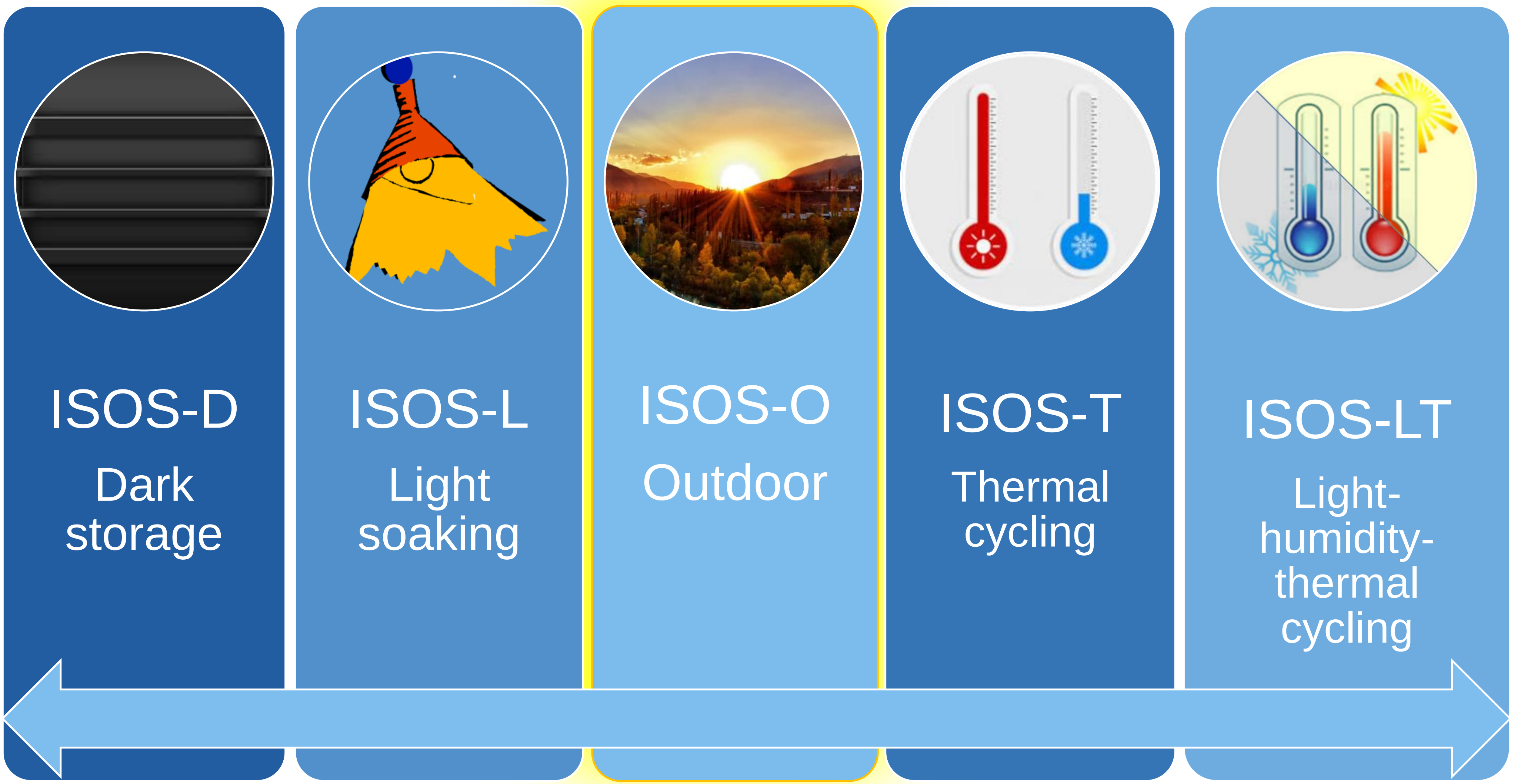




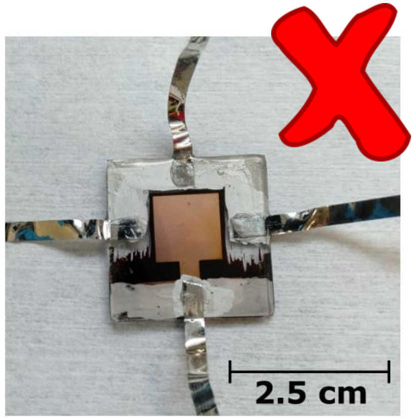
Data from “**The Perovskite Database Project**”, **Jesper Jacobsson et al., Nature Energy 7, 107 (2022)**

SPECIAL ROLE OF OUTDOOR TESTING

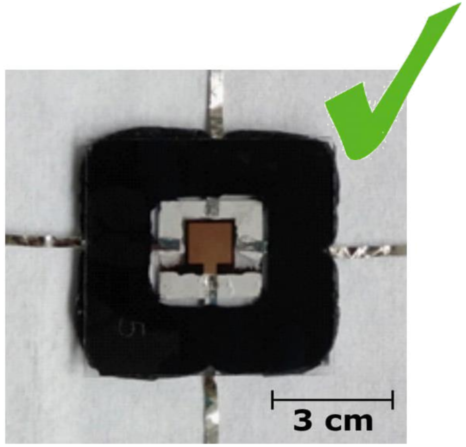
Reese et al. Solar Energy Materials and Solar Cells 2011, 95, 5,1253-1267



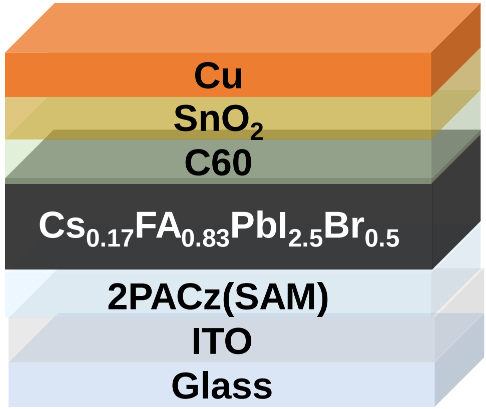
ISOS D-3: DAMP HEAT TEST



“Glued”



“Laminated”

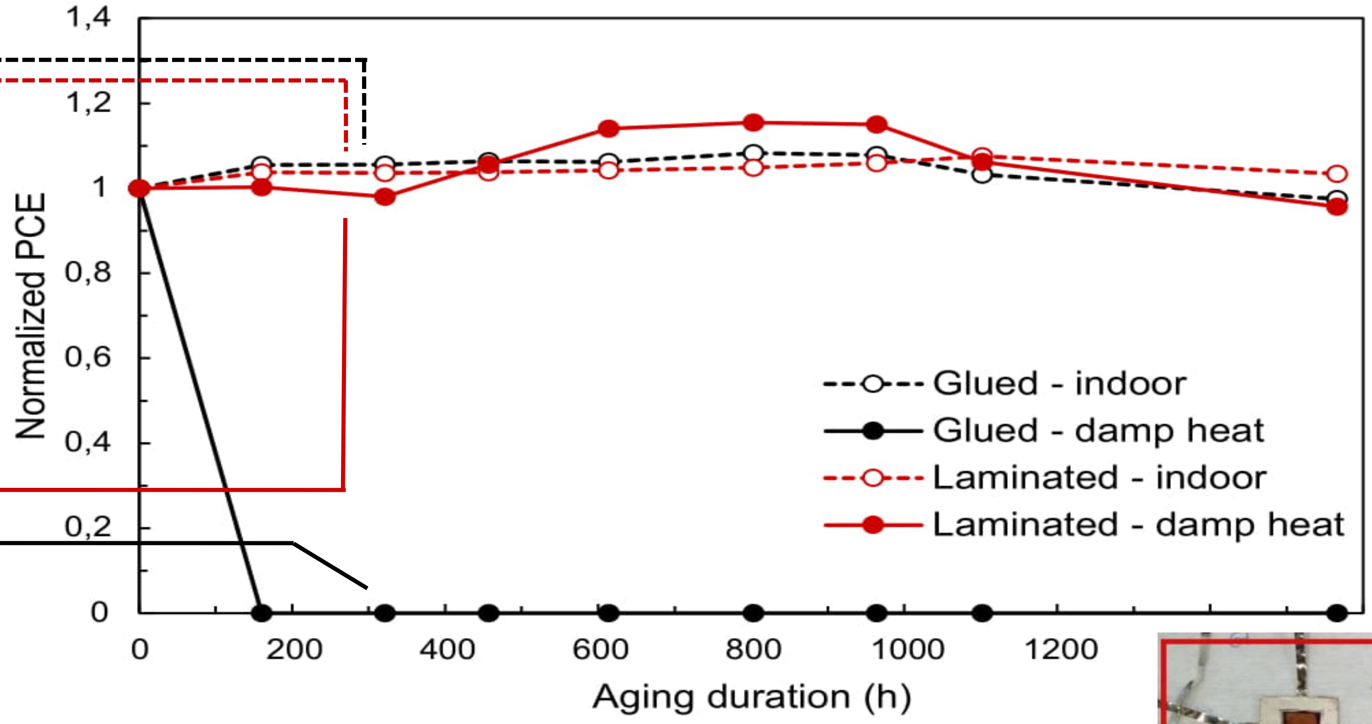


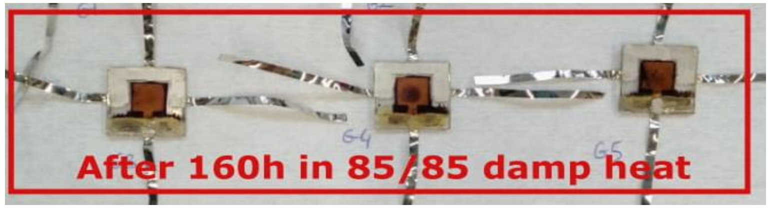
ISOS-D-1

on shelf

ISOS-D-3

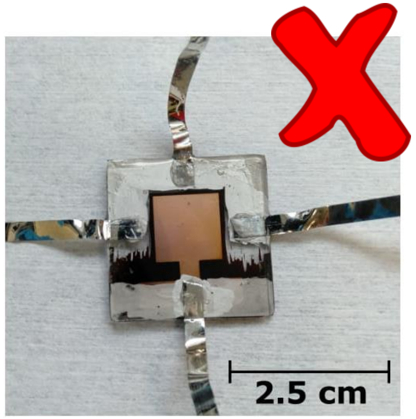
Damp-heat



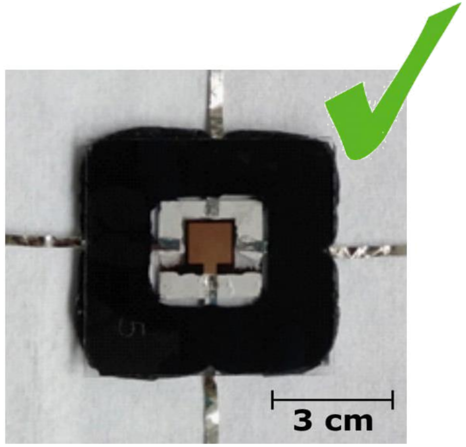


Q. Emery et al., ACS Appl. Mater. Interfaces 2022, 14, 4

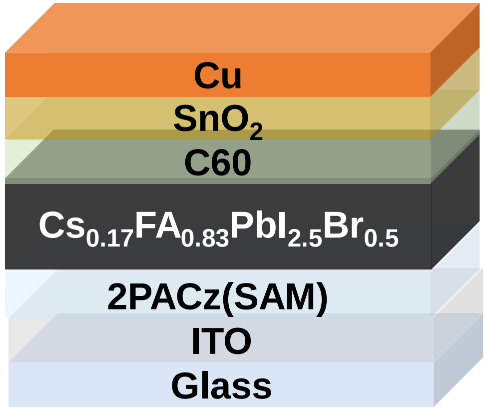
ISOS D-3: DAMP HEAT TEST



"Glued"

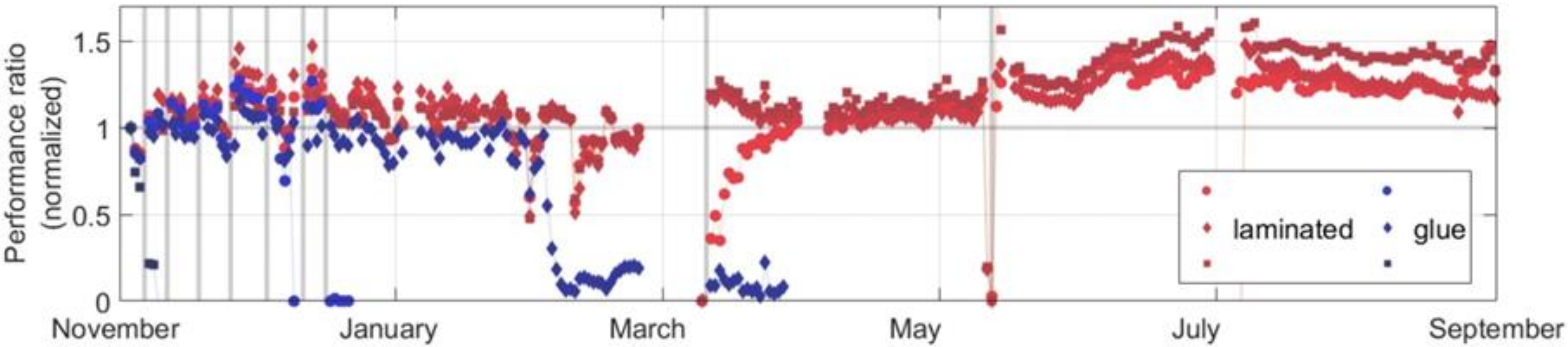


"Laminated"



ISOS-O

Outdoor



Q. Emery et al., ACS Appl. Mater. Interfaces 2022, 14, 4

CONSENSUS FOR PEROVSKITE SOLAR CELLS STABILITY

Khenkin et al. Nature Energy, 2020, 5, 35-49

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*]

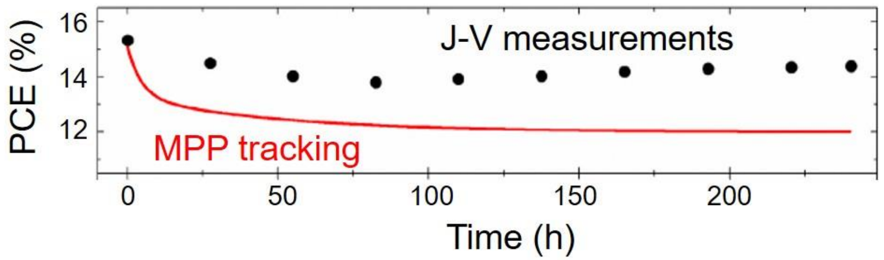
Update the procedures
in accord with the labs development over a decade after the original consensus

Introduce new protocols
specific to perovskite solar cells

Attract attention to the topic
and get a very broad perovskite research community on board with a unified research guidelines

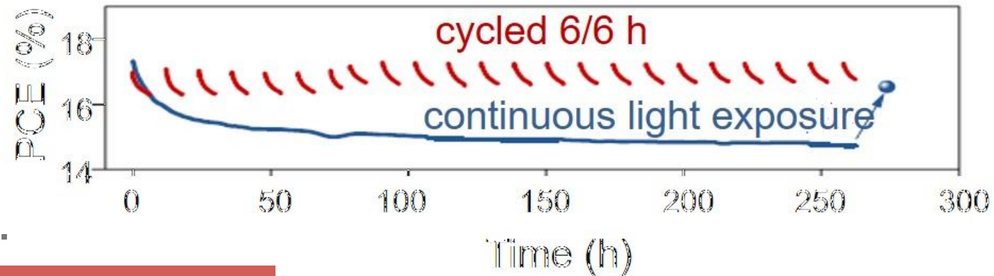
WHAT IS NEW?

Slow transient processes affecting measurements



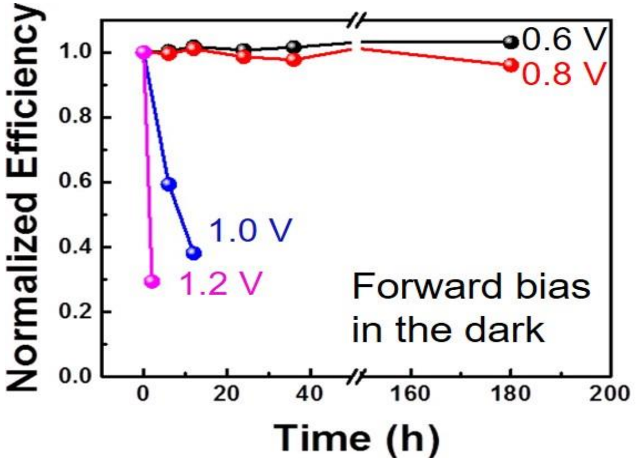
Saliba M. et al. Solar Cells. Joule 2, 1019–1024 (2018).

Strong recovery processes



Domanski K., et al. Nature Energy 3, 61 (2018).

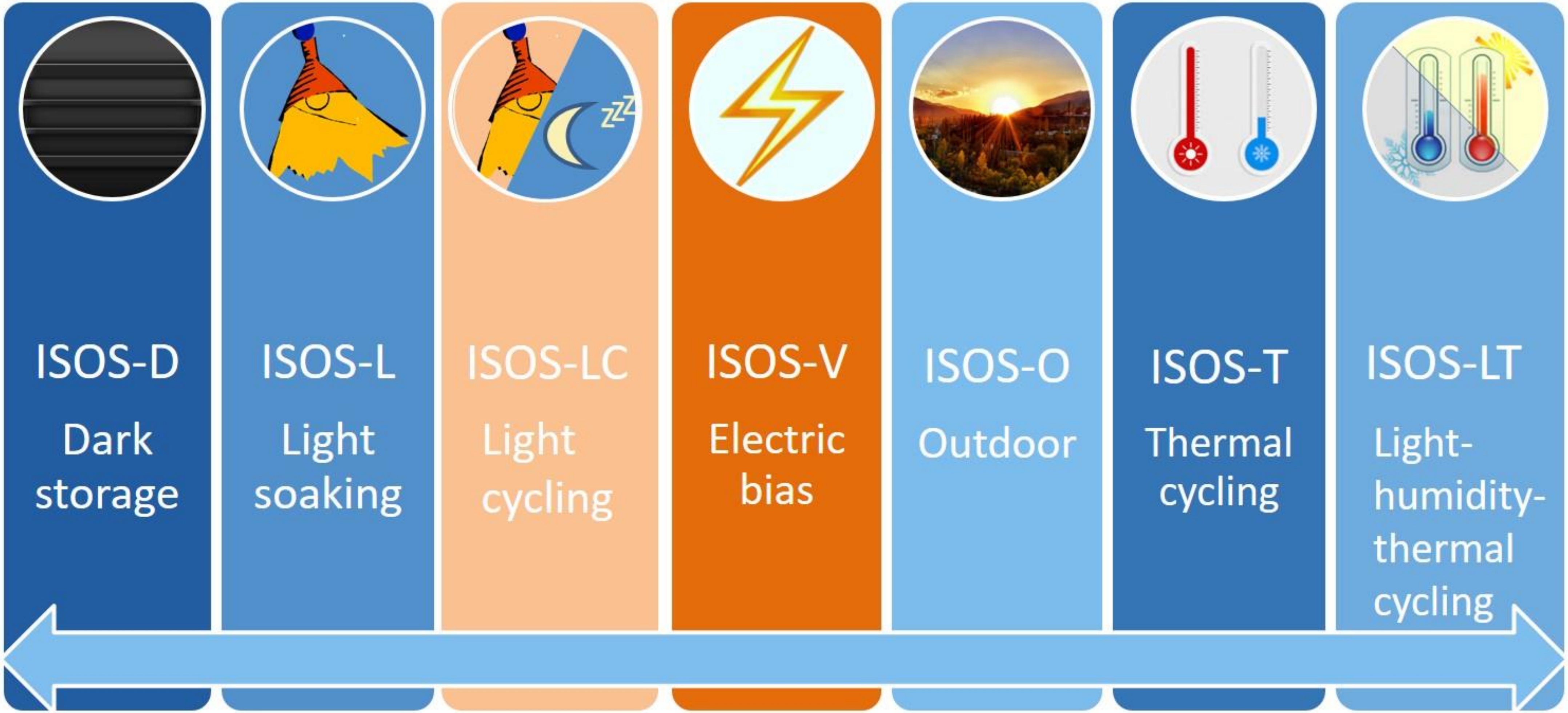
Sensitivity towards applied electric bias



Bae S. et al. J. Phys. Chem. Lett. 7, 3091–3096 (2016).

EXTENDED ISOS PROTOCOLS

Khenkin et al. Nature Energy, 2020, 5, 35-49



EXTENDED ISOS PROTOCOLS

	Dark storage (ISOS-D)			Light-soaking (ISOS-L)		
Test ID	D-1	D-2	D-3	L-1	L-2	L-3
Light source	None	None	None	Solar simulator	Solar simulator	Solar simulator
Temp.	Ambient (23±4 °C)	65/85 °C	65/85 °C	Ambient (23±4 °C)	65/85 °C	65/85 °C
Rel. humidity	Ambient	Ambient	85%	Ambient	Ambient	~ 50%
Environment /setup	Ambient air	Oven, ambient air	Env. chamber	Light only	Light & temp.	Light, temp. & R.H.
Charact. light source	Solar sim. or sunlight	Solar simulator	Solar simulator	Solar simulator	Solar simulator	Solar simulator
Load	OC	OC	OC	MPP or OC	MPP or OC	MPP

	Bias stability (ISOS-V)			Outdoor stability (ISOS-O)		
Test ID	**V-1**	**V-2**	**V-3**	O-1	O-2	O-3
Light source	**None**	**None**	**None**	Sunlight	Sunlight	Sunlight
Temp.	**Ambient (23±4 °C)**	**65/85 °C**	**65/85 °C**	Ambient	Ambient	Ambient
Rel. humidity	**Ambient**	**Ambient**	**85%**	Ambient	Ambient	Ambient
Environment /setup	**Ambient air**	**Oven, ambient air**	**Env. chamber**	Outdoor	Outdoor	Outdoor
Charact. light source	**Solar simulator**	**Solar simulator**	**Solar simulator**	Solar simulator	Sunlight	Sunlight and Solar simulator
Load/ voltage bias	**Positive: V_{MPP}; V_{OC}; E_g/q; J_{SC} Negative: $-V_{OC}$, J_{MPP} a)**	**Positive: V_{MPP}; V_{OC}; E_g/q; J_{SC} Negative: $-V_{OC}$, J_{MPP} a)**	**Positive: V_{MPP}; V_{OC}; E_g/q; J_{SC} Negative: $-V_{OC}$, J_{MPP} a)**	MPP or OC	MPP or OC	MPP

Bias (positive or negative) in the dark

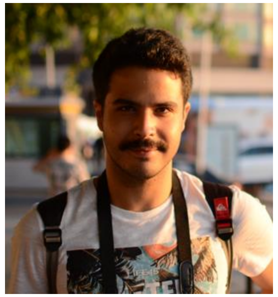
Light/dark cycling

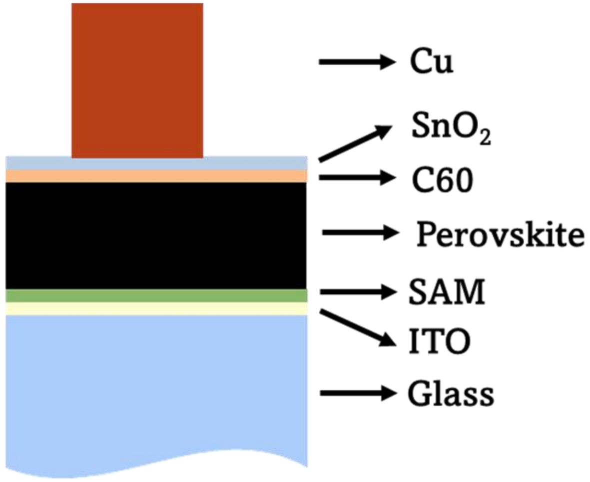
Thermal cycling (ISOS-T)			Light cycling (ISOS-LC)		
T-1	T-2	T-3	**LC-1**	**LC-2**	**LC-3**
None	None	None	**Solar Simulator/dark Cycle period: 2, 8 or 24 h Duty cycle (light:dark): 1:1 or 1:2**		
r.t. to 65/85 °C	r.t. to 65/85 °C	-40 to +85 °C	**Ambient (23±4 °C)**	**65/85 °C**	**65/85 °C**
Ambient	Ambient	<55% b)	**Ambient**	**Ambient**	**<50%**
Hot plate/ oven	Oven/env. chamber	Env. chamber	**Light only**	**Light & temp.**	**Light, temp. & R.H.**
Solar simulator	Solar simulator	Solar simulator	**Solar simulator**	**Solar simulator**	**Solar simulator**
OC	OC	OC	**MPP or OC**	**MPP or OC**	**MPP**

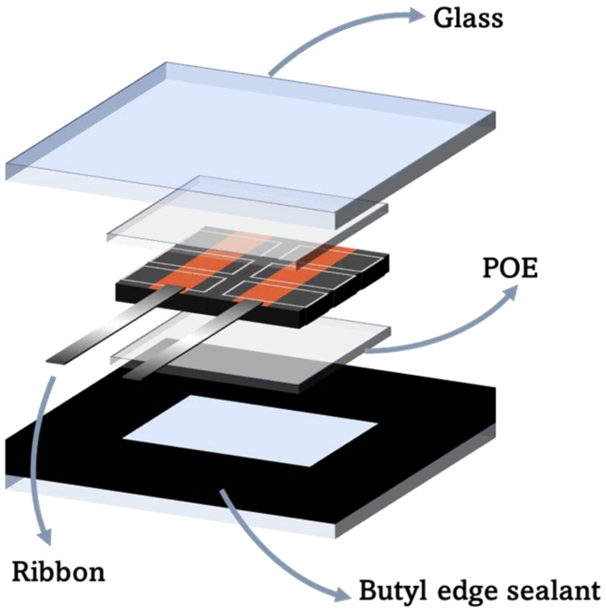
Light-humidity-thermal cycling (ISOS-LT)		
LT-1 Solar-thermal cycling	LT-2 Solar-thermal-humidity cycling	LT-3 Solar-thermal-humidity-freeze cycling
Solar simulator	Solar simulator	Solar simulator
Linear or step ramping between room temp. and 65 °C	Linear ramping between 5 °C and 65 °C	Linear ramping between -25 °C and 65 °C
Monitored, uncontrolled	Monitored, controlled at 50% beyond 40 °C	Monitored, controlled at 50% beyond 40 °C
Weathering chamber	Env. chamber with sun simulation	Env. chamber with sun simulation and freezing
Solar simulator	Solar simulator	Solar simulator
MPP or OC	MPP or OC	MPP or OC

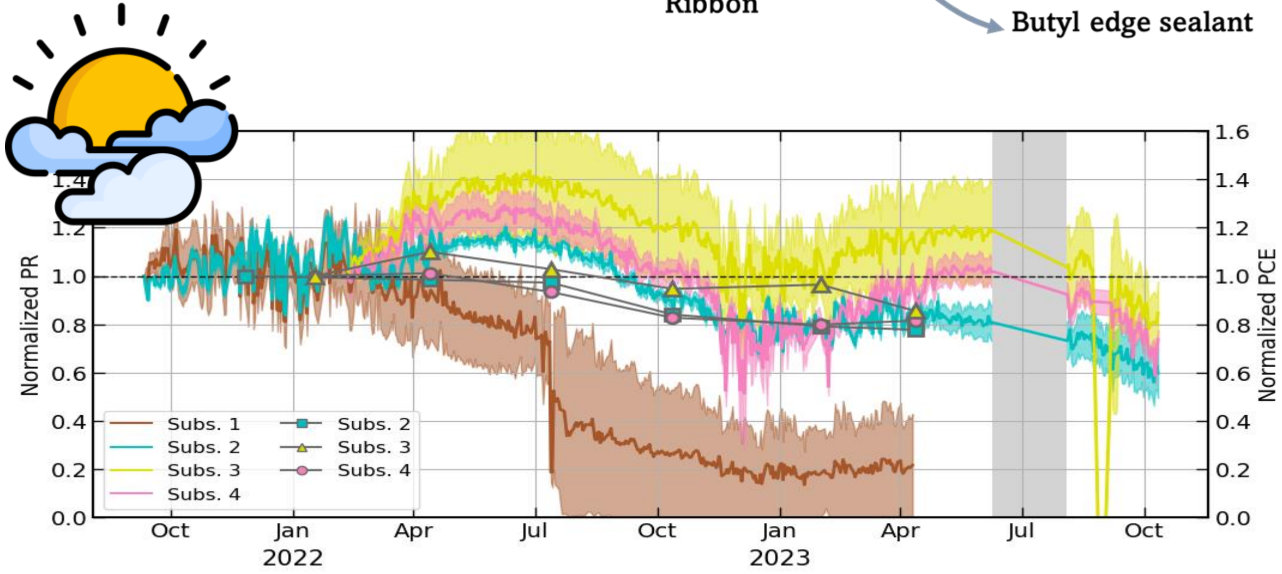
One device – all the stress tests

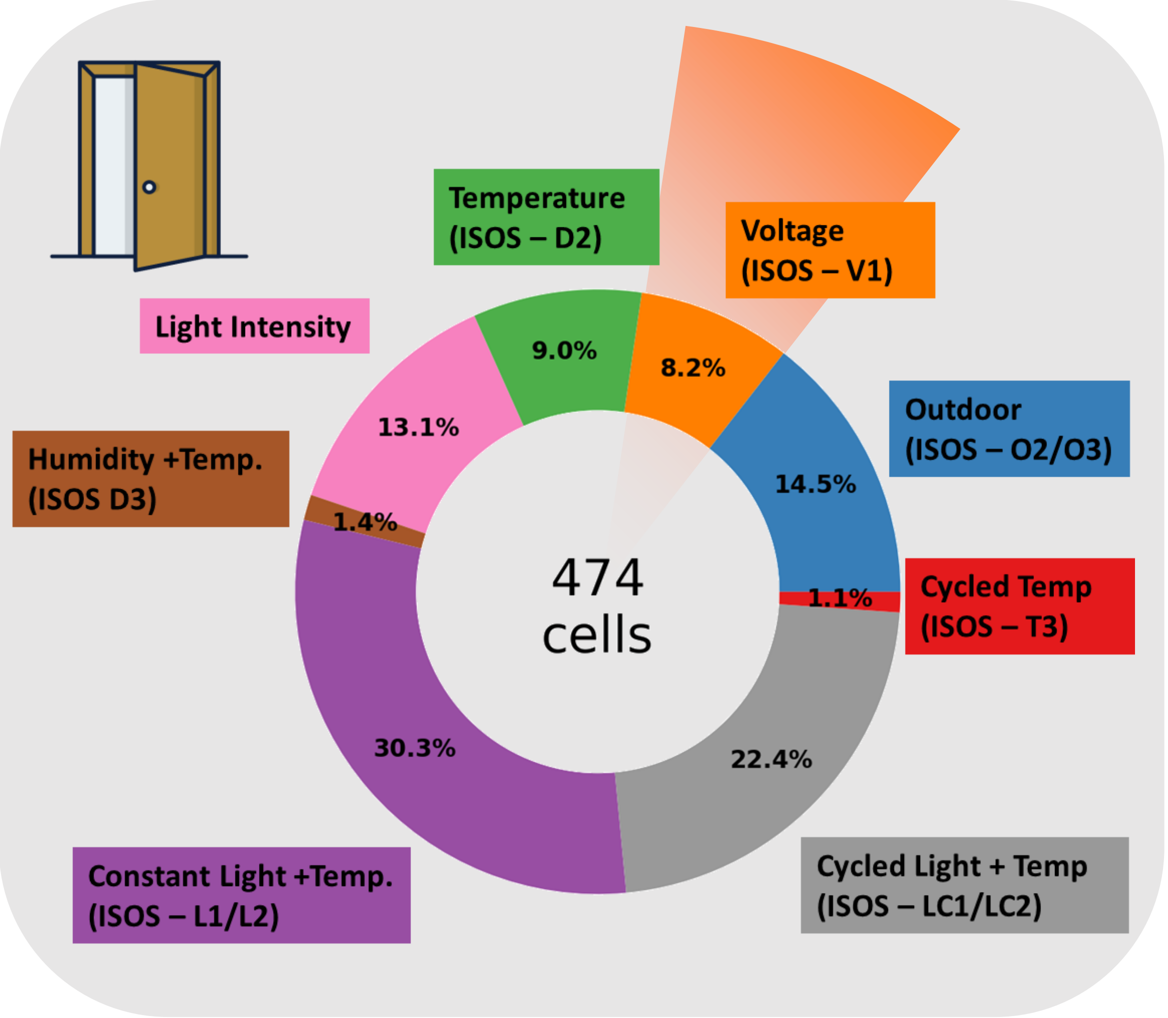
Ulas Erdil,
PhD student, HZB





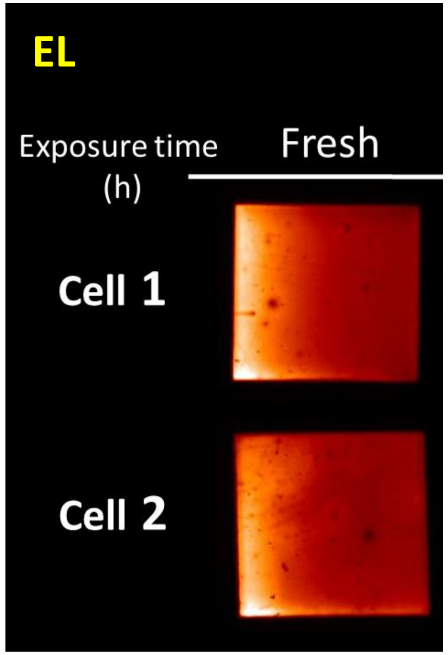


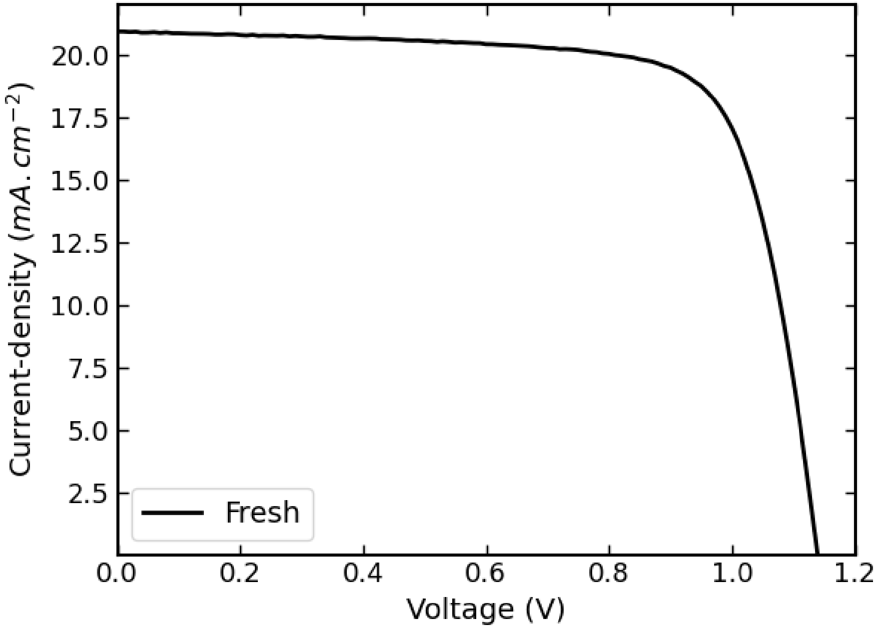




ISOS-V test

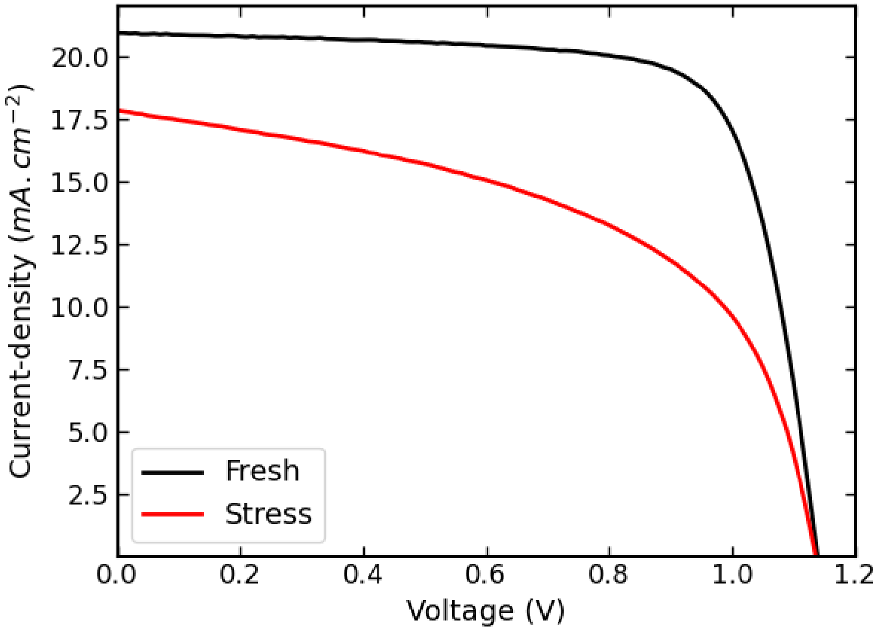

ISOS-V
Electric
bias

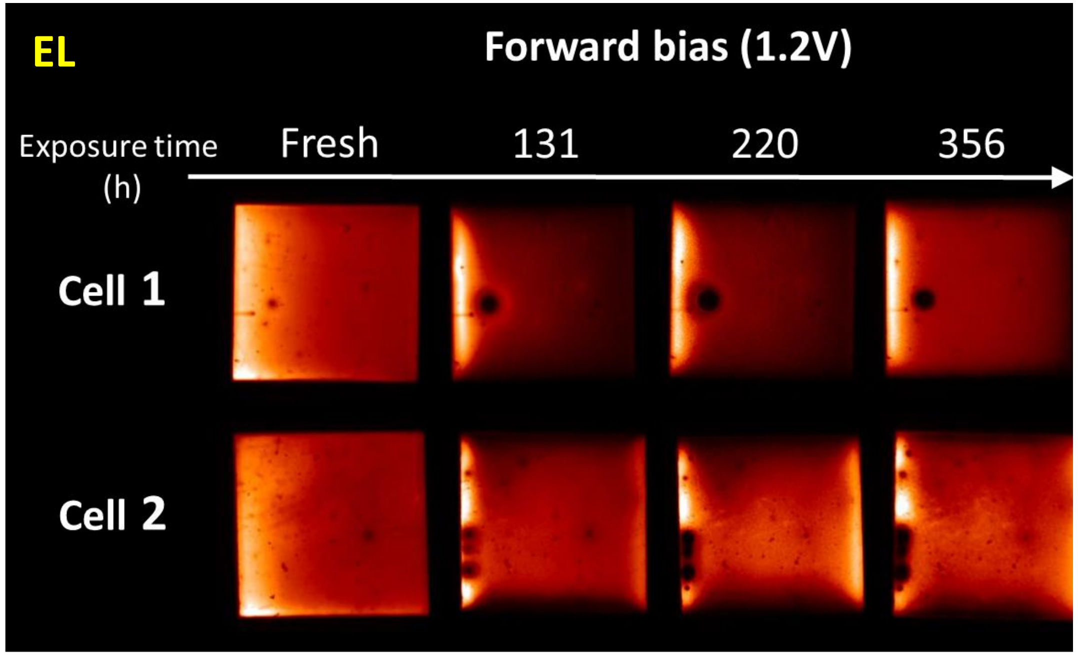

EL
Exposure time
(h)
Fresh
Cell 1
Cell 2


Current-density ($mA.cm^{-2}$)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Voltage (V)
Fresh

ISOS-V test

Forward bias: **formation of macroscopic defects, decrease in R_{SH} and J_{SC}**

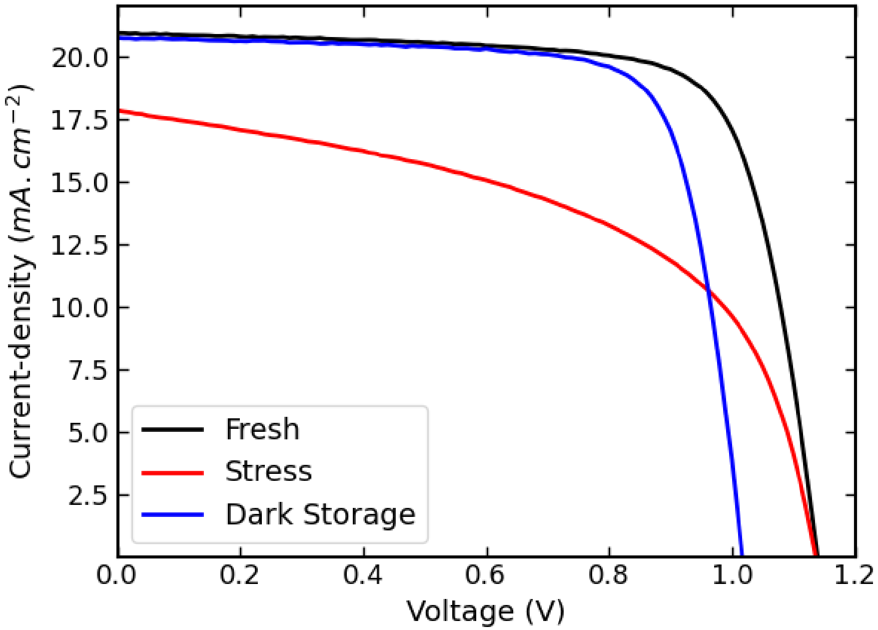


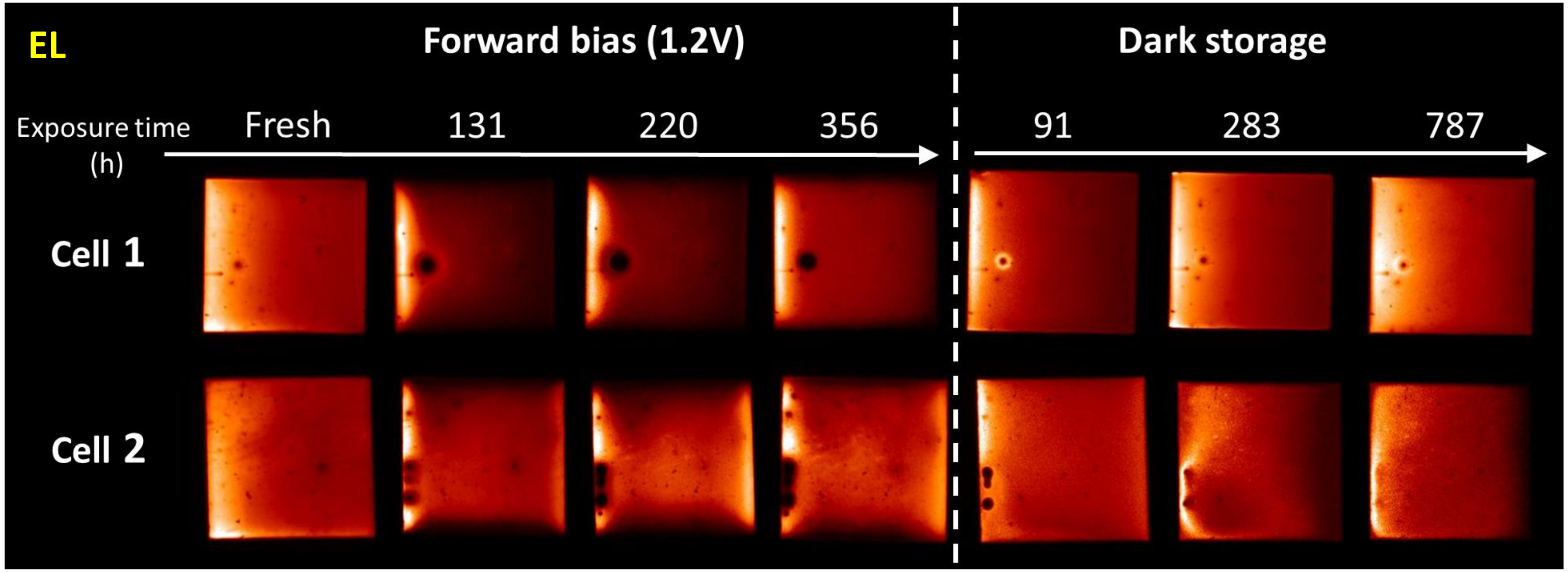


ISOS-V Macroscopic defect formation

Forward bias: formation of macroscopic defects, decrease in R_{SH} and J_{SC}

Recovery: disappearing of macroscopic defects, recovery of R_{SH} and J_{SC} decrease in V_{OC}

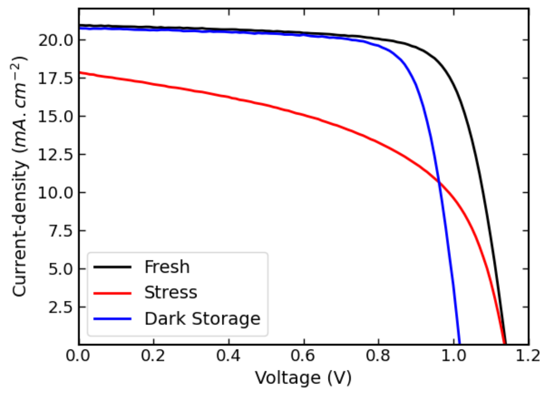




Voltage - Ion-migration induced degradation

Indoor

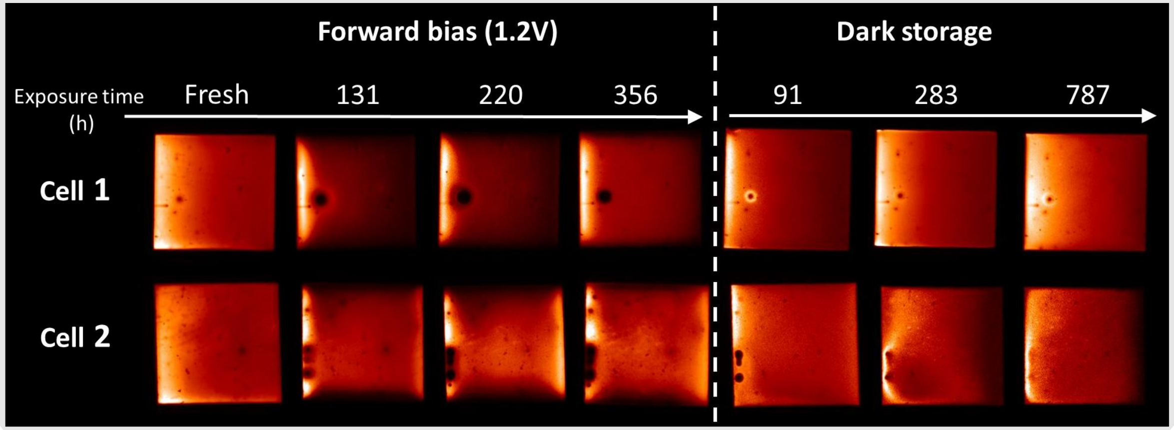
(ISOS-V1 but dark storage included)



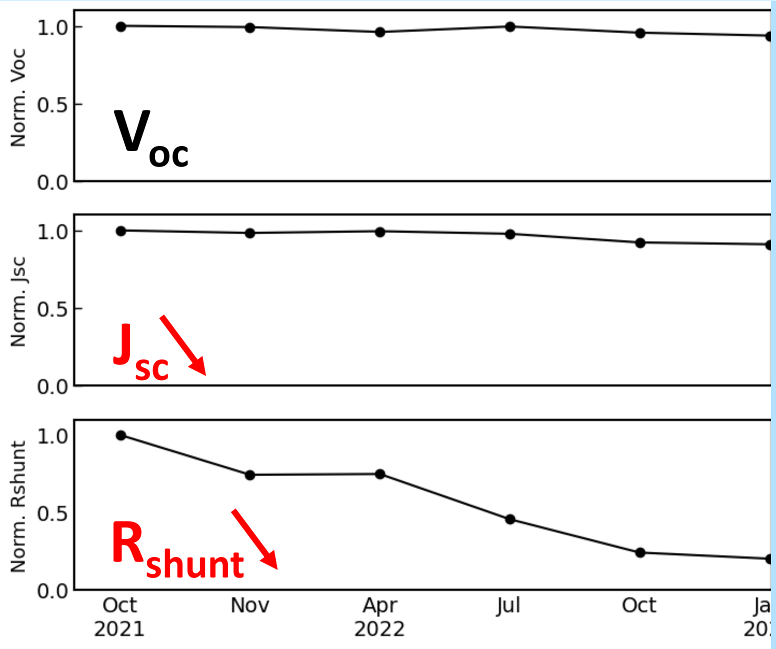
Losing R_{SH} and J_{SC}

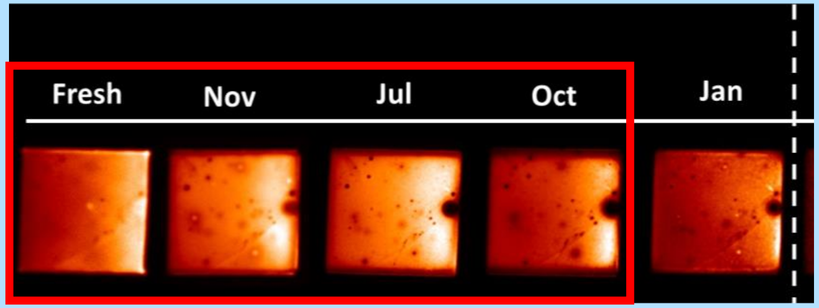
Recovering R_{SH} and J_{SC}

Losing V_{OC}



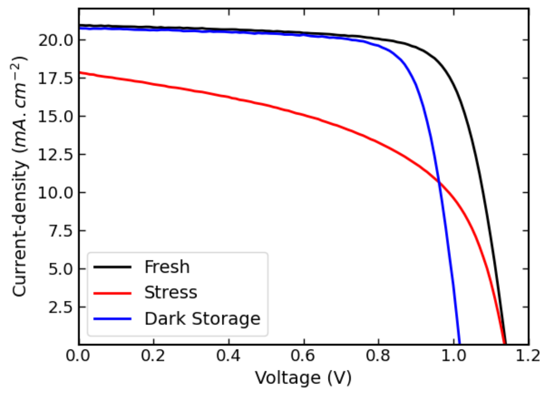
Outdoor





Voltage - Ion-migration induced degradation

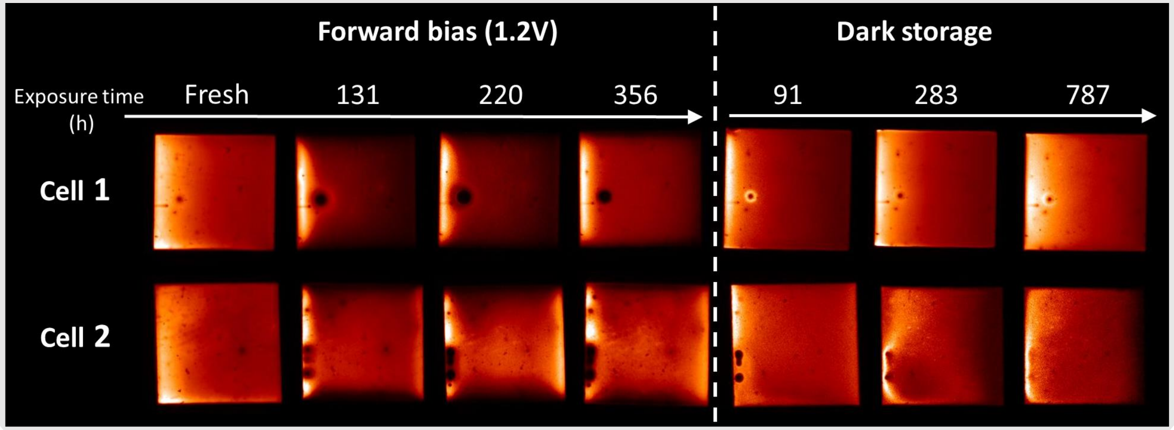
Indoor
(ISOS-V1 but dark storage included)



Losing R_{SH} and J_{SC}

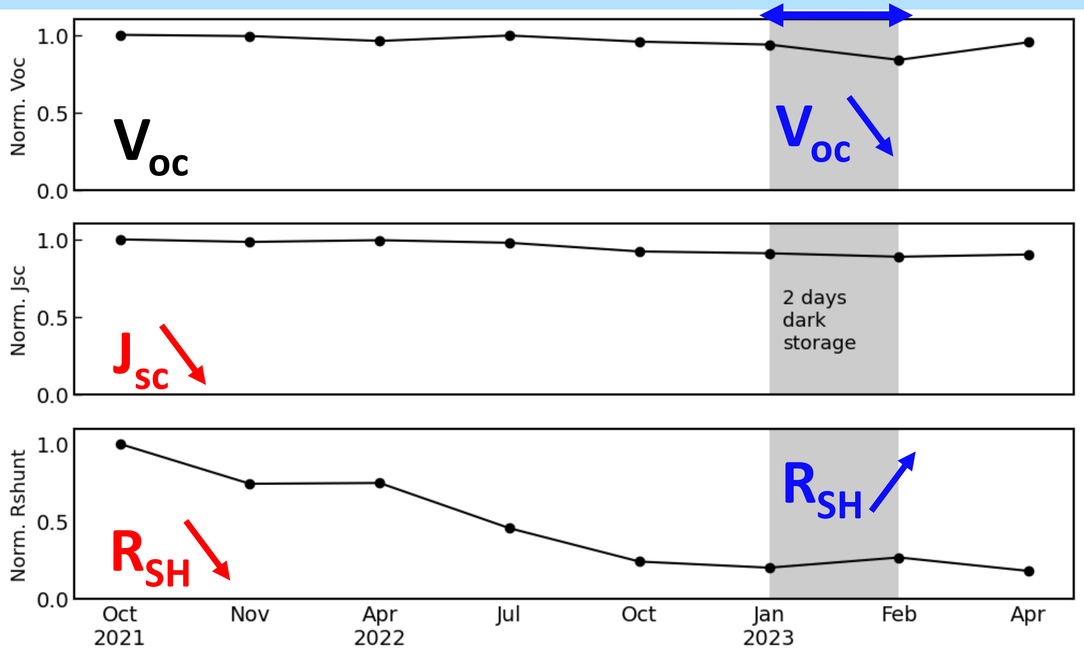
Recovering R_{SH} and J_{SC}

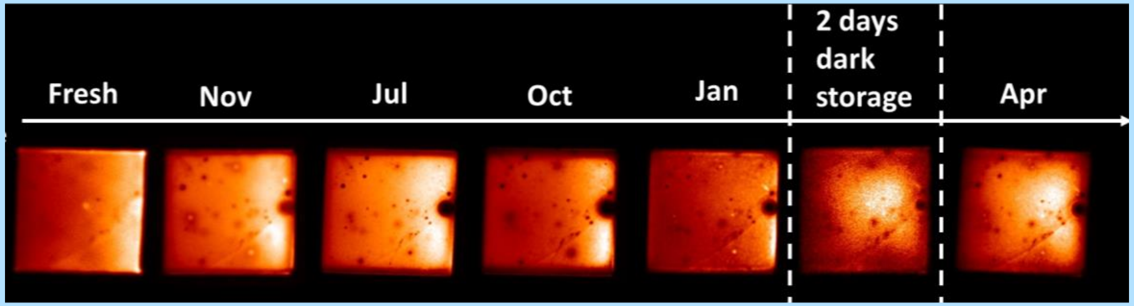
Losing V_{OC}



Outdoor

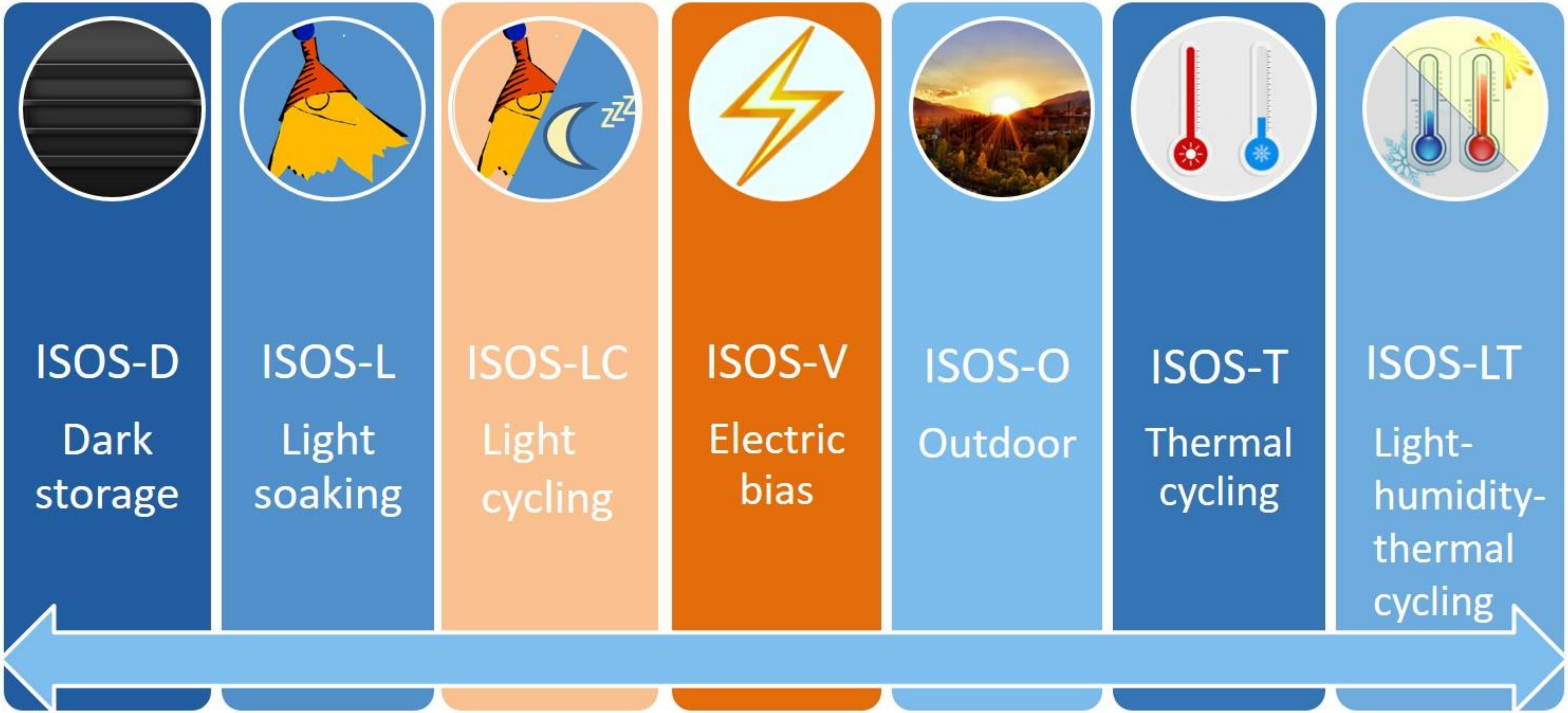
+2 days in the dark





Khenkin et al. Nature Energy, 2020, 5, 35-49

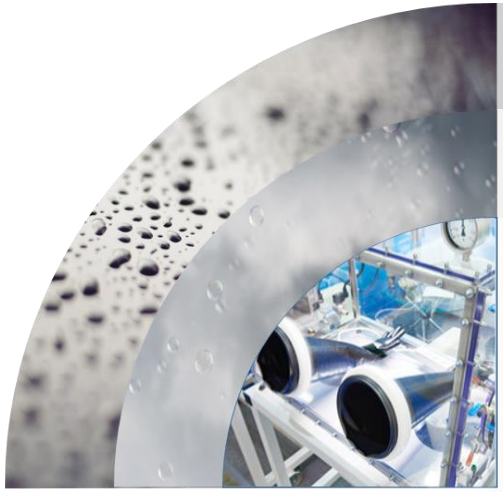
EXTENDED ISOS PROTOCOLS



INTRINSIC STABILITY (ISOS-I) PROTOCOLS

Khenkin et al. Nature Energy, 2020, 5, 35-49

Test ID	Key features
ISOS-D-1I	Inert atmosphere, room temperature, dark
ISOS-D-2I	Inert atmosphere, elevated temperature, dark
ISOS-L-1I	Inert atmosphere, room temperature, light
ISOS-L-2I	Inert atmosphere, elevated temperature, light
ISOS-V-1I	Inert atmosphere, room temperature, dark, electrical bias
ISOS-V-2I	Inert atmosphere, elevated temperature, dark, electrical bias
ISOS-LC-1I	Inert atmosphere, room temperature, cycled light
ISOS-LC-2-3I	Inert atmosphere, elevated temperature, cycled light
ISOS-T-1-3I	Inert atmosphere, cycled temperature, dark



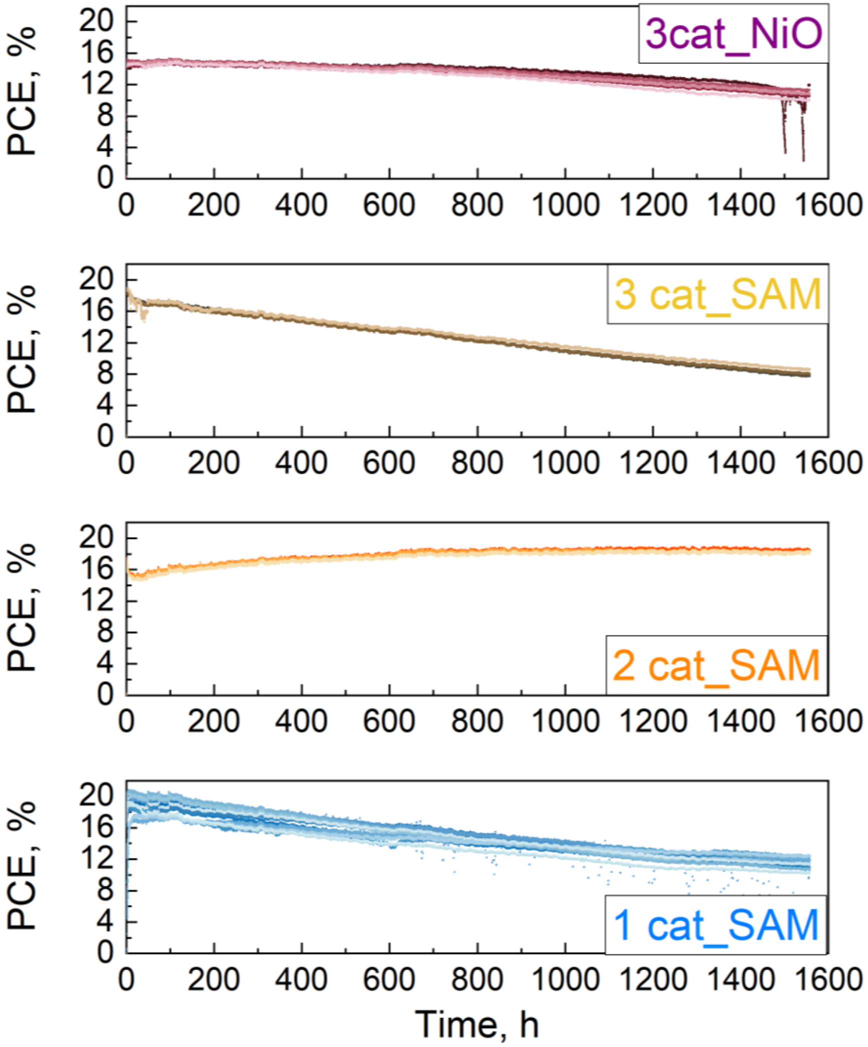
Humid atmosphere **ISOS-3**

Ambient atmosphere **ISOS-1 and 2**

Inert atmosphere **ISOS-I**

PERO AGING BEHAVIOURS UNDER ILLUMINATION

Indoor constant light



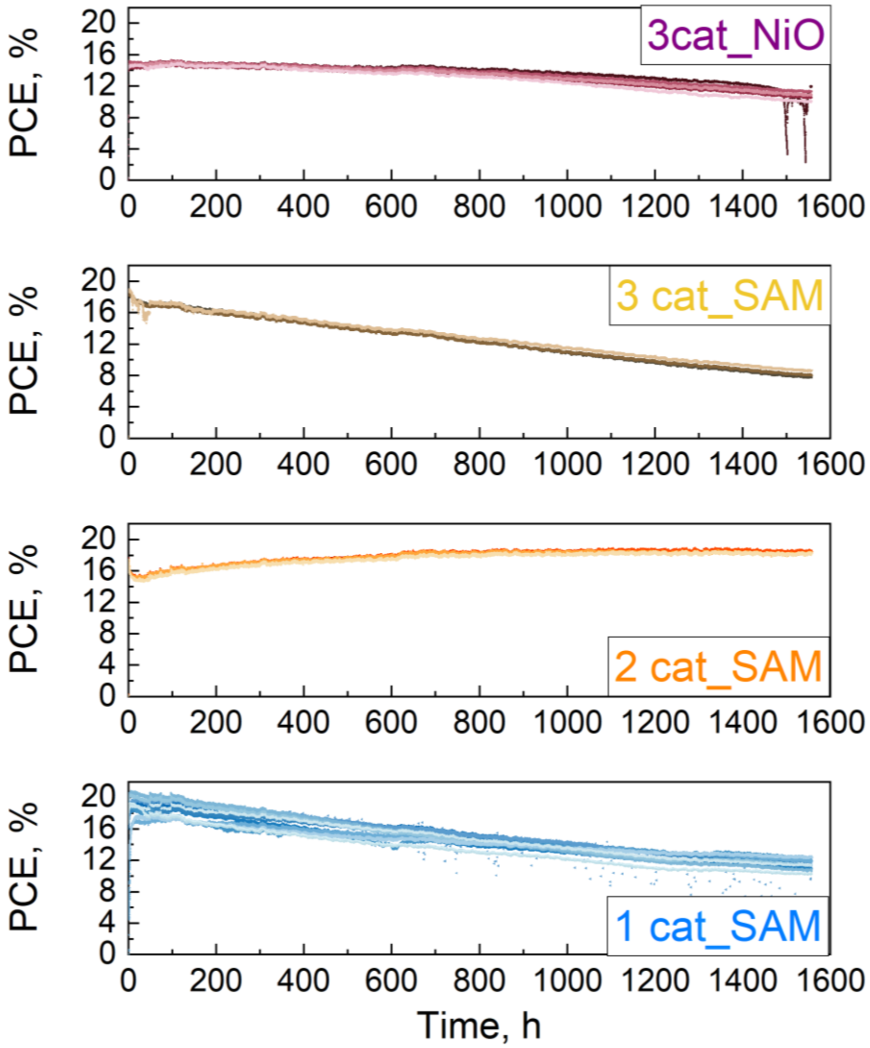
PERO AGING BEHAVIOURS UNDER ILLUMINATION

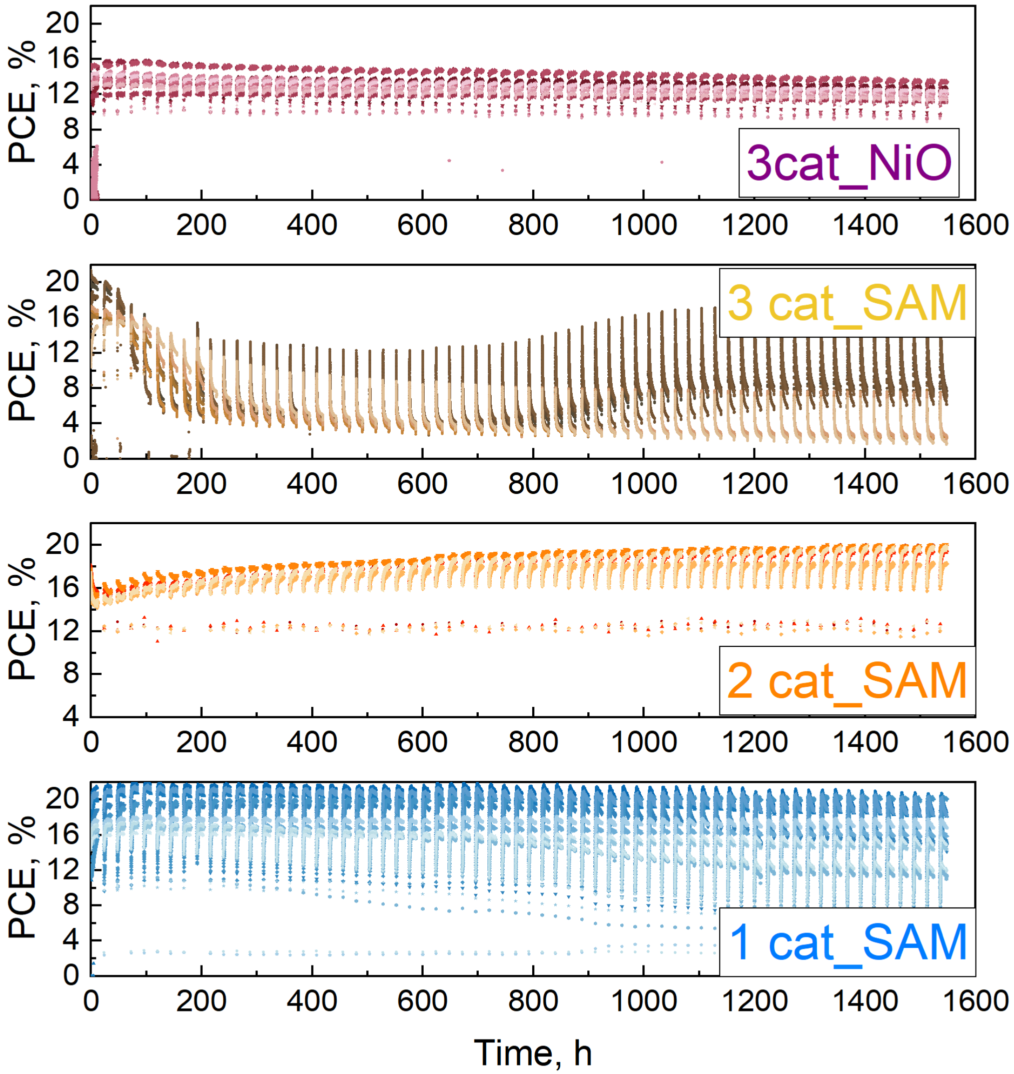
Indoor constant light

Indoor cycled light

ISOS-L

Light soaking

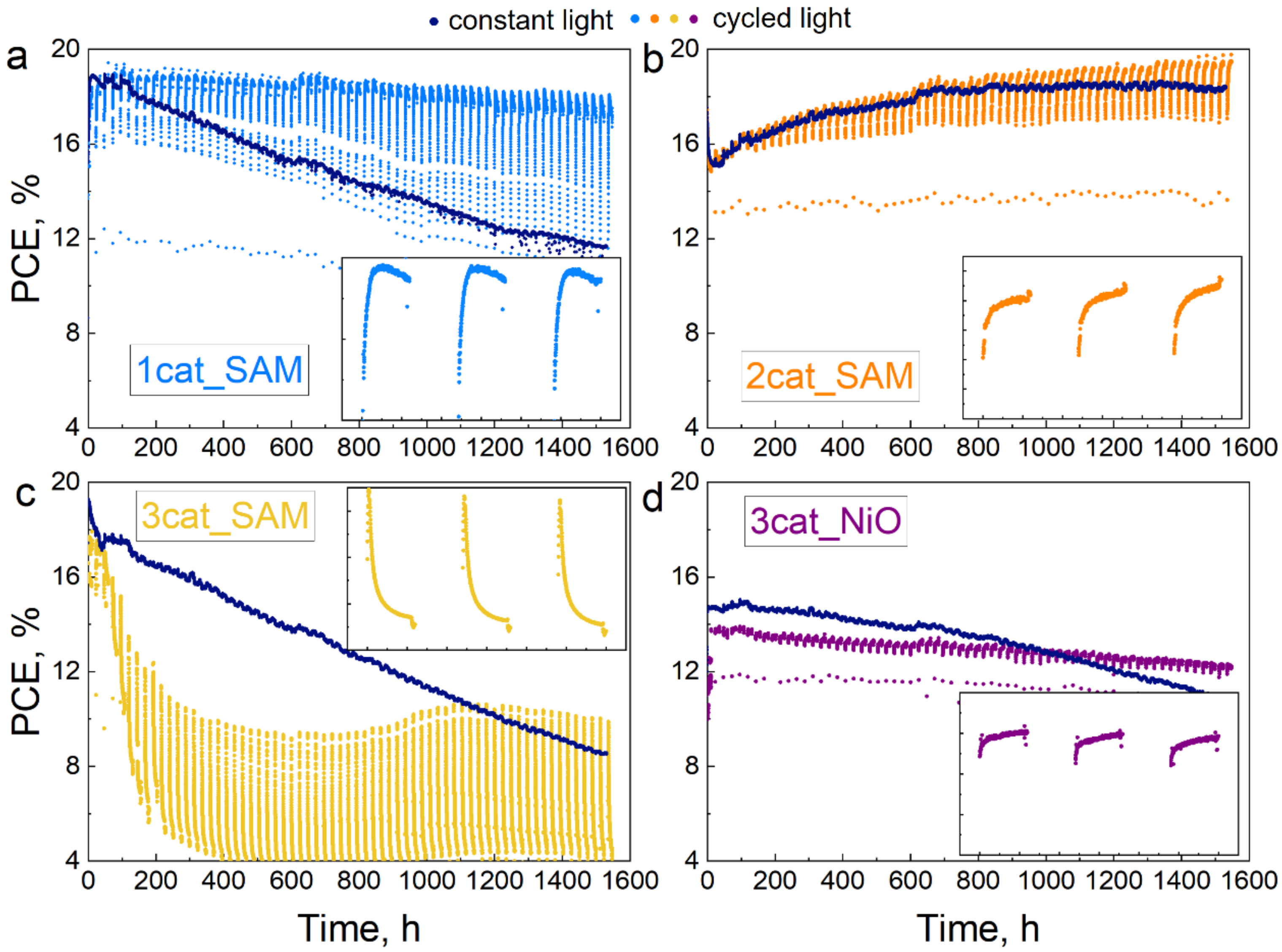




ISOS-LC

Light cycling

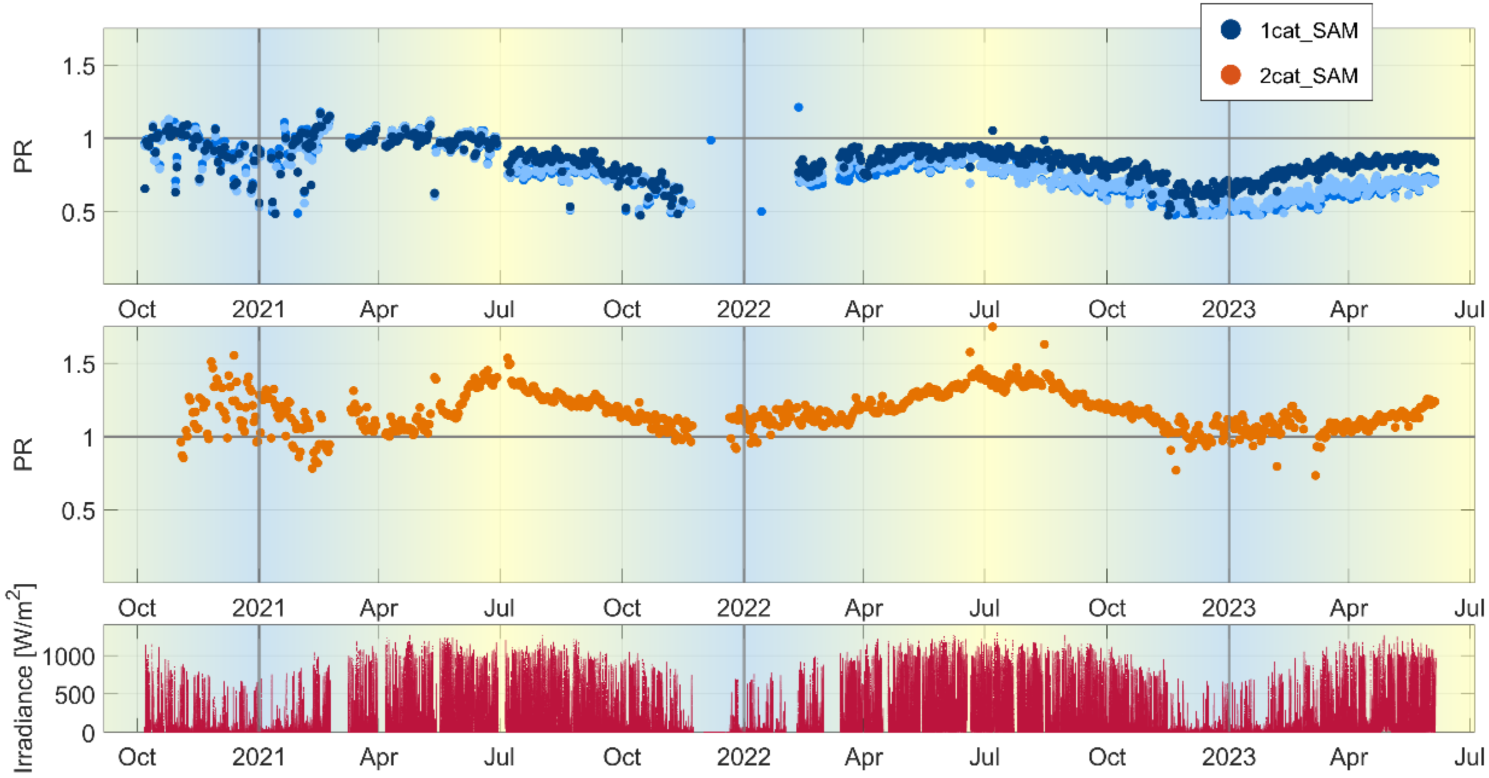
PERO AGING BEHAVIOURS UNDER ILLUMINATION



Consequences of meta-stability for outdoor data analysis

ISOS-O

Outdoor



Seasonal changes

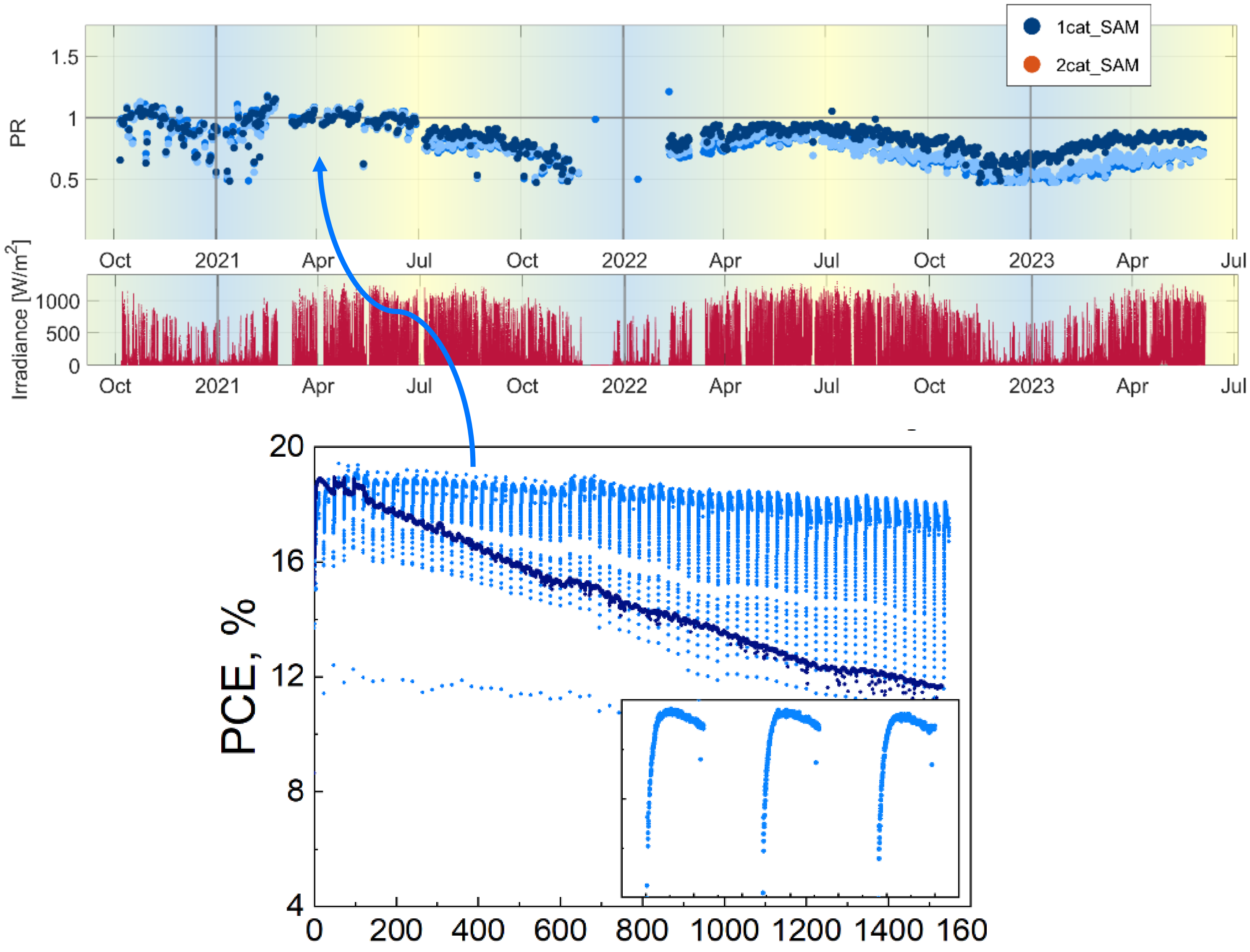
Long-term stability trends

Parameters' extraction

Affects the energy yield

M. Khenkin, H. Köbler et al. Energy Environ. Sci., 2024,17, 602-610

Consequences of meta-stability for outdoor data analysis



Seasonal changes

Long-term stability trends

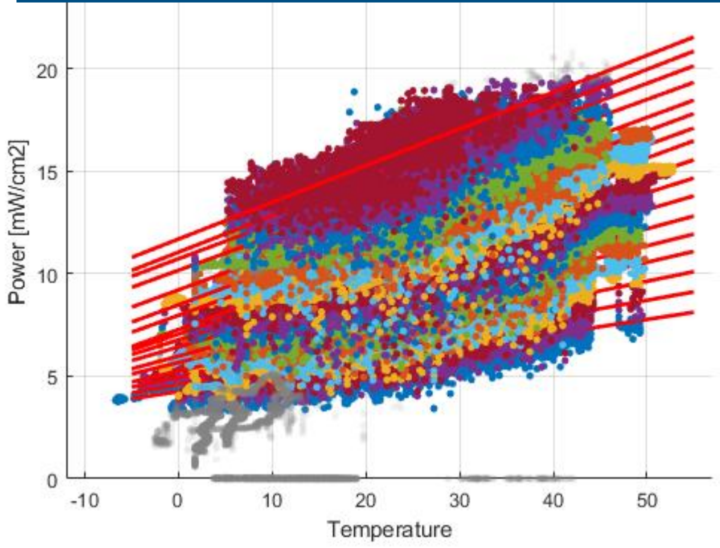
Parameters‘ extraction

Affects the energy yield

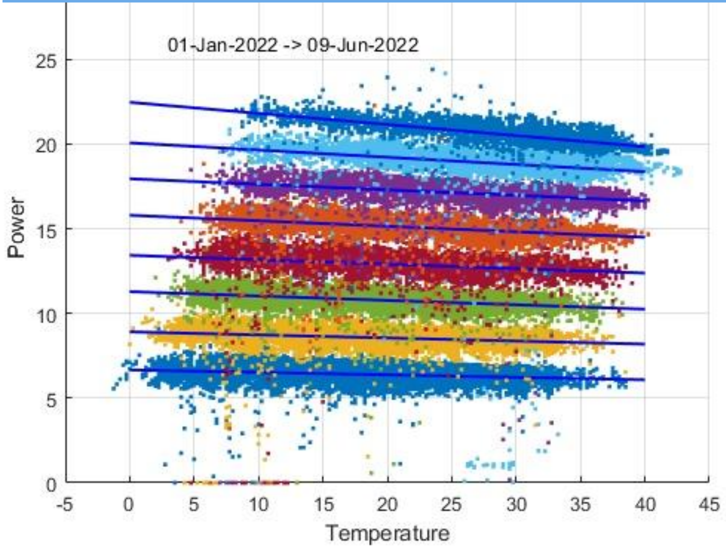
Consequences of meta-stability for outdoor data analysis

e.g. aparently positive T coefficients
Note they are actually negative, if one measures indoor with enough light soaking

Perovskite



Silicon



Seasonal changes

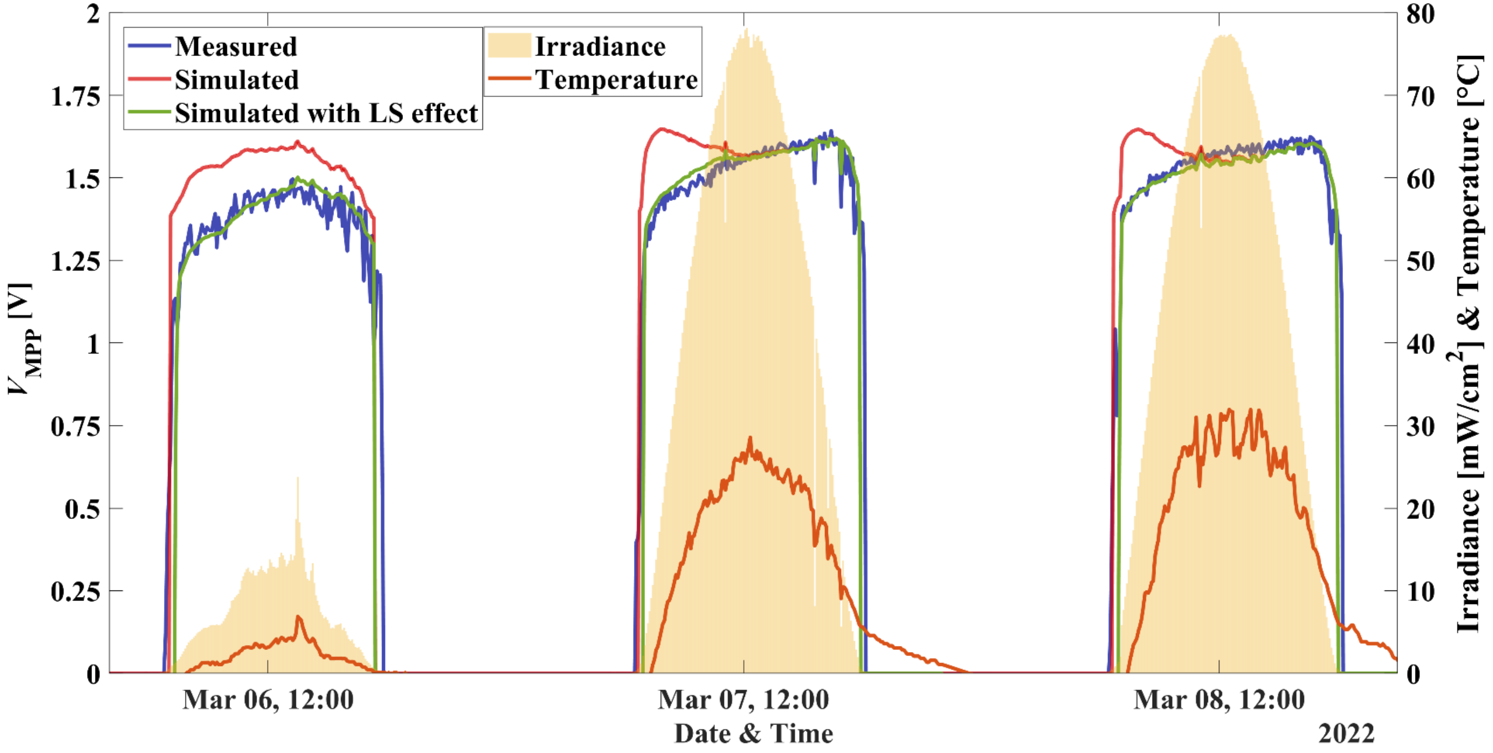
Long-term stability trends

Parameters‘ extraction artefacts

Affects the energy yield

Consequences of meta-stability for outdoor data analysis

- Model without light-soaking only fits experimental data for part of a day
- We can make a semi-empirical model with light-soaking effect which gives good fit all day/any day
- This model predicts up to 7% annual energy yield losses on light-soaking alone depending on the lcation and device



Seasonal changes

Long-term stability trends

Parameters' extraction artefacts

Affects the energy yield

M. Remec, S. Tomsic, et al. submitted

WHAT ELSE IS THERE IN ISOS PROTOCOLS?

Khenkin et al. Nature Energy, 2020, 5, 35-49

1. Reporting list
2. Discussion on the Figures of Merit for stability
3. “Best practices”

WHAT ELSE IS THERE IN ISOS PROTOCOLS?

Khenkin et al. Nature Energy, 2020, 5, 35-49

1. Reporting list
2. Discussion on the Figures of Merit for stability
3. “Best practices”

“AAA class simulator” may or may not contain UV -> reporting <u>the type of light source and its spectrum</u>

… ISOS protocols represents accelerated aging. Though acceleration factors are not yet

Use **MPPT** for long-term stability measurements and for the short term performance characterization

Report MPPT tracking algorithm and hardware employed

Avoiding the word “stable” in publications in an non-specific way

Reporting **all** the aging results, not only the champion device!

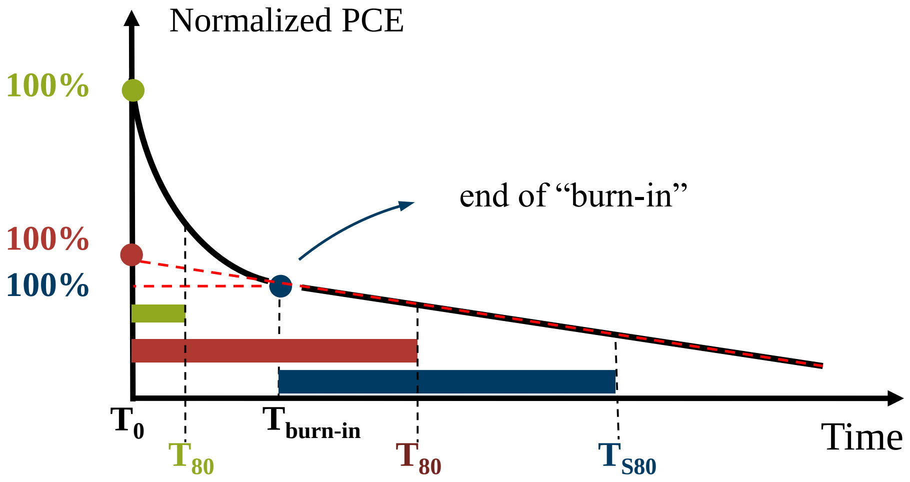
Measured values are preferred over normalized.

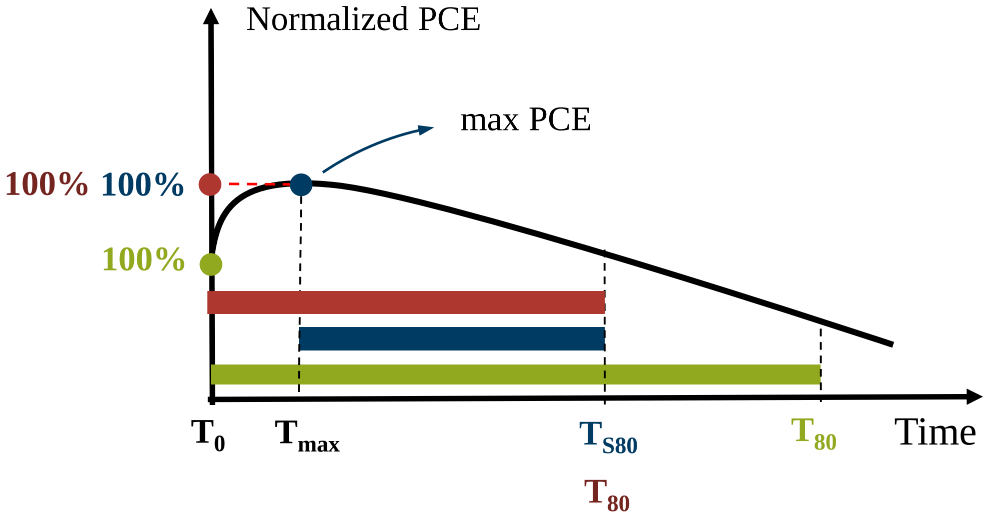
Always specifying <u>what the data was normalized to</u>.

Khenkin et al. Nature Energy, 2020, 5, 35-49

Graniero et al. Front. Energy Res. 11:1118654
doi: 10.3389/fenrg.2023.1118654

FIGURES OF MERIT FOR STABILITY





T_{80}: 20% decrease in PCE from the initial value.

"Stabilized" T_{S80}: 20% decrease counted from the "stabilized" value (i.e. after fast effects were saturated). The time it took to stabilize is discarded.

"Back extrapolated" T_{80}: 20% decrease in PCE from its back-extrapolated or maximum value. "Stabilization time" is included.

Figures of merit

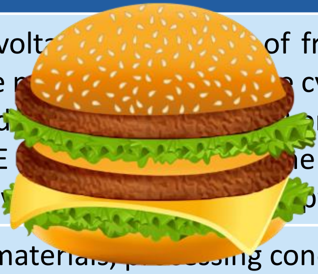
	FOM options		Description and applicability
1	T_{80}	Continuous stress	20% of PCE decay from the initial PCE (t=0).
2	T_{S80}		20% of PCE decay from a certain PCE value during the aging experiment, co $t_{burn\text{-}in}$: - for cells with "burn-in" effect, the PCE value for 80% is estimated, should burn-in or from the extrapolated t=0 value from the post-burn-in decay fitting. - for cells with PCE increase, the T_{80} should be estimated for time at which the efficiency has dropped to 80% of the maximum PCE, with the complete time from t=0 to this point quoted as the T_{80} value.
3	η_{1000} (PCE after 1000 hours)		In case T_{80} is not reached within the timeframe of the aging experiment, it is recommended to report the decrease observed over first 1000 h in addition to (optionally) extrapolation applied to determine T_{80} and/or T_{S80}.
4	T_{95} and T_{S95}		Analogous to T_{80} and T_{S80}, apart from to 95% of the t=0, maximum, or post-burn-in back-extrapolated t=0 PCE.
5	T_{80} analogue, corrected for the recovery processes	+ recovery	If the restoration process has been tested after the stress removal.
6	T_{80} analogue for energy output per cycle or average PCE value during the cycle	Cycled stress	For cycled illumination conditions, esp. in case of non-monotonous PCE vs time curves.

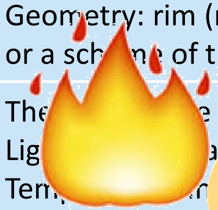
If it takes too long to reach T80,
Keep the aging for at least 1000 h

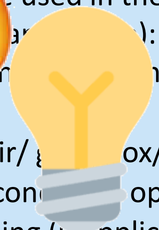
REPORTING CHECKLIST

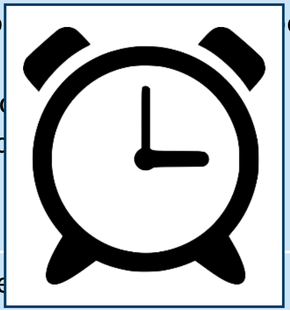
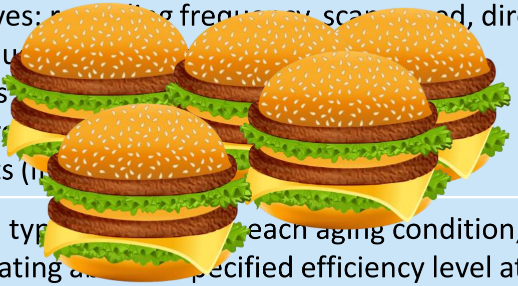
It does sound uneasy, but it is a consensus between 60 researchers in the field, that all these info is needed to reproduce your results

Parameter	Characteristics
Initial solar cell characterization	Current-volt[...] of fresh devices, including voltage scan conditions: scan speed, direction, dwelling time, the [...] cycles (NPLC), preconditioning etc. Stabilized [...]r MPP tracking data of fresh device. EQE/IPCE [...]e lock-in frequency [...] bias if used, and if monochromatic light is smaller than acti[...]ptical mask applie[...]rison to J_{SC} obtained from J-V data.
Encapsulation	Wiring: materia[...]ng conditions, addition[...]nt. Front and back side encapsulation layer(s): materia[...]nposition, thickness), processing conditions (environment, temperature, duration). Edge sealant: materials (reference, thickness, width), [...] conditions. Geometry: rim (minimum distance between encapsulation edge and active area edge), device active area; picture or a sch[...] of the device.
Aging conditions	The [...] used in the a[...]ng [...]nent: light [...]urce type, intensity, spectrum, filters applied, calibration. Lig[...]): d[...] and period tim[...] Tem[...]nd/or un[...] illumi[...]sured with thermocouple o[...]erature sensor. Atmosphere: air/ [...]ox/ sealed pouch/ env[...]onmental chamber etc.; controlled [...] Electrical bias con[...] open circuit/ maximum power point (MPP)/ short circuit/ [...] Conditions cycling ([...] applicable): dwell and period times. Specify if the test conditions comply with known protocols (IEC, ISOS etc.).
Aging time	Stress duration and corresponding performance loss, resting times (e.g. without stre[...]
Measurements during aging	Periodically recorded J-V curves: [...] frequ[...] scan [...]d, direction, NPLC, dwelling time, preconditioning, light source u[...] Recovery time and conditions [...] MPP tracking (if applied): har[...] Other periodic measurements ([...]
Number of samples	Number of solar cells of each typ[...]each aging condition, statistical analysis (if applicable). Number of samples still operating a[...]pecified efficiency level at the end of the aging test.
Outdoor stability	Location (city/coordinates) and dates of exposure. Weather conditions throughout the exposure period: temperature, humidity, sunlight irradiance (preferably in







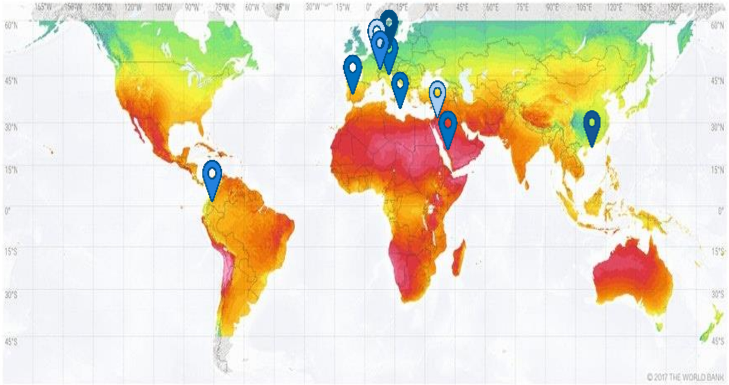



ONGOING ACTIVITIES

ISOS-15 conference

September 30th – October 2nd 2024

"Round-robin" outdoor experiment



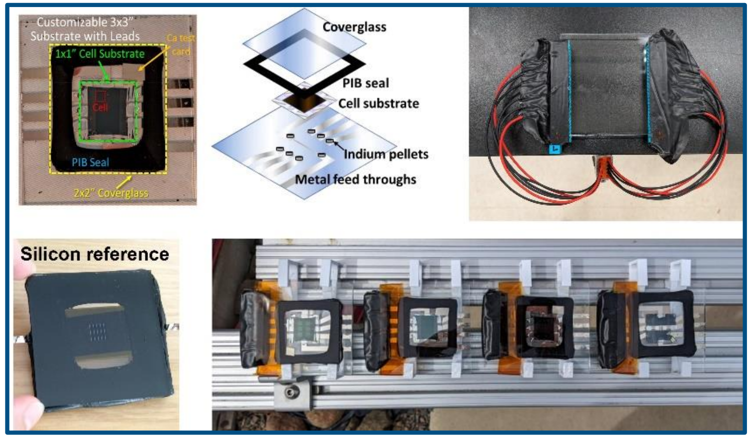


*Figure courtesy of R. Tirawat, NREL

Protocols for pero-based **tandems**

tandemPV
INTERNATIONAL WORKSHOP
June 6-8, 2023 | Chambéry, France & Online

Please, contact

Ivona Kafedjiska, HZB
Daniel Tune, ISC-Konstanz

CONCLUSIONS

ISOS protocols are applicable for Perovskite solar cells but should be extended to grasp the entire range of observed phenomena.

ISOS-V-1-3	for bias application in the dark
ISOS-LC-1-3	for light cycling experiments
ISOS-I	for aging in an inert atmosphere

Reporting checklist for aging experiments is suggested.

Good practices for aging experiments are discussed.

*The goal of these guidelines is to assist in **unifying** the procedures of PSCs stability studies, improve comparability between data from different laboratories and device architectures. It is intended as an intermediate stage in PSC technology maturing, aimed at the identification of degradation pathways and the prospects for their mitigation.*

Thank you for your attention!