VIPERLAB

FULLY CONNECTED **VI**RTUAL AND **P**HYSICAL
P**ER**OVSKITE PHOTOVOLTAICS **LAB**

D9.10: GUIDELINES FOR AGING PROCEDURES OF PEROVSKITE PV TECHNOLOGY - MAIN OUTCOMES AND FINAL CONCLUSIONS

DELIVERABLE REPORT

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FULLY CONNECTED VIRTUAL AND PHYSICAL PEROVSKITE PHOTOVOLTAICS LAB VIPERLAB

DELIVERABLE

D9.10: GUIDELINES FOR AGING PROCEDURES OF PEROVSKITE PV TECHNOLOGY - MAIN OUTCOMES AND FINAL CONCLUSIONS

Project References

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1.1	Review	16.12.2024	HZB	N. Maticiuc

DISCLAIMER

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Table of content

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EXECUTIVE SUMMARY

This deliverable report presents the key findings and guidelines derived from the VIPERLAB project's extensive aging studies on perovskite photovoltaic (PV) technologies. These studies explored the effects of critical stress factors—light, temperature, and humidity—on various perovskite PV device architectures, including single-junction devices with NIP or PIN structures and tandem perovskite-silicon devices. Both accelerated aging and outdoor experiments were conducted to simulate real-world conditions and predict long-term stability.
Key insights from the report include:

1. Round Robin Organization and Device Description:
    - Detailed protocols and experimental setups for three aging scenarios: light aging, damp heat and thermal cycling, and outdoor aging.
    - Comprehensive descriptions of devices tested, such as PIN and NIP single-junctions and tandem silicon-perovskite cells.
2. Aging Results and Recommendations:
    - Light-aging studies revealed distinct degradation patterns under continuous illumination and light cycling. Encapsulation quality significantly influenced device stability.
    - Thermal cycling and damp-heat tests highlighted encapsulation's critical role in protecting devices against thermal and humidity-induced stresses.
    - Outdoor aging demonstrated the interplay of irradiance, temperature, and encapsulation on device performance and longevity.
3. Standards, Harmonization, and Protocols:
    - Discussions on current standards like ISOS, PACT, and emerging IEC guidelines for perovskite PV technologies.
    - Recommendations for improving and standardizing accelerated aging tests to bridge the gap between lab-scale studies and real-world performance.

This report emphasizes the need for harmonized protocols to enhance reliability, scalability, and standardization of perovskite PV devices, providing a foundation for future research and development in this rapidly evolving field.

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1. ROUND ROBIN ORGANIZATION & DEVICE DESCRIPTION

During Viperlab project, we organized three round robins with various devices, single junction and tandem silicon/perovskite, Figure 1. We investigated the main stress factors related to lifetime issues considering accelerated aging conditions with light, temperature, humidity. Most of the aging conditions are related to ISOS recommendations[1]. We also considered outdoor aging to make the link with operational behaviour.

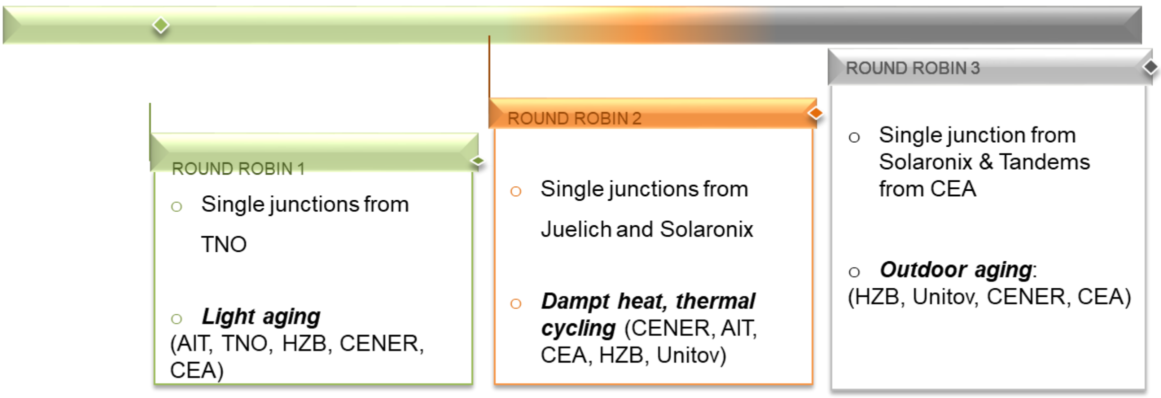

Figure 1. Summary of the three aging round robins organized during the Viperlab project.

1.1 Description of the rounds

- **round 1 organization: light aging**

This round robin is focused on light aging protocols, with either continuous or cycled light soaking. The exchange was organized by matching similar aging conditions (electrical bias, atmosphere, lamp power) between two or three institutes among HZB, AIT, TNO, CENER and CEA. The premeasurement (t_0) on TNO devices, single junction described in section 1.2, was performed in all institutes, and the aging measurements generally lasted 500 hours, sometimes up to 1000 hours.

Three type of accelerated light aging were considered, continuous light soaking (ISOS-L1) with two different electrical loads during aging (open circuit voltage (Voc) and maximum power point tracking (MPPT) or fixed MMP voltage (Vmpp) and light cycling at Voc. The details regarding each aging condition are summarized in Table 1.

[1] M. Khenkin & al. Nature Energy | VOL 5 | January 2020 | 35–49 | www.nature.com/natureenergy

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Table 1. Light soaking parameters.

PARAMETER	ISOS L1-Voc	ISOS L1-Vmpp	ISOS-LC-Voc
Cycling	-	-	8 hrs light / 16 hrs dark
Light soaking duration	Up to 1000 hrs	Up to 1000 hrs	120 hours
Electrical bias	V_{OC}	V_{MPP} or MPP tacking	V_{OC}
Measurement frequency	Once a week (~168 h)	Once a week (~168 h)	Twice per day
Lamp power	1 sun	1 sun	1 sun
Atmosphere	Ambient	Ambient	Ambient
Temperature	Near 25°C	Near 25°C	Near 25°C

The aging light spectrums of 4 institutes are shown in Figure 2. In the case of AIT and CENER, the aging was performed directly in the solar simulator: the spectrum is identical for both aging and measurement. Their aging spectrums are thus quite like the AM1.5 spectrum. At HZB and CEA, the aging was performed in a separate instrument.

HZB, AIT and TNO had an active temperature control on each substrate during the aging, and thus kept the cells near 25°C. An active control was also used at CENER, but the temperature may have reached 30-35°C due to an insulating layer placed between the chuck and the cell. At CEA, the cells were placed in a climatic chamber regulated at 25°C, which means the individual substrates reached much higher temperatures.

The electrical measurement contains the following steps:

- First J-V measurement – forward and reverse
- Second J-V measurement – forward and reverse
- J(t) at V_{MPP} or MPP tracking, 180 seconds duration
- Last J-V measurement – forward and reverse

These steps were chosen to obtain a sufficient stability of the device, and the parameters for the J-V scans are detailed in Table 2. The J(t) at V_{MPP} is performed at the average V_{MPP} obtained from the second J-V measurement.

Table 2. J-V measurement conditions.

RANGE (V)	SPEED (mV/s)	DELAY (ms)	STEP (mV)
-0.2 V to 1.2 V	50-100 mV/s range	20	Adaptable

The result graphs generally contain the following data:

- Power in mW: average value of the last 30 seconds of tracking
- Relative Power in percent: ratio compared to the power at t_0
- I_{sc} (mA), V_{oc}(V), FF (%): these values are the average of the last forward and reverse scans
- Hysteresis Factor (%): calculated with the last forward and reverse scans

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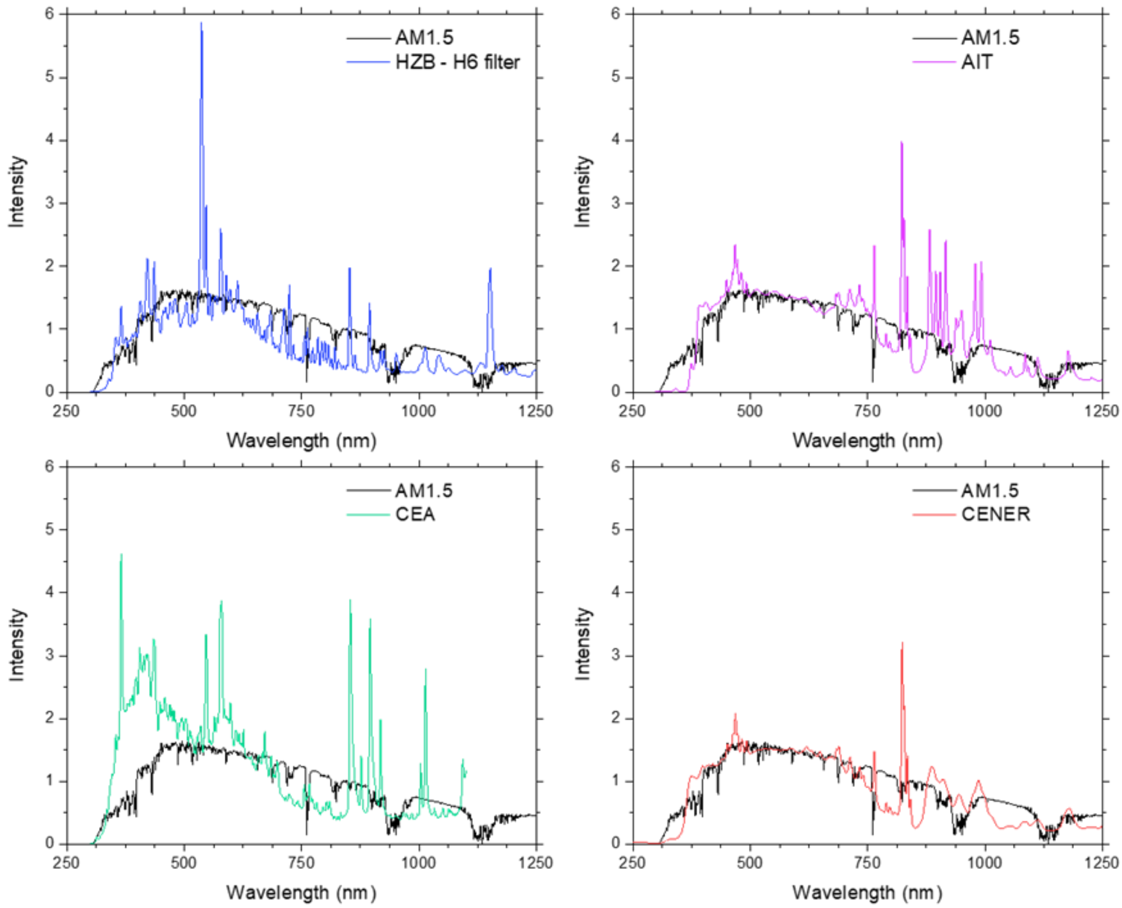

Figure 2. Light spectrums used for the light soaking at HZB, AIT, CEA and CENER.

- **round 2 organization: damp heat and thermal cycling**

In this round, we considered particularly the stress factors related to the effectiveness of the encapsulation materials and protocols.

Damp-heat allows to test the encapsulation resistance to water ingress. We aimed for 500 hours at **85°C, 85%** relative humidity, with a measurement at least once a week. There is no illumination involved, and the cells remain at Voc during the experiment.

Thermal cycling was used to test both the cell resistance to thermal stresses, and its resistance to delamination once encapsulated. The aging is performed under air in climatic chambers, and has the following steps in each cycle:

- 30 minutes at -40°C
- Ramp up at +90°C per minute, up to +85°C
- 30 minutes at +85°C
- Ramp down at -90°C per minute, to -40°C
- This cycle is repeated either 50 or 100 times.

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Two types of cells were considered, (i) single junction from Solaronix (Ch) for damp heat and outdoor experiments, and (ii) cells from Jülich (Ge) for thermal cycling experiments, see section 1.2 for details. The measurement protocol is like the one used in the first round and is designed to include several 'slow' J-V over the range designed by the manufacturer, as well as a 180 seconds MPP-tracking to obtain stabilized values. The values reported in the results section refer to either the stabilized PCE value measured during the tracking, or the values obtained during the last J-V after the stabilization. The measurements were performed at least once a week, and more frequently when possible.

The protocol was adapted when necessary:

- For outdoor testing, the cells were monitored with MPPT during the experiment. The J-V protocol is only applied at the start and finish.
- HZB system does not allow to perform the 180 s MPPT, which is replaced by a simple J-V.

The voltage range indicated by the participants are:

- Solaronix cells: -0.3 V to +1 V
- Jülich cells: -0.1 V to +1.2 V

- **round 3 organization: outdoor aging**

The HZB outdoor platform is described in the Figure 3.

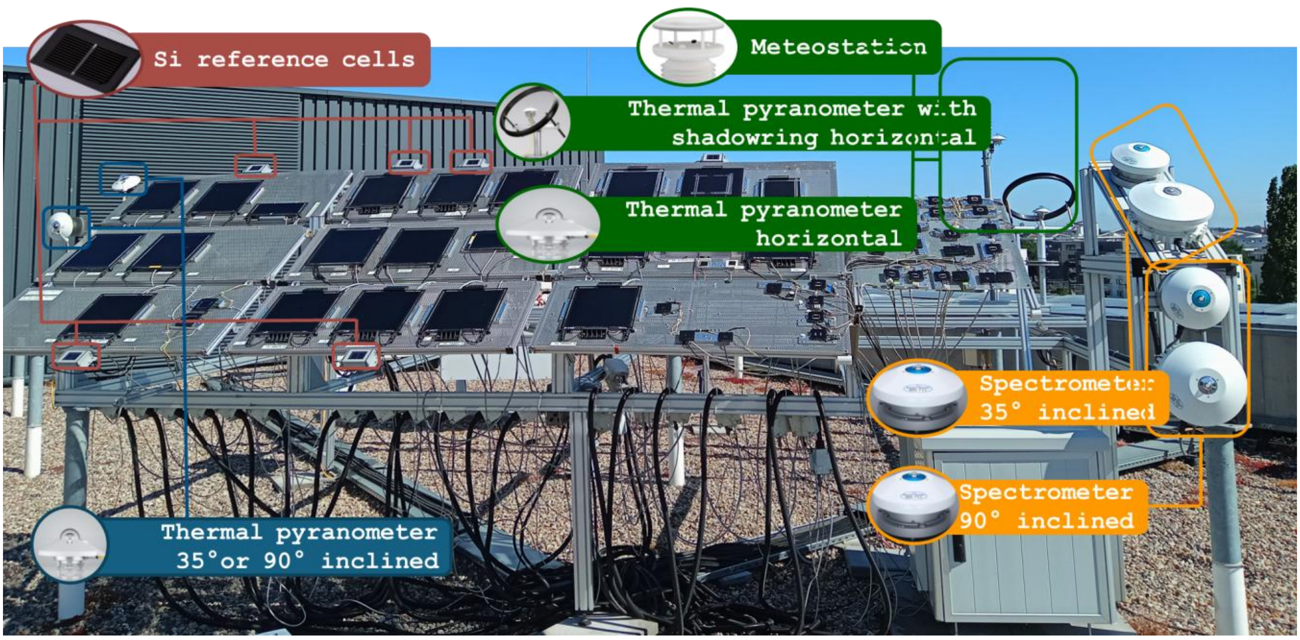

Figure 3. Description of the out-door platform in Berlin.

In CEA and HZB, the cells were maintained at the maximum power point. The P_{mpp} is recorded continuously. In CEA, there are hourly J(V) measurements, not in HZB. The cells are masked (8.88cm^2 for CEA; 5.71cm^2 for HZB).

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Figure 4. CEA set up for outdoor monitoring.

From its hand, CENER installed a 10 ohms fixed resistance, so the cells were close to the maximum power point. Complementary, regular indoor measurements are performed. For CEA and CENER, the protocol is described in D9.9 (public report, figure 22). In HZB, the protocol is 4 J(V) scan (reverse then forward). In the data analysis, HZB reported measurements from the last forward scan, i. e. after approximatively 10 minutes of light soaking.

1.2 Description of devices

- **Single junction (PIN) (TNO)**

The perovskite solar cell stack consists of glass/ITO/HTL/perovskite/passivation layer/C60/SnOx/ITO/Ag finger in p-i-n configuration. HTL, perovskite and passivation layers were deposited via slot die coating. C60 was thermally evaporated and SnOx ETL layer was deposited via atmospheric pressure spatial atomic layer deposition technique. ITO was deposited via RF sputtering and finally the Ag grids were thermally evaporated. The layout of a substrate is shown in Figure 5, showing four cells. 20 identical substrates were shared by TNO for this round robin and were send to HZB for encapsulation.

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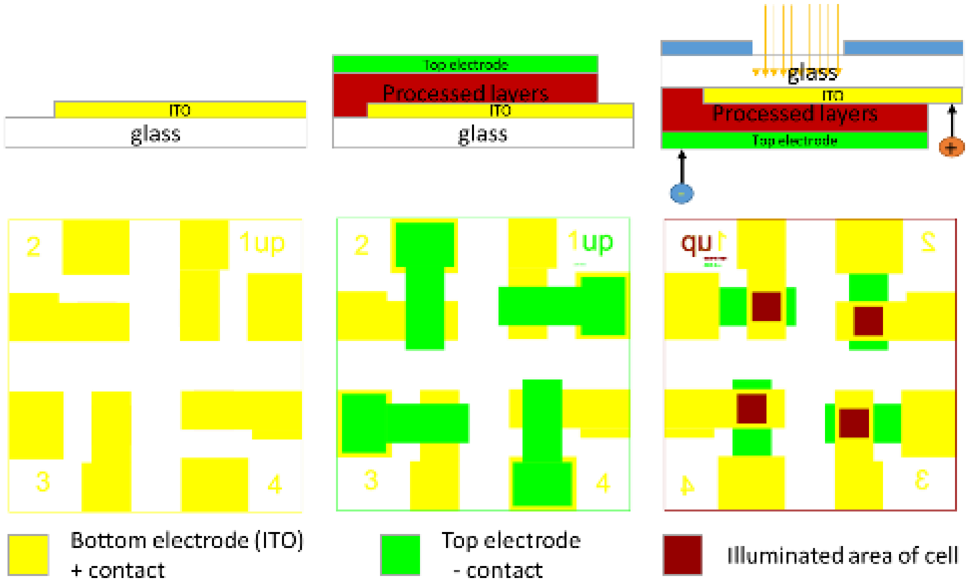

Figure 5. Layout of TNO substrates, with four 0.09 cm² active areas.

All fabricated substrates were encapsulated to ensure sufficient lifetime of the devices in ambient atmosphere. The lamination process was performed at HZB to obtain two sets of samples with different encapsulation schemes, as shown in Figure 6. Contacting ribbons were added to form contacts outside of the encapsulation box. The encapsulations were performed as follows:

- Rigid glass covers, a polyolefin encapsulant and butyl edge sealant in Figure 6(a). The lamination was performed at 150°C on 10 substrates (*i.e.* 40 cells). Some cells suffered from performance degradation.
- Rigid glass covers and butyl edge sealant in Figure 6 (b). The lamination was performed at 100°C on 15 substrates (*i.e.* 55 cells). There was no degradation observed.

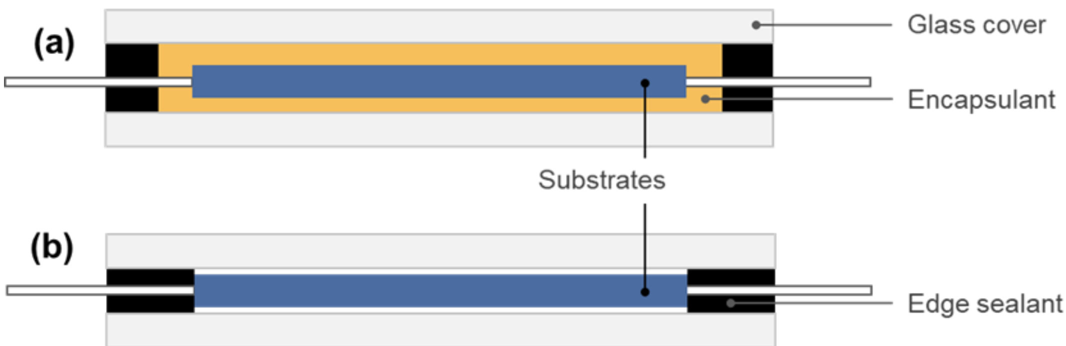

Figure 6. Rigid glass-glass encapsulation stacks (HZB) used to protect the TNO cells. In stack (a), butyl edge sealant and polyolefin encapsulant were used, while stack (b) only contains butyl edge sealant.

All substrates were identified, along with the corresponding encapsulation. The spare samples were sent to CENER, CEA or HZB in case of damage on other substrates.

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A first measurement was performed at each institute before the aging started. The initial power values are shown in Figure 7 for each measurer. The samples encapsulated with butyl only and butyl + POE are respectively represented by full or empty symbols. Most power values measured lie in the same range at all institutes, between 2 and 3 mW, with a few outliers. These differences might be due to damage during encapsulation, or during the transport.

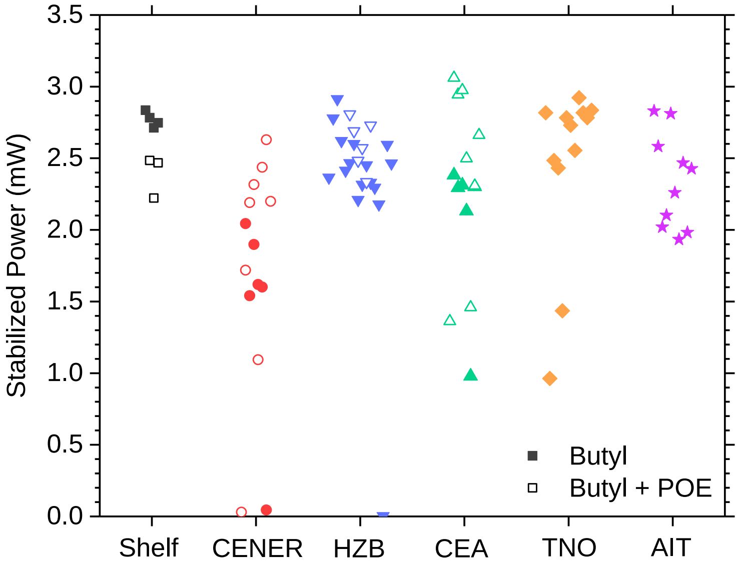

Figure 7. Initial power in mW, plotted for each measurer.

- **Single junction (PIN with carbon electrode) (Solaronix)**

40 perovskite single junction cells were shared by Solaronix (https://www.solaronix.com/). The stack is detailed in Figure 8(a) and contains the following layers:

- FTO glass substrate
- TiO_2
- 400-800 nm of mesoporous TiO_2
- 1-2 µm of mesoporous ZrO_2
- 6-10 µm of mesoporous carbon

The mesoporous layers are infiltrated by perovskite.

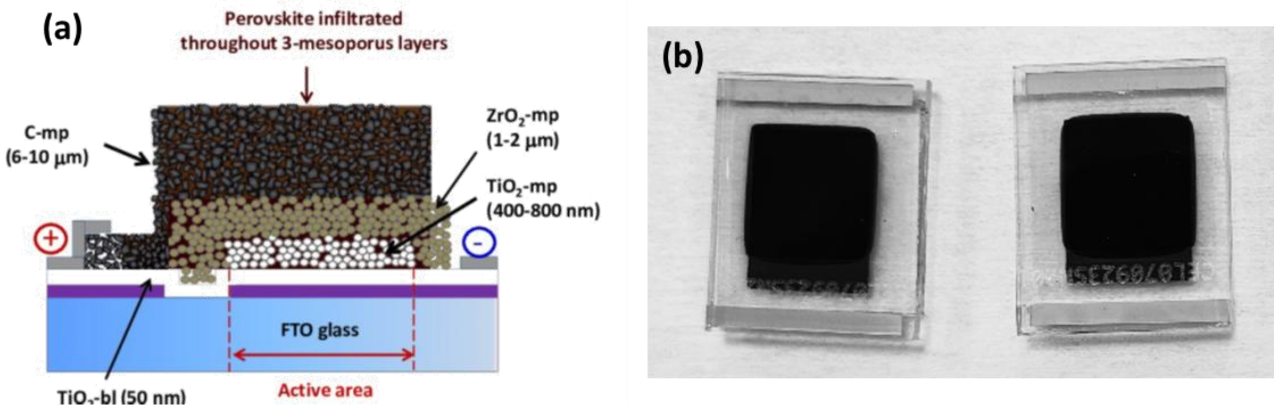

Figure 8. Active stack (a) and finished cells with encapsulation (b).

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There is one cell per substrate, with a 1.5 cm² active area. The cells were encapsulated with Surlyn ionomer and a glass cover by lamination at 100°C, as shown in Figure 8(b). The initial performance measured at Solaronix are shown in Figure 9, and indicated an average PCE of 9.4%. Adhesive contact ribbons were added to the cells dedicated to outdoor aging, to facilitate the connection to the measurement systems. The option to add identical contacts on all cells was given in case the crocodile clips system did not work. 3 cells were kept under N_2, in the dark, for the duration of the experiments.

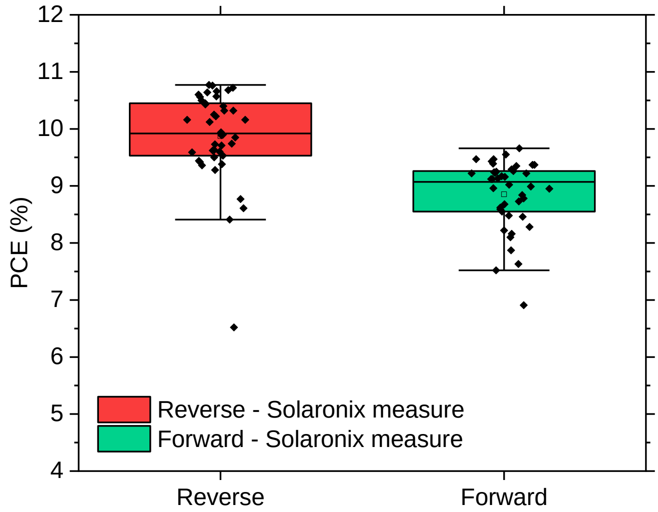

Figure 9. PCE measurements performed at Solaronix before shipment, with forward and reverse values.

- **Single junctions (NIP) (Jülich)**

50 substrates were prepared by Jülich. Each 25×25 mm² substrate contains 6 NIP single junction cells with 0.063 cm² active surface, as shown in Figure 10. They were prepared on Jülich automated line, with a stack that contains glass/ITO/SnOx/Perovskite/Spiro-O-MeTAD. The premeasurement performed at Jülich showed initial PCE in the 15% to 21% range.

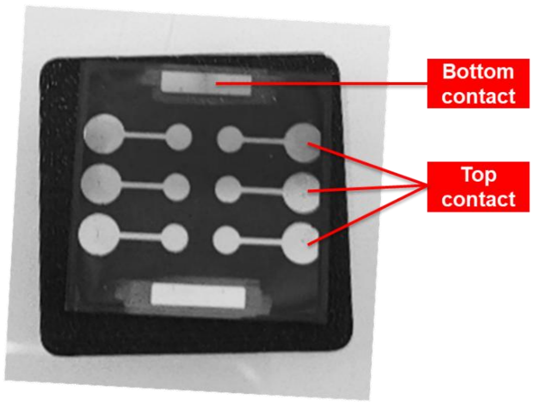

Figure 10. 2.5×2.5 cm² non-encapsulated substrate from Jülich, with 6 cells.

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Encapsulation tests were first performed on test substrates, using epoxy glue. This method largely damaged the samples, with a drop in average PCE.

It was chosen to start the Round Robin without encapsulation for the first half of the samples, by putting them in a sealed pocket during thermal cycling experiments

- **Tandem with Silicon (CEA)**

The 3rd round robin involved solely perovskite – silicon tandem solar cells. The design of the cells supplied by CEA is described in Figure 11:

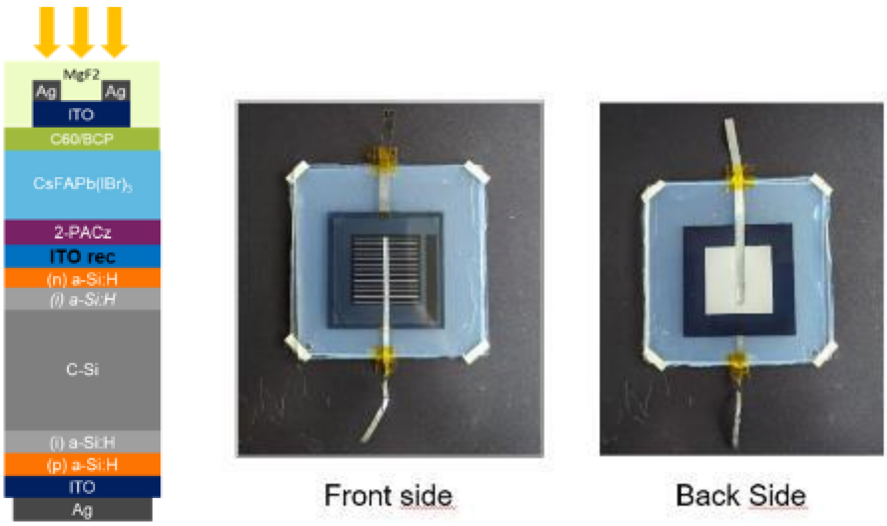

Figure 11. (Left) Scheme of perovskite-silicon tandem solar cell architecture and (right) front and rear view of tandem solar cells supplied by CEA.

The solar cells encompass a p-i-n perovskite solar cell with a heterojunction silicon solar cell in two terminals configuration, having an active area of 8.88 cm². In these “baseline” devices, there is not any passivation strategy included.

These photovoltaic solar cells feature a glass/glass encapsulation with dimensions of 80 x 80 mm or 100*100mm depending on the encapsulation process and materials. For 80 x 80 mm samples, we used UV-polymerizable epoxy glue to seal the glass cover at a low temperature without mechanical pressure and conductive tapes as connectors. For 100 x 100 mm samples, we used polyolefin encapsulant and butyl edge sealant processed with hot vacuum laminator at 130°C. In the latter case, we used electroconductive adhesives (ECA) to set up the connectors.

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2 AGING RESULTS

2.1 Light aging

- **Shelf lifetime**

In order to control the impact of shipment, two substrates, one of each encapsulation scheme, were sent back to TNO and kept in N_2 atmosphere over the whole experiment duration. The power evolution is shown in Figure 12, where the values at t0 and at t476 are respectively plotted in black and green. For this graph, the power values were taken from the last IV measurement, rather than the MPP Tracking.

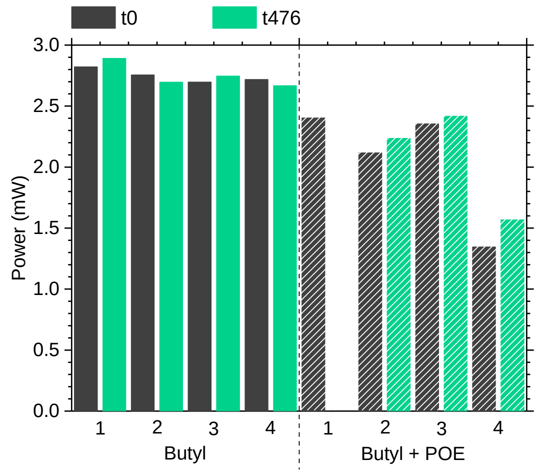

Figure 12. Power measured before (black) and after (green) the experiments, for the cells kept in the dark under N_2.

Both substrates initially had 4 active cells. For the Butyl substrates (left), all cells had very similar power at the start, and it remained stable until the end of the experiments. V_{OC} and FF values are stable, while there is a slight decrease in current (~2% loss). There is a clear increase in hysteresis for all cells. In general, we can consider the butyl cells to be stable through the duration of the experiment, though some changes occurred. The substrate with Butyl+POE initially had lower power and the hysteresis was larger, but most parameters remained stable with a small increase in FF. These cells appear relatively stable for the duration of the experiment.

- **ISOS-L1 at v_{OC}**

Cells with butyl alone

All groups had at least one cell submitted to continuous light under V_{OC}. The power results (value from MPPT) are summarized in Figure 13, and the IV measurement results are shown in **Errore. L'origine riferimento non è stata trovata.**. Each data point corresponds to an average of all cells aged at V_{OC} at each given institution, with the black curve showing the shelf-life average.

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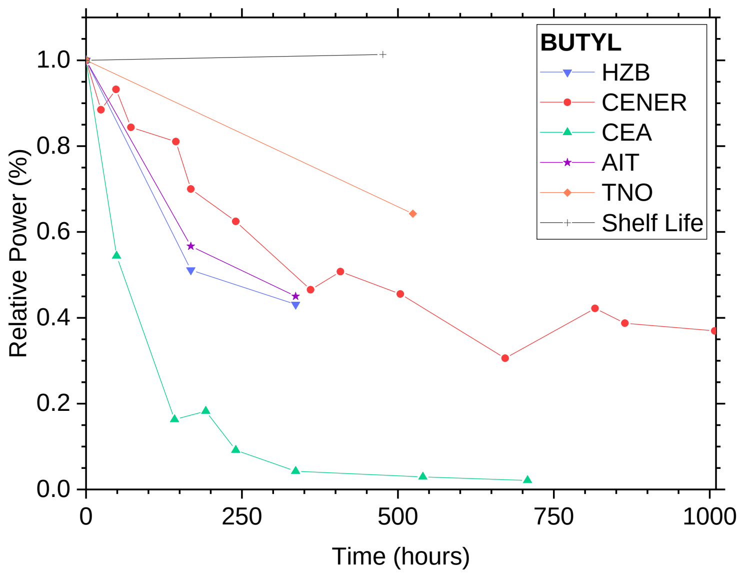

Figure 13. Power Evolution for cells with butyl encapsulation exposed to continuous light, under V_{oc} bias. The power is obtained from the last 30 seconds of tracking. The power is obtained from the last 30 seconds of tracking and is the average value per substrate.

Most results indicate that the cells lost near 50% of their power in two weeks (336 hours). CENER experiment lasted 1000 hours, and indicated that this degradation slowed afterwards, reached ~60% loss near the end. Values at CEA showed at much faster degradation, with more 80% loss in a week. This is likely due to excessive heating of the cell during the light soaking. Additional IV results indicate that the power losses are mainly related to current and fill factor degradation. The V_{OC} remained fully stable at CENER, TNO and AIT. The average V_{OC} at HZB shows degradation due to a single cell, the other two presented a stable V_{OC}. At CEA, both cells exhibited a progressive decrease of V_{OC}, confirming that their behaviour is truly different than the rest of the cells.

This general degradation in less than two weeks differs from previous observations at TNO, where similar cells were more stable. The differences might be due to the encapsulation process, and/or to differences during the manufacturing.

Cells with butyl + POE

Cells with Butyl+POE were studied by CENER, HZB and CEA. The power losses are shown as a function of time in Figure 14, along with the shelf life average (black curve). CENER and CEA have obtained very similar results, with 60% loss after one week and ~80% loss after two weeks of continuous illumination. Degradation at HZB was however much lower, with less than 30% loss after two weeks. This difference between CENER and HZB results is not explained yet and shows that further alignment of protocols is necessary. CEA has reached excessive temperatures during the illumination. The performance degradation is mainly related to a drop in current at CENER and CEA, as well is a progressive reduction in FF. Other parameters showed less degradation.

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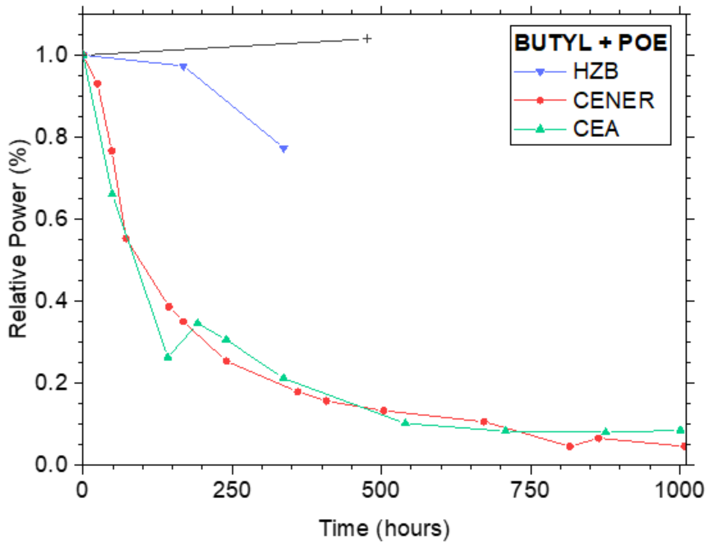

Figure 14. Power evolution for cells with butyl+POE encapsulation exposed to continuous light, under V_{oc} bias. The power is obtained from the last 30 seconds of tracking and is the average value per substrate.

- **ISOS-L1 at V_{MPP}**

MPP tracking up to 500 hours under continuous illumination was performed at HZB (8 cells), TNO (5 cells) and AIT (1 Cell). There were some differences in their tracking algorithms, as follows:

- HZB: evaluation of MPP every 3 seconds. Full measurement with IV once a week.
- TNO: evaluation of MPP every 2 minutes. Full measurement at start and end of aging.AIT: evaluation of MPP every 30 seconds. Full measurement at start and end of aging.

MPP values are plotted as a function of time in Figure 5 for each cell. At AIT, the cell degraded very quickly and lost more than 50% of its initial power in 5 hours. The experiment was thus stopped. This cell might have been damaged from the start, as it presented lower FF than the rest of the cells received at AIT (48% versus 61% on average). It is thus difficult to highlight how the aging protocol impacted the results for this cell.

Substrates from HZB showed an initial power near 2.0-2.5 mW, except for one cell at ~1.6 mW. The initial values are slightly lower at TNO, in the range 1.5-2.0 mW. In both institutes, these values are lower than the power measured during the 'full measurement protocol'. The cells behaviour is similar for cells from a given substrate, as follows:

- HZB, substrate 1: initial increase in power, and progressive decrease to 1.0-1.3 mW (~50% of initial power) after 500 hours of illumination.
- HZB, substrate 2: cell4 degrades very quickly, the others degrade at a much slower pace. These cells reach power near 1.5-1.9 mW at the end (>70% of initial power)
- TNO substrate 1: initial power increase, followed by a progressive decrease over 500 hours. The cells reach 1 mW at the end (~50% of initial power)
- TNO substrate 2: almost identical to substrate 1.

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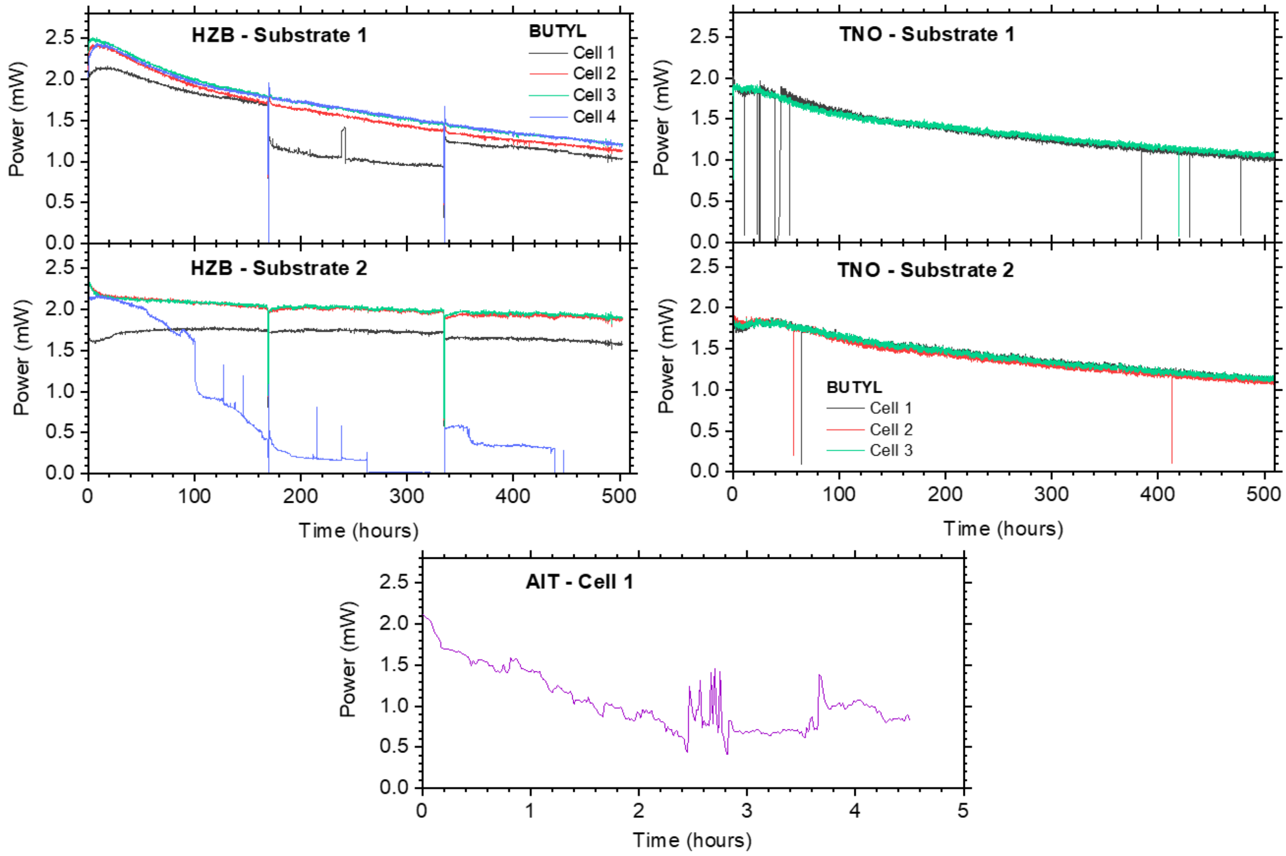

Figure 5. MPP tracking over 500 hours at HZB, TNO and AIT under continuous illumination. The power (in mW) in shown for each individual cell.

The results are quite similar for three of the substrates, and the differences in tracking protocol does not seem to have a large impact. One substrate however was more stable than the others, for an unknown reason. In general, it seems that the degradation is slower with MPP tracking rather than at V_{OC}, but the change is not drastic. It should be noticed that taking the cells out for an additional measurement can cause changes in the power value measured afterwards: this is especially visible for Substrate 1 cell 1 at HZB.

- **ISOS-LC at V_{OC}**

Cycled light soaking was performed at CENER, HZB and CEA. There were some differences in the protocols:

- At CENER and CEA: a full measurement was performed manually at each illumination change. The total duration was 120 hours as it was time-consuming.
- At HZB: automatic IV measurements (reverse and forward) were taken at each illumination change. This method allowed to extend the experiment up to 500 hours.

Power evolution over time is plotted in 16 for the cells with butyl (left) and Butyl+POE (right). Both series presented a progressive loss of power during the experiment and showed partial recovery during dark exposure. Power loss is faster at CEA, which is likely due to excessive temperature.

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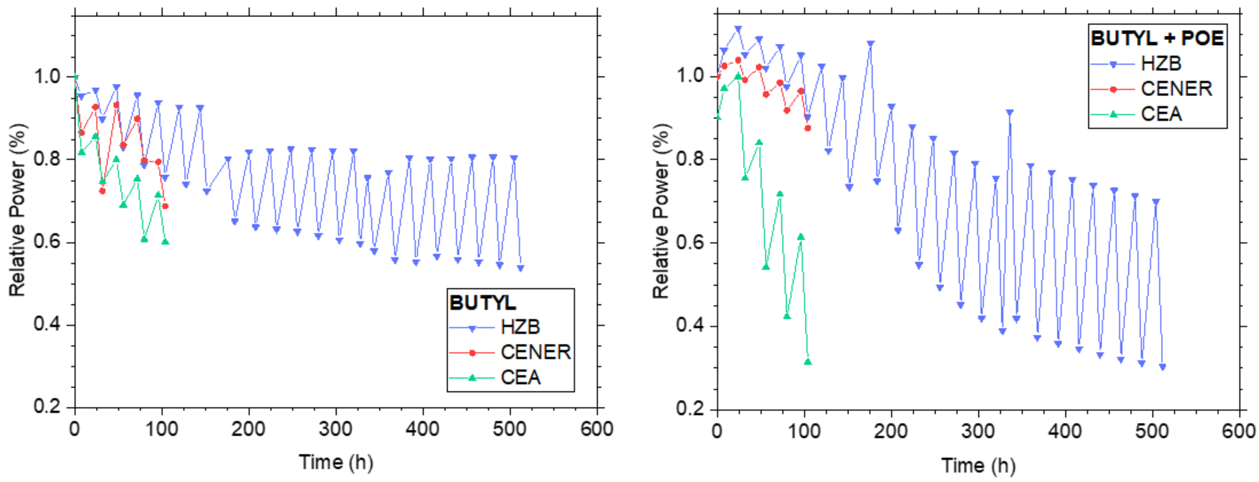

Figure 1615. Relative power evolution for substrates exposed to cycled light under V_{oc} bias. The power is obtained from the last 30 s of tracking at CEA and CENER, and from IV curves at HZB.

The degradation rates and general tendencies however differ between the two sample sets. Cells with butyl only showed a power decrease as soon as they were exposed to light and degraded during the first week. The experiment at HZB, over 500 hours, shows that the degradation rate is reduced in the following weeks. The cells are almost stable during the last week. This is similar to what was observed at CENER for the same type of cells under continuous illumination. On the contrary, cells with Butyl+POE show an initial increase in power, especially during the first day of cycling. They then continuously decrease in power through the experiment. There is no stabilization observed. This highlights that encapsulation method can have non-negligible impact on the results during light soaking. For further experiments, substrates in a sealed pocket (filled with N_2) should be added, to compare with the cell intrinsic behaviour.

- **Main conclusions and recommendations**

Two sets of single junction cells from TNO were submitted to light-soaking, following different protocols from ISOS-L or ISOS-LC, and under different bias conditions. Overall, there is a good agreement on the cell's tendencies: they showed power degradation when exposed to light. The cells at V_{OC} under continuous illumination degraded the fastest, while the cells with MPP tracking showed slightly less losses. If it is already well recognized to consider light cycling (ISOS-LC) in order to mimic outdoor behaviour[2,3] , recent studies also promote the combination of light and temperature (ISOS-L2) and even a combination of light cycling and temperature cycling in order to mimic the seasonal dependence of outdoor performance of perovskite solar cells (Ritesh Gupta, Ben-Gurion University of the Negev)

More practically, these experiments have shown that it remains difficult to perfectly align the aging and measurement protocols, often due to differences in set-ups or habits. The feasibility of experiments should be discussed and agreed to in further details to ensure comparability.

[2] M. Khenkin & al., *Light cycling as a key to understanding the outdoor behaviour of perovskite solar cells,* Energy Environ. Sci., 2024, 17, 602–610, 6

[3] M. De Bastiani & al., *Toward Stable Monolithic Perovskite/Silicon Tandem Photovoltaics: A Six-Month Outdoor Performance Study in a Hot and Humid Climate*, ACS Energy Lett., 2021, 6, 2944–2951.

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Many samples are necessary to complete the experiments, as it was the case here. The chosen encapsulation method is likely to have an impact on performance and stability results, and references should be decided accordingly.

2.3 Damp heat & Thermal cycling

- **Thermal Cycling**

The thermal cycling experiments have not been performed in several institutes due to packaging issues. The current results, shown in Figure 16, contain the results obtained at CEA on Jülich non-encapsulated cells submitted to 50 or 100 cycles. Two substrates were submitted to 50 cycles: one kept all its active cells, with a PCE like the initial state. The other only had one active cell at the end of the experiment, versus 4 at the start. After 100 cycles, most of the cells could not be measured anymore, with only 4 active cells compared to 12 at the start. Their PCE is, however, stable or improved. These first results seem to show that the behaviour is very cell- or substrate-dependent and will need to be completed with results from the other institutes.

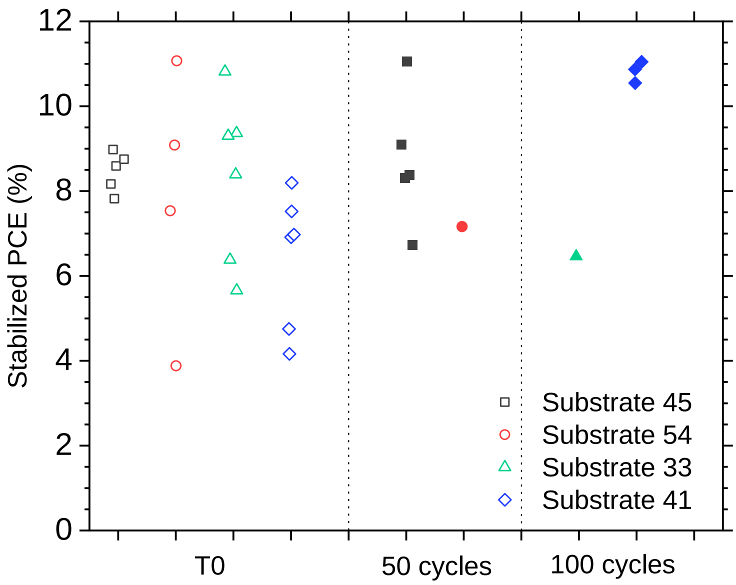

Figure 16. PCE after 50 or 100 cycles under thermal cycling, for substrates without encapsulation.

- **Damp heat:**

The Solaronix cells were kept in damp-heat for up to 600 hours. The results for CENER, AIT and CEA are shown in Figure 17: CENER and AIT cells show a partial degradation, with some cells retaining 8% of PCE and some losing up to 50% of their initial power. The cells that degraded at CENER showed an initial loss of power during the first half of the experiment and then stabilized. The behaviour for cells aged at CEA is very different: due to a malfunction of the climatic chamber, the cells were exposed to liquid water for 24 hours, which caused irreversible damage to the

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encapsulation. Two cells 'died' immediately, while those with higher initial PCE were able to resist longer.

Voc and FF values remained very stable during the experiment, or increased, even for partially degraded cells. Jsc however reduced in all cells, particularly at the beginning of the aging. For CEA cells, the rapid degradation observed in also led by a Jsc drop, this time clearly linked to a loss in active surface. In conclusion, the encapsulation was inconsistent from cell to cell in damp heat: some cells quickly experienced colour change and rapid PCE drop after exposure to DH, while other cells only showed a moderate decrease over time, mostly in Jsc.

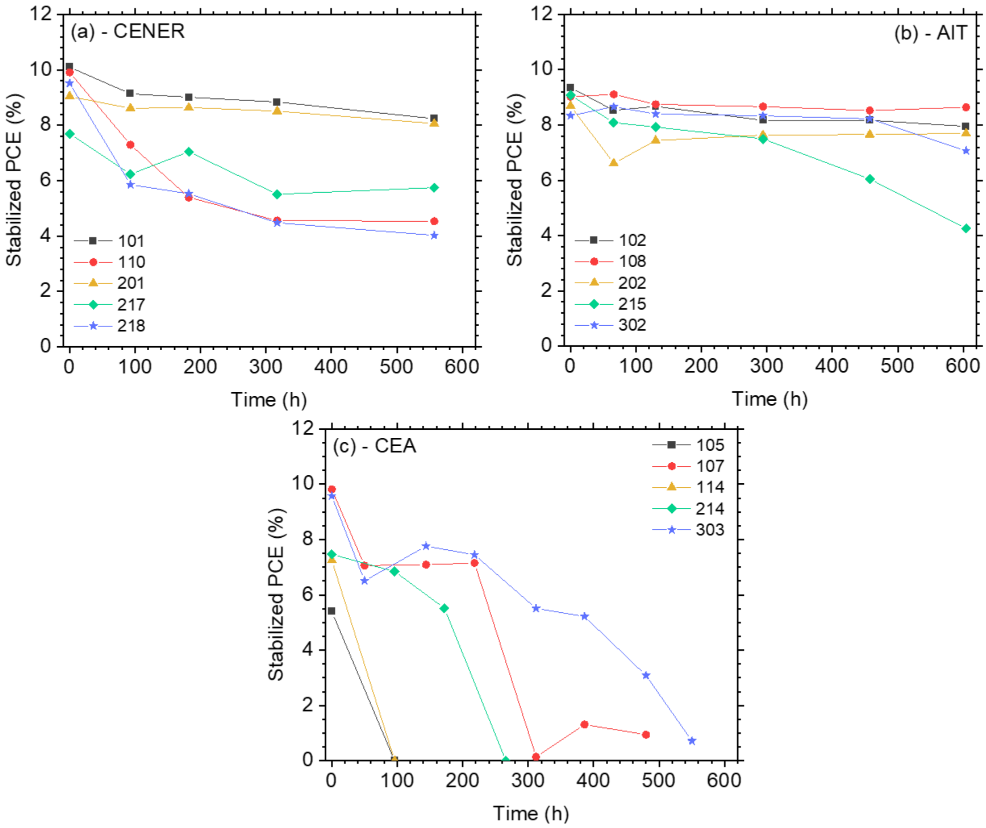

Figure 17. Evolution of PCE over more than 500 hours of damp-heat exposure.

- **Main conclusions and recommendations**
  - Regarding the sealing by hot vacuum lamination (sheet to sheet process the most used in silicon industry), the use of gas barrier encapsulant is recommended. It could be combined with edge sealant for long lifetime. If an edge sealant is used, ionomer can be replaced by less barrier materials (TPO, POE). The limit of temperature processing is related to the nature of the perovskite stack. The use of thermally sensitive layers as Spiro-MeTAD HTL make almost impossible the use of sealing materials which can be use in a hot vacuum lamination process and pass the damp heat test at 85°C.
  - Regarding the use of UV glue, some issues often occurs if the liquid glue is in contact with the perovskite stack. Such glue can be used as an edge sealant.

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- About the damp heat aging at 85°C/85%RH which the most standardized test regarding the resistance against humidity, it is important to maintain the samples out of liquid water, if not the results can be highly different.
- Regarding the thermal cycling test, in this study, we used thermo-sealed pouches to protect the devices during the aging in air. It is a way to have information about the resistance of the stack without interaction with encapsulating materials. Nevertheless, regarding the test, the most important is to use encapsulated devices considering the stress field is completely different in case of direct contact between the encapsulant and the active perovskite stack.

3 OUTDOOR

Outdoor aging has been performed with 2 types of cells, Solaronix cells with carbon electrode in the 2nd round robin (tested in HZB) and tandem Si/PVK from CEA (tested in CEA, HZB and CENER) in the 3rdround robin

- **Solaronix cells**

Regarding **Solaronix** cells, Cells are under MPP tracking in outdoor conditions in **HZB**. The measured output power of the cells follows the irradiance level, which is expected from the correctly connected cells and indicates accurate data processing. On sunny days, the outdoor measured PCE approaches ~10% that is close to the values measured in the lab, Figure 18. As could be expected from the damp-heat experiments described above, we observed a cell-to-cell variation in terms of stability against liquid water and water vapor. This observation translates quite well into the outdoor experiment, where 3 out of 4 cells found themself changing colour to grey and rapidly degrading immediately or a few weeks into the experiment. 1 out of 4 outdoor cells kept the black colour, likely indicating no encapsulation breakdown. That cell showed a comparatively slow decrease in PCE (8.2% -> 6.6%) in the first 3 months, according to the indoor STC measurements. However, "outdoor PCE" decrease on the same cell looks more dramatic going into the Spring period because this cell showed a very pronounced dependence on the irradiance (i.e. performs worse at higher irradiance, confirmed from indoor measurements). It is due to increased serial resistance related to the architecture with carbon electrode. There is likely also a contribution of the MPP tracking applied to these cells in the outdoor experiment, as HZB used a standard P&O algorithm with frequent adjustments, but the studied cells have very slow responses which results in much better performance under low light conditions.

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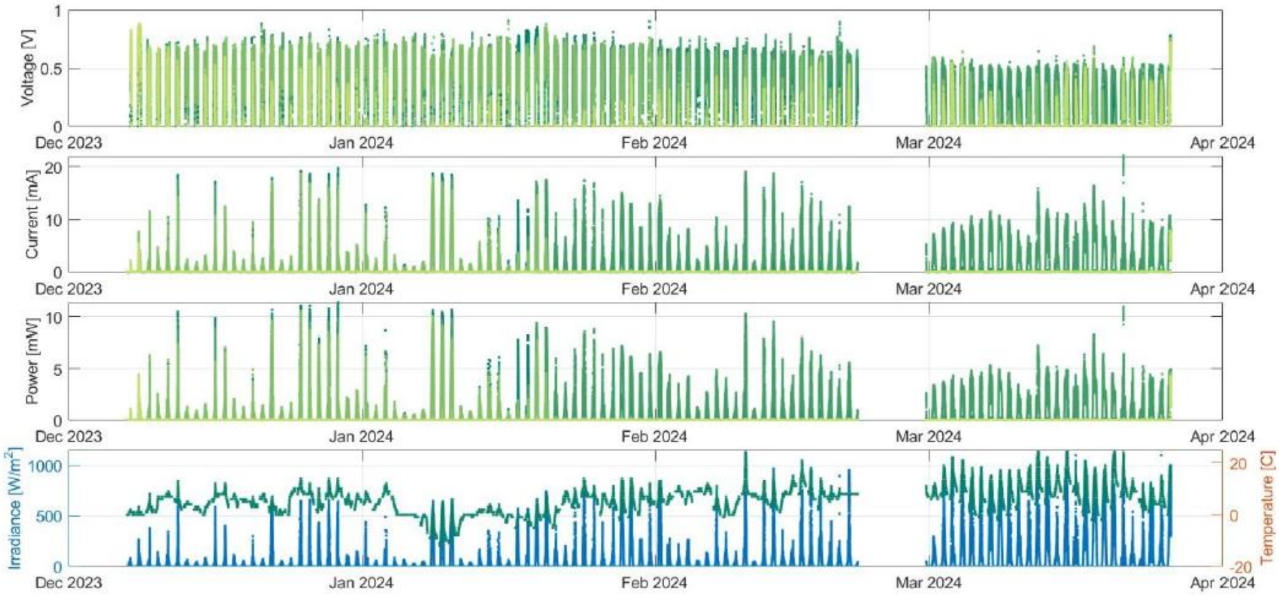

Figure 18: Overview of the electrical parameters (Solaronix cells) from outdoor platform in HZB

- **Tandem Si/PVK**

Each institute started the aging with 2 cells: 1 encapsulated with UV glue, 1 encapsulated by lamination. Outdoor aging has been conducted during different periods, the irradiance measurement along the aging is reported in Figure 16. The level of irradiance is clearly lower in HZB. During these experiments, the irradiance was globally more intense in CEA and CENER, Figure 19

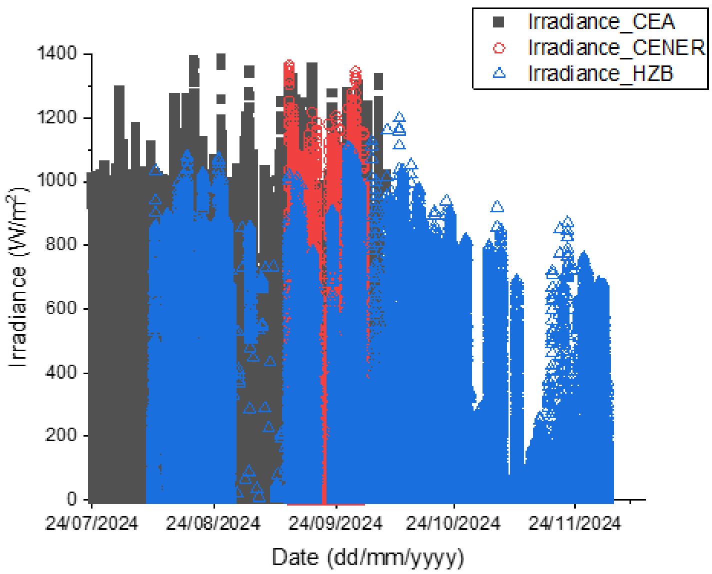

Figure 19. Irradiance data during aging.

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Regarding the outdoor data, we plotted the relative evolution of the P_{MPP} from CEA and HZB and the relative evolution of the voltage measured at a fixed load in CENER (close to V_{MPP}). The performances with time of cells glass encapsulated by UV polymerization (epoxy glue) and by hot vacuum lamination (polyolefin plus butyl edge sealant) are plotted in the Figure 20 and Figure 21 respectively. We selected the data with irradiance above 500/m².

The outdoor aging behaviour look better with cells encapsulated with UV glue. The degradation rate in HZB is slower, which is coherent with the lower irradiation. The degradation of cells is clearly related to irradiance/temperature, not to an insufficient protection against atmosphere and a weak encapsulation. We assume that the worst behaviour of cells encapsulated by lamination is related to a higher shunt resistance related to the lamination process (impact of pressure and temperature)

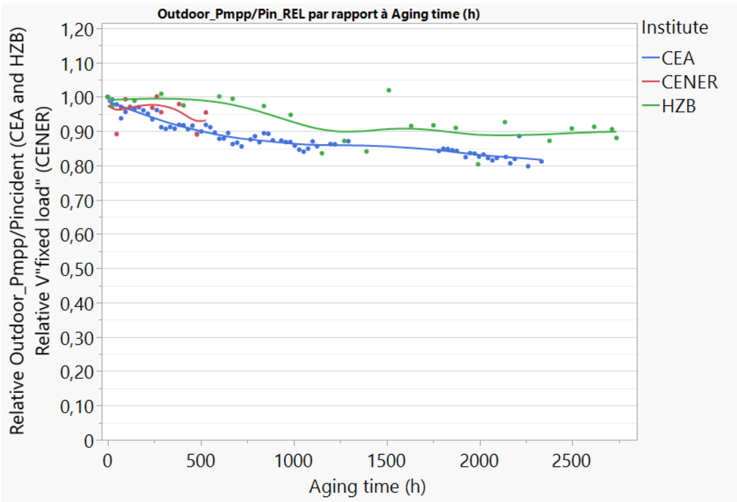

Figure 20. Outdoor data (relative $P_{mpp}/P_{incident}$ or $V_{\text{"fixed load"}}$) from CEA, HZB and CENER. Cells glass encapsulated with UV glue.

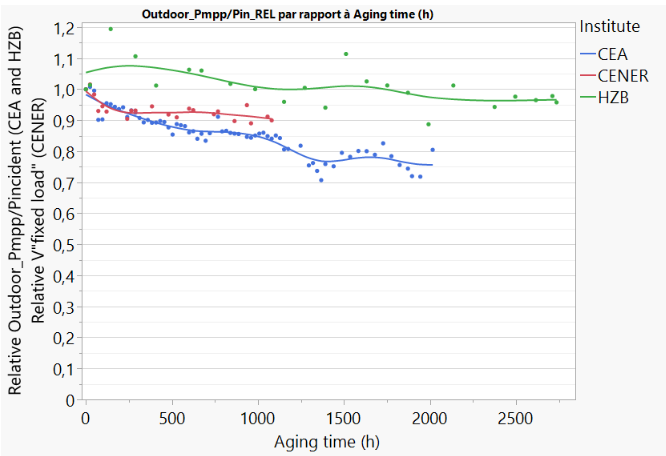

Figure 21. outdoor data (relative $P_{mpp}/P_{incident}$ or $V_{\text{"fixed load"}}$) from CEA, HZB and CENER. Cells glass encapsulated by lamination (polyolefin plus butyl edge sealant).

The indoor measurements of P_{mpp} and V_{oc} (relative) are reported in Figure 22 and Figure 23 respectively. CEA measured indoor only at the beginning and at the end of the aging. The better

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behaviour of glue encapsulated cells is clearly visible with Voc and HZB data. The recovery of these cells with light soaking was particularly important.

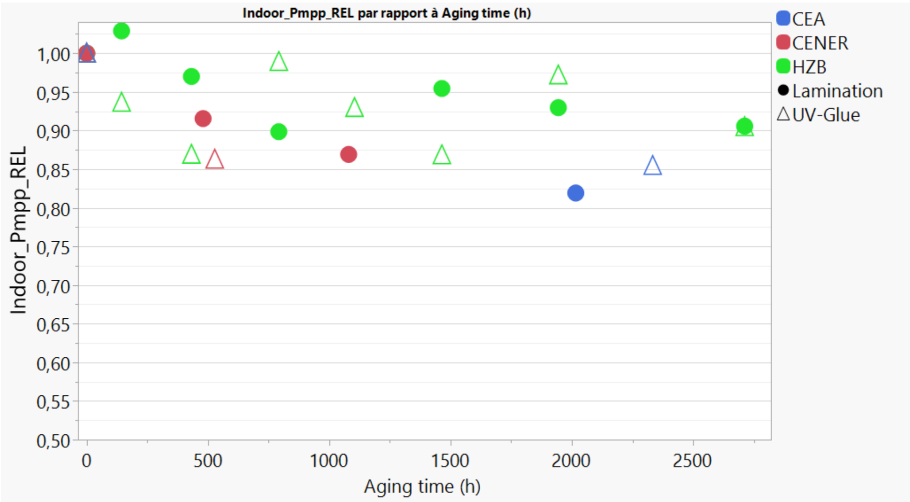

Figure 22. Relative P_{MPP} measured indoor.

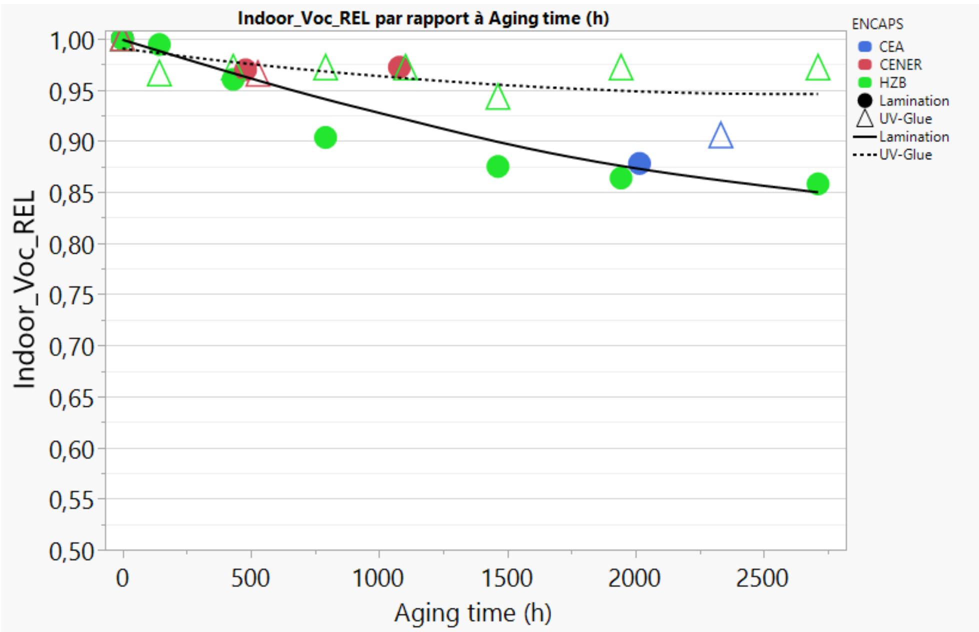

Figure 23. Relative V_{OC} measured indoor.

- **Main conclusions and recommendations:**

- Outdoor monitoring is crucial to understand the daily of perovskite based photovoltaic considering specific behaviour with light and thermal cycling
- The use of set up with maximum power point tracking is the most appropriate but the alternative fixed load can be implemented for a lower cost.
- The monitoring of irradiance and temperature is important. The position of the temperature sensor could be discussed and fixed.

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- Regular J(V) during aging is an interesting added value. It could be detrimental to have too many measurements, 1 or several times per day would be enough
- Regular indoor measurement of samples gives complementary information thank to the complete electrical measurement protocol. It also the opportunity to have look on the effect of light soaking and the eventual recovery of performances. Indoor measurement can be completed with PL and EL measurements (if non-destructive)
- The daily analysis of the outdoor data is also recommended, the shape of the output depending on the irradiance could highlight some degradation mechanism and low illumination issues.

3 GENERAL CONCLUSION AND RELATIONSHIP WITH STANDARDIZATION / HARMONIZATION OF PROTOCOLS

Beyond reviewing published protocols and standards, the Viperlab initiative, led by AIT, has highlighted key guidelines for stability studies, including ISOS, PACT, and emerging standards like IEC TS 62876-2-1:2018. These standards emphasize stress-specific evaluations that aim to complement existing frameworks, ensuring reliable lifetime predictions for perovskite-based photovoltaics. By addressing challenges associated with unique degradation mechanisms, these protocols enable harmonized performance assessments and robust long-term reliability tests for both single-junction and tandem perovskite solar cells under laboratory and outdoor conditions. A selection of these protocols and standards is presented in Table 3.

Table 3: overview of the most important recommendation or standardization initiative related to the stability (From Viperlab D4.6 deliverable).

Reference	Performance	Stability
Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures	X	X
IEC TS 62876-2-1:2018: Nanotechnology - Reliability assessment - Part 2-1: Nano-enabled photovoltaic devices - Stability test		X
IEC 61215-1:2021: Terrestrial PV modules - Design qualification and type approval - Part 1: Test requirements		X
IEC 61215-2:2021: Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 2: Test procedures		X
PACT Module Protocols	X	X

The “Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures[4]” aim to unify testing protocols applied to perovskite cells when assessing the long-term stability of lab-scale devices. These guidelines also include a comprehensive checklist for reporting results from perovskite stability studies more consistently. In the next table, we listed some key accelerated aging conditions from ISOS recommendations for which we can make further comments related to the round robin experience or some recent studies in literature.

[4] M. Khenkin & al; Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures, Nature Energy, VOL, January 2020, 35–49

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Table 4: Some ISOS aging conditions

ISOS-protocol	Light condition	Temperature	Atmosphere	Load
ISOS-D-3	Off	85 °C	85%RH	OC
ISOS-T-3	Off	-40°C/+85°C	Low	OC
ISOS-L-2	Constant	65, 85 °C	Ambiant	MPPT
ISOS-LC-2	Cycled	65, 85 °C	Ambiant	MPPT
ISOS-LT-1	Cycled	cycled: RT to 65 °C	Ambient	MPPT

OC stands for open circuit, RT for room temperature.

The condition **ISOS-D3** is similar to the test used in Silicon PV with modules. Beyond the evaluation of the resistance against atmosphere provided by encapsulation, this test, as the **ISOS-T3** (thermal cycling), will be crucial to identify possible mechanical issues related to the coupling of encapsulant with perovskite stack considering this latter could suffer of specific weak interfaces or particular sensitivity to chemical species included in encapsulation materials.

Another important point is the evaluation of the behaviour with light and the combination of light with temperature. This point looks to be well understood to predict the outdoor behaviour and then prove long lifetime, beyond 25 years. This point was specifically studied in Viperlab (deliverable by UNITOV). Therefore, by leveraging high-temperature[5] (up to 85°C) and illumination conditions (1.2-sun) in controlled indoor environments, the researchers were able to simulate and predict the degradation patterns observed in six-month outdoor aging tests. This approach allowed the identification of key degradation mechanisms, particularly the impact of combined light and heat stress on device stability. The results showed that devices aged at 85°C degraded 40 times faster than those aged at 25°C, demonstrating the effectiveness of indoor tests in mimicking real-world outdoor conditions. This point highlights the important of testing **ISOS-L-2** condition. Another point we can promote is the presence of the encapsulation, it makes easier the implementation of the test (no need of inert atmosphere) and it is closer to real life in which encapsulation could influence the intrinsic degradation mechanisms (bye products, reversible mechanisms…).

Another recent study[6], based on this outdoor measurement analysis and indoor light cycling stability tests, highlighted the effect of climate conditions on outdoor operational lifetime. It is suggested that ambient temperatures induce a more significant effect than the irradiance. The study also suggests different roles played by the temperatures during the diurnal light versus dark periods: the day/ light time maximum temperatures have a more significant effect on the long-term degradation. In contrast, minimum temperatures during the night/ dark cycles significantly affected the diurnal reversible degradation and the initial fast degradation. This study could push thinking about **ISOS-LT** conditions in which we could adapt the temperature of each cycle in order to reproduce outdoor seasonal and climatic variation.

[5] Jiang et al. Nature. 623 (2023), 313
[6] Ritesh Kant Gupta & al., Adv. Energy Mater. 2024, 2403844

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It is also interesting to note that it has become possible to predict outdoor characteristics based on accelerated indoor stress tests and Machine Learning (ML) models. By using ML[7], a model achieves a low mean squared error of 0.24 in predicting outdoor degradation behaviour. By correlating indoor testing conditions, such as 1-sun illumination in nitrogen, with real-world environmental stresses, the study identifies the most relevant factors influencing PSC performance. The approach proved robust across different climates, including Mediterranean and desert conditions, with predictions accurate within one order of magnitude even for data from external laboratories. Wavelet transformations were employed to enhance the analysis of time-series data, effectively capturing complex degradation patterns. This innovative method reduces stability testing times from months to just days, offering a practical and generalizable solution for accelerating the development of PSCs and other photovoltaic technologies, making it a valuable tool for researchers and manufacturers.

Regarding stability and outdoor testing, we can also highlight the PACT initiative with the Stress Testing Protocol (Version 0.3 June 2024), Figure 24.

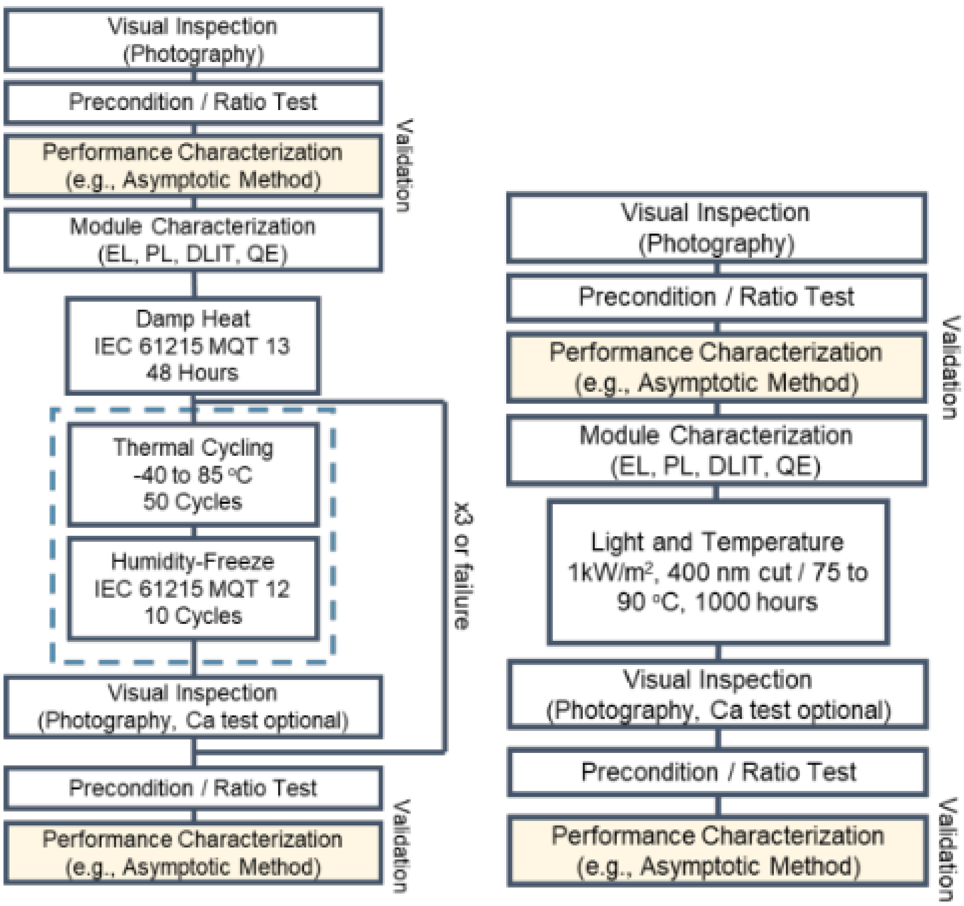

Figure 24. Test flow for examination of the package impermeability(left) and light and elevated temperature supplement stress test (right).

[7] Kouroudis, & al., ACS Energy Letters 9, 1581 (2024).

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The purpose of this protocol is to use accelerated stress testing to assess the durability of metal halide perovskite (MHP) photovoltaic (PV) modules. In its current form, the protocol aims to cover two aspects:

1) To apply field-relevant stressors to packaged MHP modules to identify early failure mechanisms which can be correlated to field-stressed modules of the same type.
2) Provide a minimum recommendation of the accelerated stress testing that may not be captured by existing standards such as IEC 61215.

This protocol still needs to be validated before it can be adopted more generally and will likely be adjusted as more data is collected. All test parameters and durations will be optimized according to field data collected on sister modules. PACT anticipates updating this document and protocol bi-annually with supporting data and modified procedures.

At another hand, the PACT Perovskite PV Module Outdoor Test Protocol) Version 0.1 May 2023) define procedures and practices to be used by the PACT centre for field testing of metal halide perovskite (MHP) photovoltaic (PV) modules. The protocol defines the physical, electrical, and analytical configuration of the tests and applies equally to mounting systems at a fixed orientation or sun tracking systems.

While standards exist for outdoor testing of conventional PV modules, these do not anticipate the unique electrical behaviour of perovskite cells. Furthermore, the existing standards are oriented toward mature, relatively stable products with lifetimes that can be measured on the scale of years to decades.

The state of the art for MHP modules is still immature with considerable sample to sample variation among nominally identical modules. Version 0.1 of this protocol does not define a minimum test duration, although the intent is for modules to be fielded for periods ranging from weeks to months. This protocol draws from relevant parts of existing standards, and where necessary includes modifications specific to the behaviour of perovskites.

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