Enabling reliability assessments of pre-commercial perovskite photovoltaics with lessons learned from industrial standards

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Abstract

Photovoltaic modules are expected to operate in the field for more than 25 years, so reliability assessment is critical for the commercialization of new photovoltaic technologies. In early development stages, understanding and addressing the device degradation mechanisms are the priorities. However, any technology targeting large-scale deployment must eventually pass industry-standard qualification tests and undergo reliability testing to validate the module lifetime. In this Perspective, we review the methodologies to assess the reliability of established photovoltaics technologies and to develop standardized qualification tests. We present the stress factors and stress levels for degradation mechanisms currently identified in pre-commercial perovskite devices, along with engineering concepts for mitigation of those degradation modes. Recommendations for complete and transparent reporting of stability tests are given, to facilitate future inter-laboratory comparisons and to further the understanding of field-relevant degradation mechanisms, which will benefit the development of accelerated stress tests.

Introduction

Abundant solar resources, lower module prices and increased efficiency bode well for a continuously increased contribution of photovoltaics (PV) in the world's energy portfolio. However, photovoltaic installations for large-scale power generation still involve large outlays of capital. Importantly, the levelized cost of energy (LCOE) does not only depend on the PV module efficiency and its initial cost but also on the performance of the PV installation over its lifetime, with LCOE increasing as system performances degrades[1]. Therefore, assessing and rating the reliability of PV modules in various climates and mounting configurations remains crucial to ensure investor confidence, electricity production and low maintenance costs. In addition, drive for cost reduction, the evolutions of commercial PV technologies (such as thinner and more environment-sensitive absorbers) and of the range of use environments can lead to more failure modes. These evolutions necessitate an increased attention to reliability.

International committees have been developing standardized qualification tests, to measure and benchmark the reliability of commercial PV technologies such as Si and thin-films modules. In particular, a suite of International Electrotechnical Commission (IEC) standards are widely used to "qualify" PV modules, that is, to provide a series of pass/fail tests that set a basic standard of quality. In this Perspective we refer specifically to the IEC 61215 standard (the terrestrial photovoltaic (PV) modules – design qualification and type approval[2]) as the qualification test.

In order to go beyond what commercially available PV technologies offer, various pre-commercial photovoltaic concepts are attempting to provide alternative operation or integration routes. For example, the main advantage of organic photovoltaics is the processability on light-weight flexible substrates at a reasonably low cost, offering a broad range of applications such as for automotive and building-integrated PV.[3] Metal halide perovskites, such as archetypical $CH_3NH_3PbI_3$ ($MAPbI_3$), are newer entries to the PV research and early stage technology communities.[4-6] With multi-junction approaches, perovskites promise to deliver higher efficiency than existing commercial thin-film and silicon PV, either by stacking perovskite solar cells (PSCs) with different band gaps on top of each other, or by stacking a wide-band gap PSC on top of a narrower band gap Si or copper indium gallium di-selenide/sulphide (CIGS) solar cell.[7] The manufacturing costs for perovskites modules are also expected to be lower than 35 $\$/m^2$.[8,9]

In the early stages of development of novel PV technologies, the emphasis is on identifying critical degradation mechanisms in laboratory conditions and associated failure modes that may occur in the field. Eventually, this understanding feeds cross-community collaborations that develop standardized testing protocols. The International summit on Stability of Organic Solar cells (ISOS) has had an effective role in the standardisation of stability measurements for organic PV research.[10] The perovskite research area has not reached the maturity stage necessary for standardization yet, as metal halide PSCs and modules have only been investigated in earnest for the last six years. While there are already considerable efforts to understand perovskite degradation mechanisms and device "infant mortality",[11-15] it is becoming clear that a broad range of (non-standardized) stressing protocols are applied, often without a clear understanding of what these experiments are aiming to reveal. There is a need for the community to consider how to move toward consistency, physical relevance, and standardization of reliability assessments.[16,17]

In this Perspective, we hope to inform future developments of standardized tests and to achieve a common frame of reference among the communities working on the reliability of various PV technologies, both commercial and pre-commercial. We first review the development of standardized qualification tests for commercial PV module reliability including their shortcomings and failures. We show how stress tests can reveal material, cell, and module degradation mechanisms and can be used to extract module lifetimes. We then discuss published stability studies of pre-commercial PSCs, and highlight key stress factors and the associated degradation mechanisms. We finish by highlighting the stress factors that should be described when reporting laboratory-based stability measurements of PSC, in order to make fair comparisons between different device architectures and tests undertaken in different laboratories.

Development and shortcomings of qualification tests

Hoffman and coworkers laid out an approach to developing qualification tests for flat-plate terrestrial PV modules in 1982.[18] It is a learning-cycle process that starts with the identification of environmental degradation mechanisms that lead to the failure of field-deployed modules. The stress factors, such as the atmosphere composition, humidity and temperature, and stress levels (for example, the temperature value, light intensity and its spectral composition) required to replicate the failure are defined to form a stress test. This step is sometimes accompanied by modelling. Stress tests and models are then validated against field results. Revised module designs are developed and stress-tested for the previously encountered failure modes, with recurring field checks. As confidence in the stress tests becomes clear, they are incorporated into standardized qualification protocols.

However, in practice, the sequences of stress tests that appear in the qualification test were developed for a subset of the observed failure modes. Inclusion of the corresponding tests depends on the module manufacturing community's ability to understand the degradation mechanism and to meet the test requirements, the costs in time or money to implement it, and industry pushback when technical solutions to the degradation mechanism are not at hand. For example, the effect of high system voltage stress (now known as potential induced degradation, PID) has been known since 1978,[19] but its inclusion into standardized tests has been delayed until 2015; as has the testing for irreversible shunting defects due to shading in most module types outside of Si-based modules.[20]

Largely due to time and cost, standards for application of field-relevant ultraviolet (UV) light exposure of modules are also missing as of today, in spite of the degradation effects being well-known by the community.

Another shortcoming of standardized qualification tests is that that they largely originate from work on silicon-based cells and modules (both crystalline silicon and to some extent amorphous silicon, a-Si), whereas in practice degradation rates for different cell and module technologies under a given accelerated stress level differ. As a result, some PV technologies require longer or shorter stress tests to evaluate the effects of a given stress factor. For example, a conventional crystalline Si cell encapsulated using a polymeric backsheet experiences moisture ingress quickly in the field and in the damp heat chamber because these typical backsheets are not moisture barriers. In contrast, in a glass-glass module with edge seal performing as a moisture barrier, it takes more than 3000 h at 85°C, 85 % RH condition to test for moisture ingress that would occur in 25 years in the Miami environment.[21] Therefore, consideration of the actual absorber materials and module designs is necessary to design reliability testing procedures (see for instance Box 1), but is not considered in current standardized qualification tests.

Finally, it should be clear that a qualification test is not a quantitative prediction of the module lifetime; the pass/fail nature of the test does not provide much resolution for purchasers of modules. The qualification test is rather a necessary “ticket” for a module vendor to enter negotiations for large volume sales. Often, extended stress tests or comparative tests, which go well beyond the qualification tests, are requested.[22] These involve exposure of modules to several times the IEC qualification test criteria and measurement of the degradation intermittently over the course of the testing. It is however necessary to interpret any observed degradation or failures for significance, to avoid either missing potential future field failures, or to the contrary, instituting unneeded expensive solutions to artefacts from extensive tests.[23]

Box 1. Designing accelerated tests for water ingress degradation

To evaluate the service life of flexible superstrate of CIGS modules considering the degradation mechanism of moisture ingress, the effect of humidity as a stress factor was examined on multiple CIGS cells. Three degradation processes are thermally activated and can be described using activation energies: the degradation of the cell itself and of the electrical interconnection adhesive ($E_{a,deg}$), the moisture solubility in the encapsulant ($E_{a,S}$) and the permeability of moisture through the encapsulation ($E_{a,perm}$). Based on these processes working in tandem, an acceleration factor (A) can be calculated to describe the ratio between lifetime under characteristic use conditions L_u (temperature T_u and relative humidity RH_u) and the lifetime under the accelerated stress condition L_a (at T_a and RH_a).

$$A = \frac{L_u}{L_a} = \exp\left(\frac{E_{a,\deg} + E_{a,perm} - E_{a,S}}{2R}\left(\frac{1}{T_u} - \frac{1}{T_a}\right)\right)\left(\frac{RH_a}{RH_u}\right)^{\frac{1}{2}}$$

This model for degradation by moisture ingress was validated in damp heat chamber tests and in the field, and allows to predict degradation rates of several CIGS module types.

In the future, complete validation for resistance to moisture ingress must not only consider the laminate, but edges, interfaces (which may weaken under stress), and wire penetrations. Further, moisture ingress through the edges can increase the sensitivity of cells to system voltage stress (PID).[24] Standards for evaluating electrical properties, adhesion, and moisture ingress through edge seals are at their nascent stages.[25]

Box 2. Forecasting optically-induced degradation

Many types of PV modules degrade when they are exposed to light. Photons of higher energy, such as those in the UV range, can break chemical bonds in the polymeric encapsulant and in the photovoltaic absorber layers. Identifying these light-induced physical reactions as a function of wavelength is required to understand the device degradation and to establish light-source requirements for accelerated testing. Band-pass filters are used to examine degradation in polymeric materials as a function of incident wavelength.[26] In absence of wavelength-specific information, light sources simulating the solar spectrum should be used. A given amount of degradation is described by Schwarzschild law, where $t(I)^{p}$=constant, with time t, irradiance I, and exponent p. If expressed as a degradation rate k, the law is written as k=A$(I)^{p}$, where A is a proportionality constant depending on the material system. In a study of 50 polymeric encapsulants, the exponent p was found on average to be 0.64 with large standard deviation of 0.64.[27] Optically-induced degradation is closely linked with thermally activated processes, including diffusion of reactants and products; therefore, increasing temperature leads to an increase in light-induced reaction rates. For example, the "yellowing" degradation of the polymeric backsheet in ref. 35 occurred for wavelengths < 360 nm (3.44 eV) with a thermal activation energy of 0.42 eV (these values of course depend on the material under study).

In many PV absorbers, defects are created by UV light irradiation causing increase recombination losses. For example, hydrogen-terminated Si bonds that normally passivate a-SiN_x:H coated cells can be broken by UV light – this phenomenon has been associated with solar cell degradation for energies above that required to break this H-bond, between 3.34 and 3.5 eV.[28] The light-induced degradation mechanism depends on the absorber, so the mechanism and rate equations must be evaluated on a case-by-case basis. For example, in a study on crystalline Si solar modules, the number of non-passivating bonds N_{NP} increases as a function of time t_{UV} under UV light:

$$N_{NP} = N_T - N_{P0}\, exp(-\sigma_{UV}(\lambda)\phi_B t_{UV})$$

where $\sigma_{UV}(\lambda)$ is the capture cross section for a photon of wavelength λ, ϕ_B is the photon flux of energy capable of being absorbed that is incident on the material, N_T is the total number of bonds, and N_{PO} is the initial number of non-passivated bonds before exposure to light.[28] Considering the most energetic and therefore damaging photons are primarily absorbed toward the front surface, the recombination current density at the front surface J_{os} is

$$J_{0s} = qN_{it}v_{th}\sigma_p \frac{n_i^2}{n_s}$$

Where q is the electronic charge, N_{it} the interface states density, v_{th} the thermal velocity, and σ_p is hole capture cross section (hole being the minority carrier in an n^+ emitter). n_i and n_s are the intrinsic and surface charge carrier concentrations, respectively. The device open circuit voltage V_{oc} and photocurrent density J_{sc} are related to the recombination current via the Shockley diode equation and hence to the number of non-passivating bonds.

Appropriate encapsulation can cut off energetic UV photons and can be used to mitigate optical degradation.

Stress factors and their known effects on PSCs

Figure 1: Perovskite Solar Cell Structure. *Efficient PSCs comprise an anode (e.g indium tin oxide), an optional "buffer layer", an electron selective charge extraction layer (n-type layer), a polycrystalline perovskite absorber layer (typically intrinsic in charged state), a hole-selective charge extraction layer (p-type layer), an optional buffer layer, and a cathode. (a) Cross-sectional scanning electron microscopy image (SEM) of an example of such a cell taken from ref. 38 and (b) annotated diagram cell. In some embodiments a thin mesoporous scaffold (typically* TiO_2 *or* Al_2O_3*) infiltrated with absorber material is present between a charge extraction layer and the polycrystalline absorber layer. If we include the anode, cathode and buffer layers, there are seven different materials in a PSC, with 6 internal material interfaces.*

Typical PSC can comprise up to seven material layers (Figure 1). Any of these materials may degrade, and even materials whose intrinsic degradation mechanisms have been contained may induce a failure mode when contacted to new materials. Below we discuss several stress factors used so far in failure mode analysis for PSCs. We also discuss the related known failure modes for PSCs along with the relevant solutions presented so far (Table 1).

Solar light and UV stresses

In an inert atmosphere or when sealed, $MAPbI_3$ perovskite absorber material is relatively stable, even when exposed to simulated sun light.[4] However, under full solar spectrum light exposure, the charge extraction layers can induce degradation: TiO_2 and ZnO are typical n-type charge extraction layers and reduce their oxygen stoichiometry under UV illumination. This creates a large density of electron traps which reduces the short-circuit current of the PV cells.[29] This process has been observed to be partially reversible.[30] Other n-type charge extraction materials,[31,32] can be used to overcome this UV-induced extraction layer degradation**.** A notable yet-to-be-understood exception to this degradation mechanism is the "triple layer cell" which comprises porous TiO_2-porous zirconia and porous carbon as the charge transport layers, all infiltrated with perovskite that contains aminovaleric acid.[33]

In a recent study, researchers argue that a UV filter could be employed in commercial PV modules, making the question of UV stability obsolete and compare the accelerated degradation of solar cells containing mesoporous TiO_2 under a xenon lamp light source (which contains UV), and under an LED light (which does not contain UV), with the prior exhibiting slightly faster degredation.[17] As we describe in Box 2 for silicon PV, the critical UV wavelength which results in degradation of the hydrogen-passivated surface is between 350 to 370nm. In commercial PV modules, polymer encapsulant foils cut-off UV-light transmission below 300 to 390 nm, depending upon the precise foil used,[34] so using up to 390 nm cut-off filter to assess PSCs degradation in laboratories is indeed justifiable. However, for any light filtering at longer wavelengths than 390 nm, the UV absorbing material requires rigorous assessment for stability itself. Indeed, while foils are now stable against light-induced degradation, yellowing and delamination have been serious challenges in the past[35]. The precise wavelength of UV sensitivity needs investigating, but the safest option is to adapt the solar cell materials or design to minimize UV instabilities.

How the cell or module is loaded electrically during any test may affect any degradation processes which is being monitored.[17] Therefore understanding the influence of electrical load upon degradation rates under illumination is important.

Atmosphere composition

Under pure oxygen atmosphere, the degradation of the $MAPbI_3$ absorber layer stressed at 85 ˚C in the dark is not significantly accelerated compared to similar thermal aging in nitrogen.[36] However, a combined effect of oxygen and supra-band gap illumination has been observed to induce a very rapid degradation in $MAPbI_3$.[37] Reactive superoxide generation at the perovskite surface drives the degradation, and requires both electrons in the perovskite and atmospheric oxygen. This failure mode appears to be less problematic when MA is substituted by formamidinium (FA), as inferred from relatively good air-ambient stability under full spectrum illumination.[31,38]

Humidity is also a key degradation factor, as lead halide perovskite crystals can become hydrated.[39] This hydration process is reversible; however, the hydrated perovskite has poor thermal stability and can decompose irreversibly within hours, particularly in the presence of supra-band gap illumination. This clearly shows that, in order to understand the relevance of IEC damp heat tests (85˚C/85% RH) to predict the 25 years operational stability for perovskite modules, combined stress factors, such as light, temperature and humidity, need to be investigated experimentally and complemented by careful modelling (see Box 2 for the example of CIGS modules).

Interfacial material reactions

The organic p-type extraction layers usually require partial chemical oxidization in order to increase their hole-conductivity. The ionic additives can react with the perovskite absorber layer.[40] Devices employing additive-free organic extraction layers are starting to make good progress.[41,42] Replacing the organic hole-conductors with more thermally stable inorganic hole-conductors has progressed with mixed success. For example, copper thiocyanate (CuSCN) can be employed in PSC and delivers respectable efficiencies.[43] However, an interface reaction between $MAPbI_3$ and CuSCN, appears to produce CuI and MA-SCN, inducing rapid degradation.[44] CuSCN has also been observed to react with metallic electrodes, but this appears to be resolved by adding an additional inter-layer of reduced graphene oxide.[45] Carbon nanotubes are another potential more stable alternative to organic hole-conductors.[40] For PSCs constructed in the "p-i-n" configuration, NiO has proven to be a good p-type material for high efficiency,[46] and longer term stability,[47] but detailed investigations of reactions at this heterojunction have not yet been undertaken.

Temperature

$MAPbI_3$ possess low thermal stability, with degradation accelerated in the presence of moisture and supra-band gap light.[11] Of significance, decomposition has been observed in an inert dry atmosphere at 85°C, even in the dark, indicating that the absorber would decompose even with "perfect sealing" from atmosphere. One route to inhibit the thermal decomposition is to coat the films with layers that have a low permeability to the degradation products (methylamine, hydroiodic acid).[48] A second route is to use all-inorganic caesium (Cs) lead trihalide perovskites, which are thermally stable up to 400˚C.[49,50] However, the lower bandgap iodide-rich Cs-compounds have a room temperature structural instability. The third solution is to form an FA-based perovskite, and specifically a FA-Cs based mixed cation perovskite, which appear to be thermally stable at 130˚C and also structurally stable.[51,52]

Importantly, heat accelerates other degradation mechanisms, for example temperature ingress described in Box 1 for CIGS PV. It is also the major factor in many degradation mechanisms of encapsulation materials, such as the oxidative degradation of polymers used in encapsulants and backsheets.[53] In the qualification test, full PV modules are tested under combined heat and humidity stresses for 1000 h (85°C and 85% relative humidity, known as the damp heat test).[2] Following IEC 61215,[2] temperature cycling is usually performed between -40°C and 85°C for 200 cycles, but there is consensus that higher temperature or more than 500 cycles are preferable to evaluate for a 25 year service life, specifically for stress testing of solder bonds.[54] Natural environments with high temperature (i.e. ambient above 30 °C) also yield a faster onset of thermomechanical fatigue failures. Some examples of thermal cycling tests and other environmental stress tests of PSCs using various encapsulants and edge seal materials can be found in the literature.[55,56] Some thermal cycling studies reveal degradations induced by the mechanical expansion mismatch between the perovskite absorber material and the lamination foil material.[57]

Other stress factors

In many PV technologies, degradation can arise from electrical stress. For example, a large electrical potential difference between the cell circuit and the ground, which can be over 1000 V in a string of modules, leads to potential induced degradation (PID) in silicon, CIGS and CdTe solar cells, involving mechanisms that differ depending on the cell type. It is generally of concern when one or both encapsulant of the module is glass, because Na ions can drift through it and cause high levels of electric field build-up in regions of the cell.[58] In PSC, potential degradation mechanisms in various bias configurations must be studied and understood (load, open-circuit, short-circuit) when glass or similar materials with mobile ions are used for encapsulation. In addition, mobile ionic species in the perovskite absorber layer represent an unknown for long term stability. Recently, partially reversible degradations of PSCs under reverse bias have been observed and identified to originate from these mobile ionic species from within the perovskite absorber.[59] This situation occurs in PV modules when a cell is partially or completely shaded, where some cells in the module are driven into reverse bias.

Mechanical loading in the qualification test is performed with the static load test (minimum 2,400 Pascal (Pa), that scales with the expected load of the module), and cyclic (dynamic) mechanical loading with 1000 cycles of positive and negative 1000 Pa pressure.[2] A bend test for flexible modules (25 cycles) is under consideration.

There are currently no commonly applied standardized qualification tests for mechanical wear (such as erosion due to blown sand), soiling, and pollution, though evaluations are being performed for the development of future standards.[60] Finally, since stress factors frequently work together or in sequence to cause degradation mechanisms that are seen in the field, work is under way to develop protocols with multiple stress factors applied together and in sequences.[61]

Table 1. Different light soaking and thermal stressing protocols for PSCs, indicating which degradation mechanism these test for and what potential solutions have emerged so far. For these stress tests, the cells or materials can be tested without external encapsulation, or with partial or complete module level encapsulation. When degradation is observed under any stress test, evaluation for field relevance should be considered.

Stress Test	Atmosphere	Temp	Stress Factor(s)	Degradation Mechanism(s)	Candidate solution(s)
Light Soak (no UV) Under load, open-circuit or short-circuit	Inert	RT	Photogenerated charge induced and internal electric field induced	Ion and defect migration	a) Improved crystallinity and improved optoelectronic quality (fewer defects).
	Inert	60 or 85 ˚C	Charge + Thermal	Decomposition of perovskite. Detrimental changes to charge extraction layers	a)+ b) Move to Formamidinium (FA) or Cs cations and/or c) 2D/3D perovskites. d) Thermally stable extraction layers.
	Dry, Air or Oxygen	RT	Charge + Oxygen	Superoxide generation and degradation (precise mechanism remains uncertain)	a, b or c + e) employ protective charge extraction layers to inhibit oxygen ingress. f) Inhibit escape of degradation products by "sealing in" with subsequent layers.
	Dry, Air or Oxygen	60 or 85 ˚C	Charge + Oxygen+ Thermal	Superoxide and thermal degradation	a, b, c, d, e and f.
	Air (ambient or high humidity)	RT, 60 or 85 ˚C	Charge + Oxygen + Thermal + Humidity	Hydration and degradation of the crystal + Thermal acceleration	a-f + g) more hydrophobic surface treatments and charge extraction layers
UV light soak	Inert, dry air or oxygen or humid air (85%RH)	RT, 60 or 85 ˚C	UV induced+ Charge + Oxygen + Thermal + Humidity	Changes to the n-type metal oxides (TiO_2, ZnO, SnO_2). Photoionization, degradation of organics. + All of the above for charge, oxygen, humidity and thermal.	a-g + h) Move to stable organic n-type or more stable oxides such as $BaSnO_2$. i) Assess UV changes in organics and choose most stable charge extraction material.
Thermal stress (Dark)	Inert, ambient air or high humidity (85%RH).	85 ˚C	Thermal, Oxidization, Hydration	Decomposition of perovskite, de-doping or organics. Chemical reaction between different materials, thermomechanical fatigue, delamination	j) Assess stability of individual materials and combinations of materials for structural, mechanical and electronic degradations. Select appropriately stable materials.
Thermal Cycling	Dry air or 85% RH	+85 to -40 Degrees	Expansion and contraction stresses + Thermal + Phase changes+ Encapsulation	Delamination of active layers in device stack, thermal degradation, phase transitions of perovskite into non-favourable yellow phases. Failures in encapsulation methodology.	k) Tune perovskite absorbers, as to not suffer from phase changes within the temperature range. l) Ensure good mechanical adhesion between layers. m) Develop appropriate encapsulation strategy, including close matching of expansion coefficients.
Voltage	Inert, dry air or 85% RH	RT, 60 or 85 °C	Humidity, electric field between the exterior surfaces of the module and active cell circuit.	Ion formation and drift (with conventional PV, usually through glass), electrochemical corrosion, loss of adhesion, Unknown role of mobile ionic species within perovskite absorber layer.	a-f + n) minimise mobile ionic species density in all semiconducting layers and packaging. o) introduce ion-blocking layers. p) Employ highly electrically insulating packaging and mounting.

A common approach to stability investigations

Stress tests should be designed to reproduce the failure modes that would emerge under real world operating conditions and should assess if any given change to the cell design or material set has modified the likelihood of a failure mode emerging. There is limited benefit of performing stress tests that do not represent the stress factors in the natural or intended use environment. An example of this is measuring how long a solar cell will last stored in the dark, in a nitrogen atmosphere or in air. While these “shelf-life” tests may indicate the existence of a failure mode when degradation is observed, they do not indicate any substantial level of stability in the natural environment if degradation is not observed. Additionally, there is limited benefit in stressing a PSC under a light source which does not contain a UV component in a completely inert atmosphere. In the presence of oxygen, light soaking without a UV component does accelerate PSCs degradation (superoxide generation mechanism). Light soaking with a UV component, or a specific UV exposure test, is more likely to test for key failure modes induced by long-term exposure to sunlight.

Temperature alone can induce thermal decomposition of perovskites, and 85 ˚C or even higher thermal stress tests investigate for such failures. Furthermore, by definition, temperature accelerates thermally activated degradation mechanisms. For Si PV cells, a typical degradation “acceleration factor” is ~ 2 fold for a 10 °C temperature rise, depending upon precisely which failure mode is being investigated.[62,63] There is a clear requirement to assess the activation energy for the various failure modes in PSC. If PSCs degradation mechanisms were to have similar activation energies to those responsible for degradation in silicon, then the difference in degradation rate between stressing at for instance 85 ˚C and 40 ˚C is $2^{4.5}$, that is over 20 fold, which is important to consider when comparing between different reports.

Developing materials and methodologies for the effective encapsulation of PV modules is an industry in its own right, and much effort is on-going to improve encapsulation of commercial PV modules. It is difficult to seal regions where electrical contacts are made. In most commercial modules the charge conducting ribbons are extracted through a small hole in the rear of the module, which can be subsequently sealed. Extracting current through thin edge seals presents challenges and can be prone to failure. However, there is still value in sealing small cells to make comparative assessments of different solar cell materials or designs under different stress conditions. In addition, as we describe in Box 2, investigating non-encapsulated cells can be of great utility for probing failure modes and understanding degradation rates.

The perovskite research community partly overlaps with the organic PV community and can benefit from the presence of ISOS. In particular ISOS may be the appropriate forum to specify a set of standardised test protocols for PSCs for a certain range of applications outside of general use environments.[10] However, as long as perovskite PV technologies seek to compete with main-stream utility scale PV, we believe that it is most useful to adhere closely to the IEC international standards for reliability testing, since this will be most convincing to the existing PV industry.

PSCs may not yet be mature enough in their development to set standardized test protocols. However, we believe that the community would benefit from transparent reporting of stress test conditions. This would accelerate understanding PSC degradation mechanisms and would enable quantitative comparisons between research reports. In Table 2, we highlight the stress factors identified as being crucial for PSC degradation, and whose value should be given in scientific studies. We also provide stress level ranges, which we currently believe to give a fair indication of the severity of stress test, considering both known PSC degradation mechanisms and known environmental conditions in the field. This table is expected to expand as new failure modes emerge, for example to include reverse bias stability factors and physically relevant levels of reverse breakdown voltages.[59]

Table 2. Important stress factors for PSC light soaking and thermal stability. We propose this to be used as a checklist to ensure all stress factors 1-4 are clearly reported in scientific studies of PSC degradation. Increasing UV component in the illumination spectrum, increasing temperature, increasing oxygen content in atmosphere and increasing humidity all lead to an increase in the severity of the stressing conditions.

Test	Stress Factor 1	Stress Factor 2	Stress Factor 3	Stress Factor 4
Light Soak	Illumination spectrum should be clearly stated and ideally shown, critically highlighting presence or absence of UV component.	Temperature (RT, 60 or 85˚C)	Atmosphere (inert, dry air, ambient Air with quoted RH, 85% RH)	Electrical Load (short-circuit, open-circuit or maximum power point)
Thermal	Spectrum: Dark	Temperature (60, 85 ˚C or higher)	Atmosphere (inert, dry air, ambient air with quoted RH, 85% RH)	N/A

Outlook

There have been a number of failure modes identified so far for PSC. However, more investigations are required to improve our understanding of the degradation mechanisms. In addition, it is necessary to identify how to test for any specific failure mode and degradation process.

Box 2 describes a model for the combined light and heat degradation of Si solar cells, arising from yellowing of the backsheet and loss of hydrogen passivation. Investigating and understanding how multiple stress factors work together in PSCs and result in failure modes is an important research direction.

Comparisons between individual stress tests and stress factor combinations designed to replicate field operation conditions greatly enrich the confidence and utility of laboratory stress testing, and may also reveal new failure modes. Going beyond the pass/fail nature of the qualification test, the ability to predict real-world operation lifetime relies on accelerated stress testing. Temperature, humidity, and light intensity are common stress factors applied for accelerate stress testing. Determination of activation energies for each degradation mechanism, and the determination or verification of the acceleration factor induced by increase irradiance levels, will enable proper estimations of the expected lifetime for new PV technologies.

Specifically for perovskites, the mobility of ionic species within the absorber layer makes them relatively unique. Assessment of electric field induced degradation mechanism(s), and specifically PID is still required. Initial steps have been taken to asses reverse bias degradation,[59] to simulate shading effects, but considerable understanding of what material and interface properties govern these degradations is still required, along with identification of suitable reporting metrics. Further IEC-like tests, such as thermal cycling, also warrant considerably more investigations.

We caution that stability investigations should be a research theme in their own right, and justifiably a central theme, and not simply used as a “tag on” to an investigation aimed at increasing efficiency. With the latter, there is a significant risk of researchers selecting unrepresentative, non-standardized stress tests where the specific cell shows no failure. Low severity stress factor tests may be valid when attempting to isolate certain fatal degradation mechanisms, but are not useful for making general claims about stability in the anticipated use environment of the field. The community would also benefit from inter-laboratory exchanges of cells, benefiting from sharing knowledge and expertise, in the pursuit understanding and resolving failure modes.

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Competing interests

Henry Snaith is Founder and CSO of Oxford PV Ltd, a company commercialising perovskite photovoltaics.

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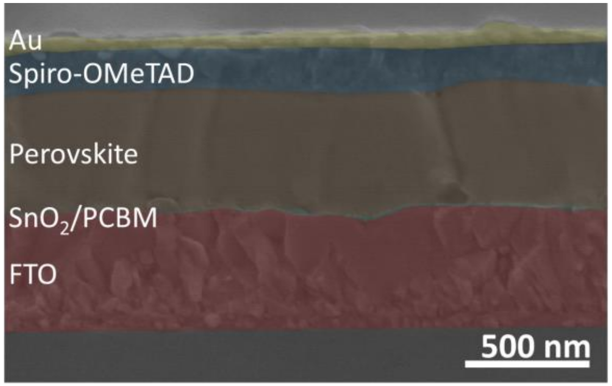
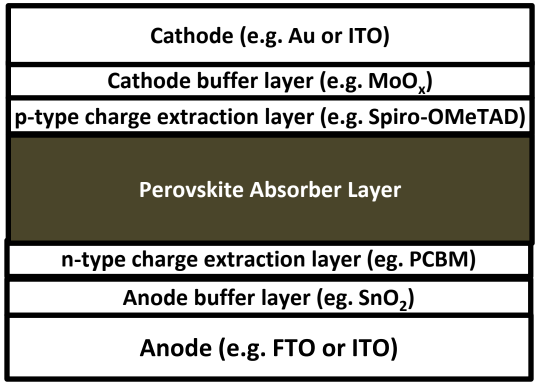
a)


Au
Spiro-OMeTAD
Perovskite
SnO_2/PCBM
FTO
500 nm

b)


Cathode (e.g. Au or ITO)
Cathode buffer layer (e.g. MoO_x)
p-type charge extraction layer (e.g. Spiro-OMeTAD)
Perovskite Absorber Layer
n-type charge extraction layer (eg. PCBM)
Anode buffer layer (eg. SnO_2)
Anode (e.g. FTO or ITO)