



Stability and reliability of perovskite photovoltaics: Are we there yet?

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The power-conversion efficiency (PCE) of perovskite solar cells (PSCs) has exceeded in 2024 the theoretical single-junction Shockley–Queisser limit of 33.7% with the perovskite/silicon tandem version. The commercialization of the technology is now a reality with the PV industry demonstrating its first commercial products. Many companies have shown excellent module reliability with most of them passing the IEC standardization (required for commercial silicon solar cells). In this article, we want to bring some light on the most intriguing question regarding the stability and reliability of PSC technology: Are we there yet? Issues on stability are still under strong investigation and research on the topic has increased exponentially in the last 10 years. Since some companies have already promised excellent reliability of their modules, with 80% retention of the initial PCE after 25 years, the following two or three years will be crucial to demonstrate these pledges. In this work, we present an outline of the most stable PSC devices reported to date and discuss the most important strategies leading to highly stable devices.

Introduction

Perovskite solar cells (PSCs) and modules (PSMs) exhibit meteoritic growth in their power-conversion efficiency (PCE) reaching 26.7% and 34.7% for single-junction and tandem (with Si) configurations, respectively. PSC technology has, in 2024 and for the first time, surpassed the single-junction Shockley–Queisser limit of 33.7% PCE.¹ Investments in the technology have reached billions of Euros² and the commercialization of the technology is now a reality. Companies such as RenShine Solar, GCL-Si, LONGi, or Oxford PV, among many others, have announced the commercialization of their PSM. Oxford PV has informed the commercialization of their tandem perovskite-silicon PSM with PCE of 24 percent.³ The world's first commercial gigawatt-scale manufacturing of PSCs (1.2 m × 2.4 m module size) was announced in December 2023 by GCL Solar Energy for their single-junction PSCs.⁴ RenShine Solar announced in 2024, their 1.2 megawatt-scale perovskite distributed power station connected to the grid.⁵ PV industries are also promising very competitive module

reliability with most passing the International Electrotechnical Commission (IEC) standardization (compulsory for commercial silicon solar cells).

In this article, we want to bring some light on the most intriguing question about the stability of PSC technology, its laboratory-scale stability and commercial-module reliability: Are we there yet? Although efficiency values have reached astonishing values, issues on stability are still under investigation and research on the topic has increased exponentially in the last 10 years. Some companies are already promising excellent reliability of their PSM retaining 80% of the initial PCE after 25 years.⁶ Confirming these promises will be crucial in the next two or three years for the success of this PV technology. In this work, we present an outline of the most stable PSC devices reported to date, Pb-free PSC and commercial PSCs in both single-junction and tandem configurations. We will discuss the most important strategies leading to highly stable devices. We will focus our attention on the ISOS protocols for stability testing, especially International Summit on Organic and Hybrid Photovoltaics

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Stability (ISOS) protocols under light irradiation conditions (ISOS-L) and outdoor stability assessment (ISOS-O).⁷

Pb-containing perovskites. The presence of 6s2 (5s2) lone-pair electrons on the B-site Pb (also Sn) in hybrid halide ABX₃ perovskites is fundamental to many of their appealing and special optoelectronic properties. This lone pair leads to mobile holes, favorable bandwidths and band alignments, large ionic dielectric response, and large positive thermal expansion. This lone-pair electron configuration gives halide perovskite its defect tolerance nature and affects lattice dynamics and large ionic dielectric response, among many other properties.⁹ The BX₆ octahedron framework that constitutes the metal halide perovskite crystal structure ABX₃ is believed to be mainly responsible for the structural instability of halide perovskite materials. Ion migration along the PbI₆ octahedron rules this stability, because the iodide ion has the lowest activation energy for ion migration, followed by the MA⁺ cation.^{10–12} These mobile iodide ions are also known for their easy oxidation and can decompose into bimolecular iodine by photogenerated holes. As a result, Pb defects are formed with time, leading to irreversible phase separation and halide perovskite degradation.^{13–15}

Indoor stability. ISOS-L. Figure 1 summarizes the recently published data for PSCs, in inverted and normal configurations.⁸ The data correspond to the stability under continuous illumination, which is one of the most important PSC

stability tests. To complement this graph, Table I displays the most recent stability reports for PSCs for ISOS-L protocol, published only in 2024.

Another important stability test under constant illumination encompasses high temperatures. Real outdoor conditions of PSCs can reach up to 85°C in some locations during summer at 1 sun (noon). 85°C is also the temperature mark for the standardization of commercial PV devices as stated in the IEC 61215 standard. For PSCs, we have identified no more than eight published works (See Table I and Figure 1) where the stability of PSCs is reported under these extreme conditions of continuous light irradiation of 1 sun and 85°C (ISOS-L2).^{16–21} Among them, the most recent and most robust devices include inverted PSCs and the use of self-assembly monolayers (SAMs) containing carbazole units and methoxysilane or phosphonate anchoring groups. For example, Li and Zhu et al. report the fabrication of inverted PSCs with 25.6% efficiency and 1.53 V_{oc}, able to maintain 90% of the initial efficiency after 1200 h of continuous light irradiation of 1 sun at 65°C. The authors employ the SAM molecule (4-(3,11-dimethoxy-7H-dibenzo[c,g]carbazol-7-yl)butyl) phosphonic acid (MeO-4PADBC), which is located at the NiO_x/perovskite interface creating a strong bond of the MeO-4PADBC with the oxide. The authors report that the favorable contact and energetic alignment of the NiO/MeO-4PADBC/

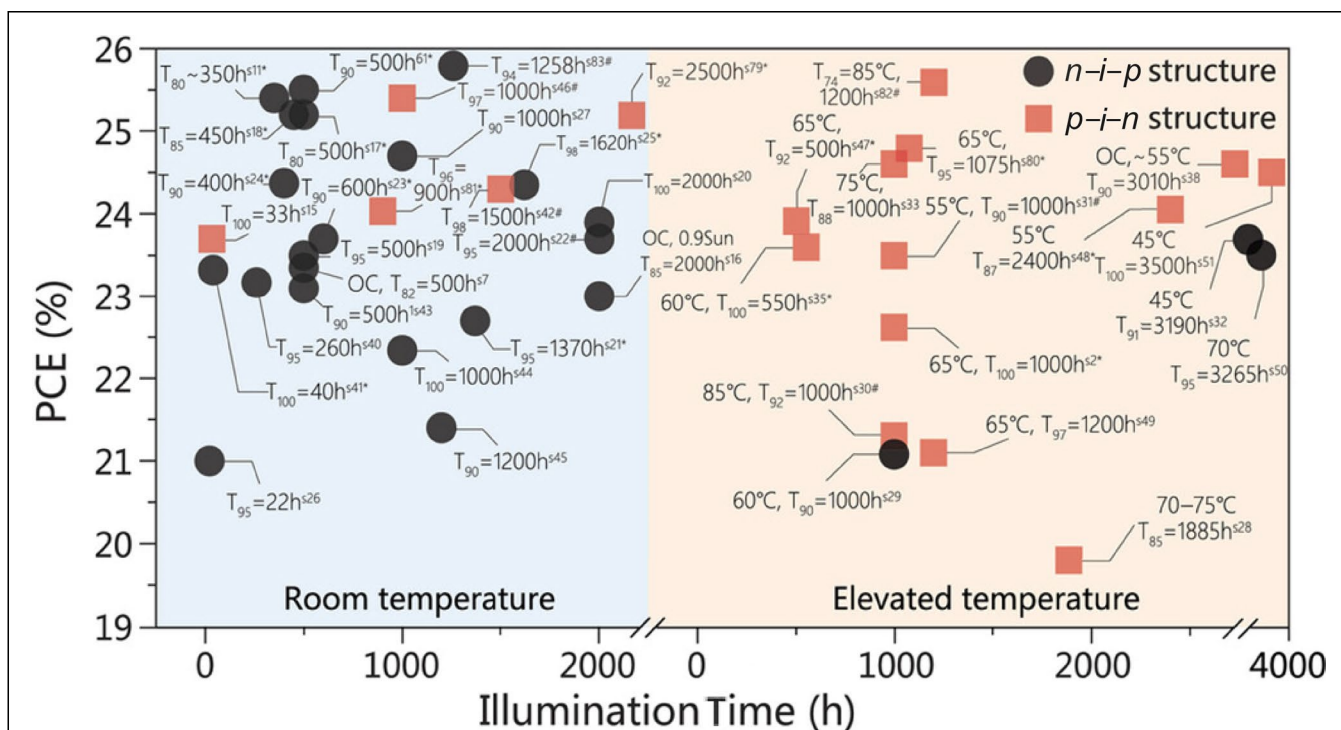


Figure 1. Evolution of efficiency and stability of perovskite solar cells. Typical stability of perovskite solar cells under continuous illumination. Txx = Y h means that the power-conversion efficiencies (PCEs) drop to xx% of the initial value after Y-hour aging. Reprinted with permission from Reference 8. © 2024 Wiley.⁸

Table I. Indoor stability analysis (for published PSCs in 2024 only).

Structure	PCE (%)	Light Intensity	Temp (°C)	Tracking Method	Test Time (h)	PR (%)	Reference
FTO/SnO ₂ /(FAPbI ₃) _{0.95} (MAPbBr ₃) _{0.05} /Polyspiro/Spiro-OMeTAD/Au	24.54	1 sun	23	MPP	1250	95	22
FTO/c-TiO ₂ /m-TiO ₂ /Perovskite/Spiro-OMeTAD/Au	23	1 sun	r.t	MPP	4500	99	23
ITO/SnO ₂ /FAPbI ₃ /HTL (SBF-FC)/Au	25.3	1 sun	65	MPP	500	92	24
ITO/P3CT-N/CsPbI ₂ Br/PCBM/C ₆₀ /2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline (BCP)/Ag	15.92	1 sun	45	MPP	500	81.8	25
Glass/ITO/SnO ₂ /Perovskite/C ₆₀ /BCP/Ag	25	1 sun	40	MPP	1000	90	21
ITO/NiO _x /2PACz/Perovskite/PCBM/BCP/Cr/Au	24.6	1 sun	45	MPP	1000	82	26
Glass/FTO/SnO ₂ /Perov/Spiro-OMeTAD/Ag	24.6	1 sun	65	MPP	1920	88	27
FTO glass/SnO ₂ /Perov/Spiro-OMeTAD/Ag	24.57	1 sun	rt	MPP	1000	92	28
Glass/Gold/SnO _x /Perov-Perov/NiO _x /FTO/glass	21	1 sun	40	V _{oc}	1000	75	29
FTO/NiO _x /Me-4PACz/Perovskite/C60/ALD-interlayer/Cu	24.6	1 sun	65	MPP	1350	88	30
FTO/SnO ₂ /Perovskite/B(CE)ACI or CEACI/Spiro-OMeTAD/Au	25.6	1sun	55	MPP	500	91	31
ITO/MeO-2PACz/Perovskite/Phenethylammonium iodide (PEAI)/C ₆₀ /ZnO/Au	23.2		85	MPP	1200	98.2	19
ITO/MeO-2PACz/Cs _{0.05} MA _{0.10} FA _{0.85} PbI ₃ /PI/C ₆₀ /bathocuproine/Ag	25.07	1 sun	rt	MPP	1000	95	32
FTO/TiO ₂ /DDE/MAPbI ₃ /Spiro-OMeTAD/Ag	22.1	1 sun	rt	OC	1000	90	33
FTO/SnO ₂ /Perovskite/Spiro-OMeTAD/MoO ₃ /ITO	223	1 sun	rt	MPP	2000	90	34
FTO/c-TiO ₂ /m-TiO ₂ /Perovskite/Spiro-OMeTAD/Au	22.3	1 sun	rt	OC	720	82	35
ITO/NiO _x /Me-4PACz/Perovskite/C ₆₀ /Bathocuproine (BCP)/Cu	22.1	1 sun	rt	MPP	500	100	36
ITO/SnO ₂ /PCBM/Cs _{0.05} FA _{0.85} MA _{0.1} Pb(I _{0.95} Br _{0.05}) ₃ /PTAA/BCF/Au	21.3	0.84 sun	85	MPP	937	75	20
Glass/ITO/NiO _x /Me-4PACz/WBG perov./C ₆₀ /BCP/Ag	22.2	1 sun	rt	MPP	985	90	37
FTO/SnO ₂ /Perovskite (FAPbI ₃) _{0.95} (MAPbBr ₃) _{0.05} /Poly-v-Spiro/Spiro-OMeTAD/Au	24.5	1 sun	rt	MPP	1250	95	38
ITO/SnO ₂ /Perov. (PTAFAPbI ₃ Cl _{4-x})/Spiro-OMeTAD/Au	24.5	1 sun	rt	MPP	1000	90	39
ITO/SnO ₂ /Perov. (PTAFAPbI ₃ Cl _{4-x})/Spiro-OMeTAD/Au	24.5	1 sun	85	MPP	200	97	39
ITO/2PACz/CsFAPbI ₃ /C ₆₀ /SnO ₂ /IZO/Cu	25.6	1 sun	85		1000	95	21
ITO/NiO _x /2PACz/Perovskite without or with 1,3-PDI or P(1,3-PDI) additive/PCBM + C ₆₀ /BCP/Cr/Au	24.7	1 sun	45	MPP	1000	82	26
FTO/Al-HAc-SnO ₂ (ETL)/PVK/PCBM/Ag	22.2	1 sun		MPP	1000 h	90	40
Glass/FTO/SnO ₂ /Perovskite/Spiro-OMeTAD/Ag	24.6	1 sun	65	MPP	1920	88	27
Glass/FTO/SnO ₂ /Perovskite/Spiro-OMeTAD/Ag	24.6	1 sun	65	LC 12 h on/off	10,000	98	27
Glass/ITO/SnO ₂ /Perovskite/PC61BM/Au	25.3	1 sun	rt	MPP	1000	85	41
Glass/FTO/SnO ₂ /Perovskite/Polymer interlayer/Spiro-OMeTAD/Au	17.8	0.5 sun	65	OC	1440	94	42

PR, performance retention; MPP, max power point tracking; OC, open-circuit voltage.

perovskite reduces the voltage deficit leading to strong interface toughening effects under thermal stress.¹⁸ Tang et al. report an inverted PSC with 23.2% efficiency able to retain 98.2% of the initial PCE after 1200 h under continuous light irradiation and 85°C (ISOS-L2). This impressive result has also been attributed to the use of self-assembly monolayers (SAMs) employed as hole-transport layer (HTL). The authors observed that strong polar solvents in the perovskite precursor desorb the SAM if it is anchored on substrates by hydrogen-bonded, rather than covalently bonded, hydroxyl groups. Thus, they created a strong bond between the SAM molecule and a thin layer of indium tin oxide (ITO) deposited by atomic-layer deposition (ALD). The SAM molecule anchors covalently with the oxide substrate via a trimethoxysilane group that exhibited strong tridentate anchoring to the substrate.¹⁹

J. Luo et al. reported a normal configuration PSC of the type ITO/SnO₂/PCBM/Cs_{0.05}FA_{0.85}MA_{0.1}Pb(I_{0.95}Br_{0.05})₃/PTAA/BCF/Au with a 21.3% efficiency analyzed under ISOS-L2 protocol and able to retain 75% of the initial efficiency after 937 h of testing under continuous light irradiation at 85°C.²⁰ The key of this stable PSC resides in the use of the poly[2,2'''-bis [[(2-butyloctyl)oxy]carbonyl] [2,2':5',2'':5'',2'''-quaterthiophene]-5,5'''-diyl] (PDCBT) and tris(pentafluorophenyl)borane (BCF), in a PDCBT/BCF/Au structure, which permits the formation of a robust quasi-ohmic contact boosting the hole injection process from the polymer into metal by two orders of magnitude.²⁰ DeWolf et al. report the use of SAM molecules of the type ((2-(9H-carbazol-9-yl) ethyl)phosphonic acid) (2PACz) in an inverted PSC of the type ITO/2PACz/CsFAPbI₃/C₆₀/SnO₂/IZO/Cu with a PCE of 25.6% (certified 25.0%), which stands 1000 h under continuous light

irradiation and 85°C (ISOS-L2) retaining 95% of the initial efficiency after analysis. The key of this PSC resides in the use of double-sided 2D/3D perovskite heterojunctions and the SAM molecules. Long alkyl amine ligands can generate near-phase-pure 2D perovskites at the top and bottom of 3D perovskite interfaces. At the rear-contact side the alkyl amine ligand strengthens the interactions with the substrate through acid–base reactions with the phosphonic acid group from the organic hole-transporting self-assembled monolayer molecule, thus regulating the 2D perovskite formation.²¹

Most of these stable PSCs contain methoxysilane or phosphonate anchoring groups as SAM molecules working as HTL. These functional groups bond strongly with the oxide of the transport layer of the PSC. However, the use of molecules as additives or SAM molecules with strong anchoring groups such as phosphonates have also been reported to be of high importance for the effective immobilization of the halide ions of the perovskite absorber (in the bulk), improving device stability.^{43–45} Several groups, including our group, reported the strong interaction of phosphonate groups with the halide perovskite through hydrogen bonds and the effective passivation of shallow defects such as iodine.¹⁸ In our case, the phosphonate-based additive employed is a simple molecule added to the bulk of the halide perovskite as an additive with excellent stability at 25°C. Despite these favorable results, our PSCs didn't pass the stability analysis

at high temperatures. On the contrary, SAM molecules with phosphonate anchoring groups and a carbazole core, seem to be the key factor driving the high temperature stability of PSCs samples previously described. This SAM structure is effective when the SAM molecule bonds strongly to an oxide such as the NiO HTL. The latter was observed for PSCs in both single-junction^{46,47} and perovskite-based tandem solar cell configurations.^{18,48–52} In addition, the variation of temperature during the ISOS-L tests are a useful tool employed for the prediction of the PSC lifetime under outdoor or standard test conditions (STC, 1 sun, 25°C) (see the section “Accelerated aging”).

Outdoor stability. ISOS-O. A major challenge for PSCs is improving their operational stability under real outdoor conditions that should be monitored under ISOS-O protocol. Besides the practical complication of device encapsulation for outdoor analysis,⁵³ the PSC devices have to sustain multiple stressors with great variability and doses: day/night cycling, different “years” seasons (weather, sun irradiance, and temperature), detrimental reverse bias voltage under some cloudy or shadow conditions, among others.⁵⁴ The reports of outdoor stability analyses are very scarce in the literature but highly important for the success of these new commercial PSCs. **Table II** encompasses the most important (with respect to testing time) outdoor stability analysis found in the literature to date.

Table II. Outdoor stability of PSCs (ISOS-O protocol).

Year	Structure	Initial PCE (%)	Test Mode	Test Time (h)	PR (%)	Reference
<i>p-i-n</i>						
2024	ITO/2PACz (SAM)/Cs _{0.15} FA _{0.85} PbI _{2.55} Br _{0.45} /C ₆₀ /SnO ₂ /Cu	16	MPP	21,900	100	55
2023	Glass/ITO/MeO-2PACz/Rb _{0.05} Cs _{0.05} MA _{0.05} FA _{0.85} Pb(I _{0.95} Br _{0.05}) ₃ /C ₆₀ /SnO ₂ /Ag	25.5	MPP	4368	65	56
2023	Glass/ITO/MeO-2PACz/FAPbI ₃ /LiF (1 nm)/C ₆₀ /BCP/Cu	22.35	MPP	8760	74	57
2021	ITO/HTL/3D/2D PVK/C ₁₆ SubPc/C ₆₀ /BCP/Ag	19.1	OC	1728	87	58
2020	Glass/ITO/MeO-2PACz/Perovskite/C ₆₀ /SnO ₂ /Cu	18.5	MPP	140	100	59
2022	ITO/2PACz (SAM)/Cs _{0.15} FA _{0.85} PbI _{2.55} Br _{0.45} /C ₆₀ /SnO ₂ /Cu	16	MPP	2880	20	60
2020	FTO/NiOx/Perovskite/PCBM/ITO	12.5	OC	2100	100	61
2019	ITO/NiOx/m-Al ₂ O ₃ /MAPbI ₃ /CH ₃ NH ₃ PbI ₃ /PCBM/Rhodamine/Ag	9.6		2000	70	62
<i>n-i-p</i>						
2016	FTO/c-TiO ₂ /m-TiO ₂ /Perovskite/Spiro-OMeTAD/Au	19	OC	2160	95	63
2021	FTO/c-TiO ₂ /m-TiO ₂ /Cs _{0.5} (MA _{0.17} FA _{0.83} 0.95Pb(I _{0.83} Br _{0.17}) ₃ /Spiro-OMeTAD/Au	18.5	MPP	500	90	64
2018	Glass/ITO/TiO ₂ /MAPbI ₃ /Spiro-OMeTAD/Au	15	OC	336	60	65
2020	FTO/c-TiO ₂ /m-TiO ₂ /ZrO ₂ /Perovskite/Carbon	15.6	OC	3600	100	66
2019	Plastic/ITO/SnO ₂ /CH ₃ NH ₃ PbI _{3-x} Cl _x /Spiro-OMeTAD/Ag	12.7	OC	10	0	67
2015	FTO/c-TiO ₂ /m-TiO ₂ /ZrO ₂ /MAPbI ₃ /Carbon	8.2	OC	168	100	68
2016	FTO/c-TiO ₂ /m-TiO ₂ /FAPbI ₃ (0.85)/MAPbBr ₃ (0.15)/Spiro-MeOTAD/Au	11	OC	1080	60	69
2020	FTO/TiO ₂ /FA _{0.55} MA _{0.25} Cs _{0.2} PbI ₃ /P3HT/Carbon	18.3	OC	504	37	70
2020	FTO/c-TiO ₂ /m-TiO ₂ /ZrO ₂ /Perovskite/Carbon	6	OC	720	100	71
2022	FTO/c-TiO ₂ /mp-TiO ₂ /CH ₃ NH ₃ PbI _{3-x} Cl _x /GC@CH ₃ NH ₃ PbI _{3-x} Cl _x /C	5.88	OC	81	81	72
2023	FTO/c-TiO ₂ /m-TiO ₂ /HP/MXene:H3pp/Spiro-OMeTAD/Au	19.85	MPP	350	60	73
2016	FTO/c-TiO ₂ /HP/Perovskite/Spiro-OMeTAD/MoO ₃ /Al	15.3	OC	432	72	74

PR, performance retention.

One of the first outdoor stability assessments of PSCs under outdoor conditions was carried out in Barcelona (Spain) by our group back in 2016. The MAPI-based PSCs sustained almost 1000 h under ISOS-3 protocol.⁷⁴ Currently, excellent work is being carried out by Helmholtz-Zentrum Berlin with respect to PSC stability under outdoor conditions. Khenkin et al. have recently demonstrated the stability of PSCs under ISOS-O protocol for more than 22,000 h (2.5 years). Results of their work is depicted in **Figure 2**. The devices are inverted PSCs of the type ITO/2PACz(SAM)/Cs_{0.15}FA_{0.85}PbI_{0.55}Br_{0.45}/C₆₀/SnO₂/Cu. In this case, the SAM molecules with phosphonate functional groups (MeO-2PACz and 2PACz) are present together with the adjacent oxide layer (ITO) next to the SAM molecule.⁵⁵

Pb-free perovskites. Toxicity concerns on Pb-containing PSCs have delayed the widespread application of halide perovskite materials and has raised concerns about the commercialization of this PV technology.⁸ Berry et al. reminded us that electricity generation from coal results in more lead emitted into the atmosphere than PSCs (assuming a 20% module

efficiency and an ~700-nm active layer). In addition, some Pb-containing salts employed in PSCs are not water-soluble and thus, cannot be washed away by rain on a cracked panel. The rapid hydrolysis observed on Pb²⁺ materials results in the formation of Pb(OH)₂, which is insoluble.⁷⁵ The concern of the solubility of Pb(OH)₂ and PbO in acid (acid rain) results in their transformation into the corresponding sulfate species in pH equilibrium, also insoluble. Visoly-Fisher et al. also report the slow dissolution of Pb salts in water, which allows inspection and correction. In addition, Pb is used in paint and cosmetics and that might be a better starting point for prioritizing Pb removal.⁷⁶

Despite all the latter, ongoing research to develop Pb-free halide perovskites has flourished in the past years. In halide perovskite materials, Pb can be replaced with other less-toxic, environmentally benign metals, including Sn, Ge, Bi, or Sb, among others. However, only Sn and Ge can form the perovskite crystal structure (they both have the same coordination, ion size, and charge balance).⁷⁷ Sn is possibly the most

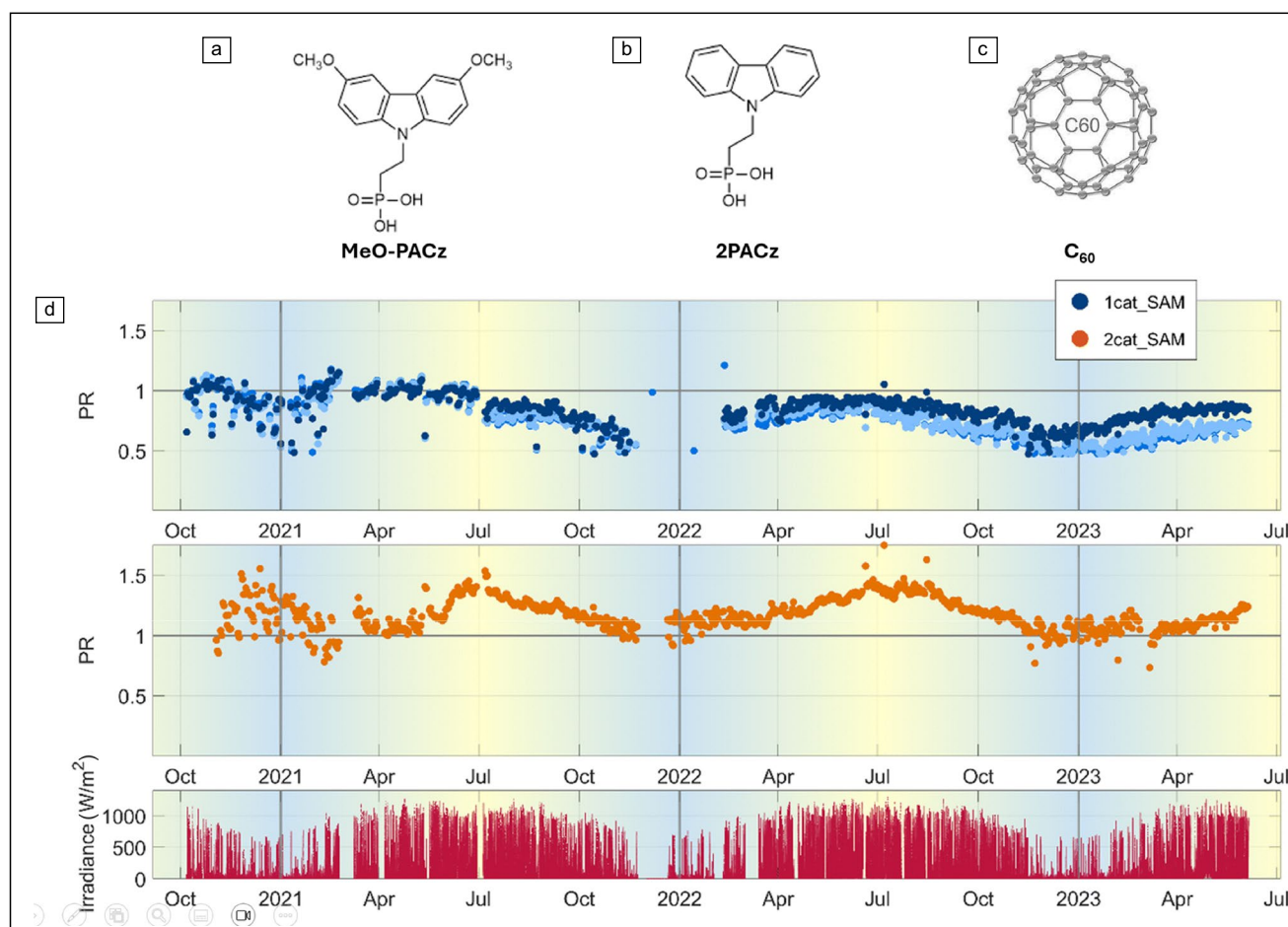
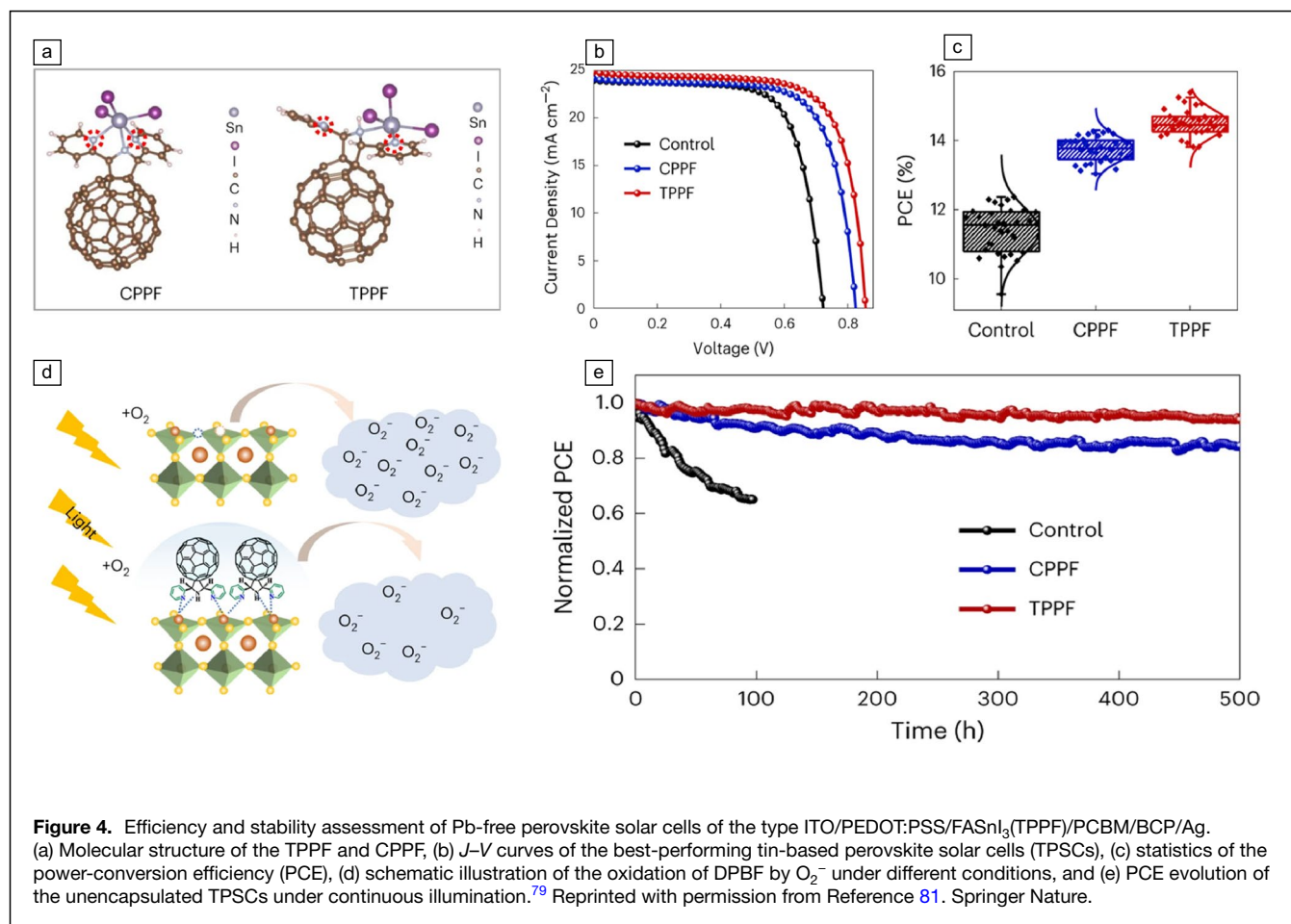


Figure 2. One of the longest outdoor stability assessments reported to date for perovskite solar cells (PSCs). (a–c) The molecules applied as self-assembly monolayers (SAMs) and the electron-transport material employed in the device. (d) The long-term outdoor data for 2.5 years of continuous operation of laminated PSCs under maximum power point tracking at Helmholtz-Zentrum Berlin (Germany). PR, performance retention. Reprinted with permission from Reference 75. © 2024 Royal Society of Chemistry.⁵⁵



modules with efficiencies above 19% and 26%, respectively.⁸⁴ RenShine Solar reports 18–20% efficiency for single-junction PSM and about 21% for tandem devices.⁸⁵ Oxford PV has announced the commercialization of its tandem perovskite/Si modules with 24.5% efficiency, which can generate 20% more efficiency than silicon modules.⁸⁶

Major PSC industry players are depicted in **Figure 6** for single-junction and tandem modules. The graph depicts the PCE with respect to the active area (single cells) or aperture area (modules) and is separated by the type of PSC architecture: single-junction (■), perovskite/silicon tandem (●), and perovskite/perovskite tandem (▲) solar cells. It has been already reported that the final PCE of laboratory-scale single-cell PSCs depends on the devices active (with small active areas usually showing the largest PCE).⁹² However, we can observe in **Figure 6** that the situation seems not to be the same for industrial single and tandem modules. PCEs for single-junction modules are reported to be between 19% and 21.5% for a large range of active areas that varies between 800 cm² and 20,000 cm² (here we are not considering the difference made between laboratory-scale devices and industrial modules). Some differences can be observed within a single company; for example, RenShine reports efficiencies

between 18% and 21% for active areas between 25 cm² and 100 cm²; SolaEon reports PCEs from 19% to 21% for active areas between 1000 cm² and 1200 cm² for single modules and between 21% and 29% for tandem modules with area of 300 mm × 400 mm. Compared with single-junction cells, all-perovskite tandem cells require accurate control of the different layers of the tandem device. This involves careful optimization of materials formulation and thin-film deposition thickness and homogeneity, including material stability and preparation process. In comparison of the PCE for PVSK/Si tandem modules, we can find PCEs between 30% and 33.9% for modules with varying active area from 1 cm² up to 25.832 cm² (LONGi), or between 26% and 27% PCE for areas between 1 cm² and 17,000 cm² (GCL). Oxford PV reported 25–28.6% for active areas between 1 cm² and 16,800 cm². SolaEon, a Chinese manufacturer, has reported a 29.34% PCE for monolithic PVSK/Si tandem solar cells and 21.95% for a 300 mm × 400 mm monolithic tandem PSC.

It is important to note that data shown in **Figure 6**, and the corresponding Table SII, represent values obtained from published sources and thus, their variability can be substantial. PCE values coming from the same device/module can differ greatly if coming from certified or noncertified sources, if they

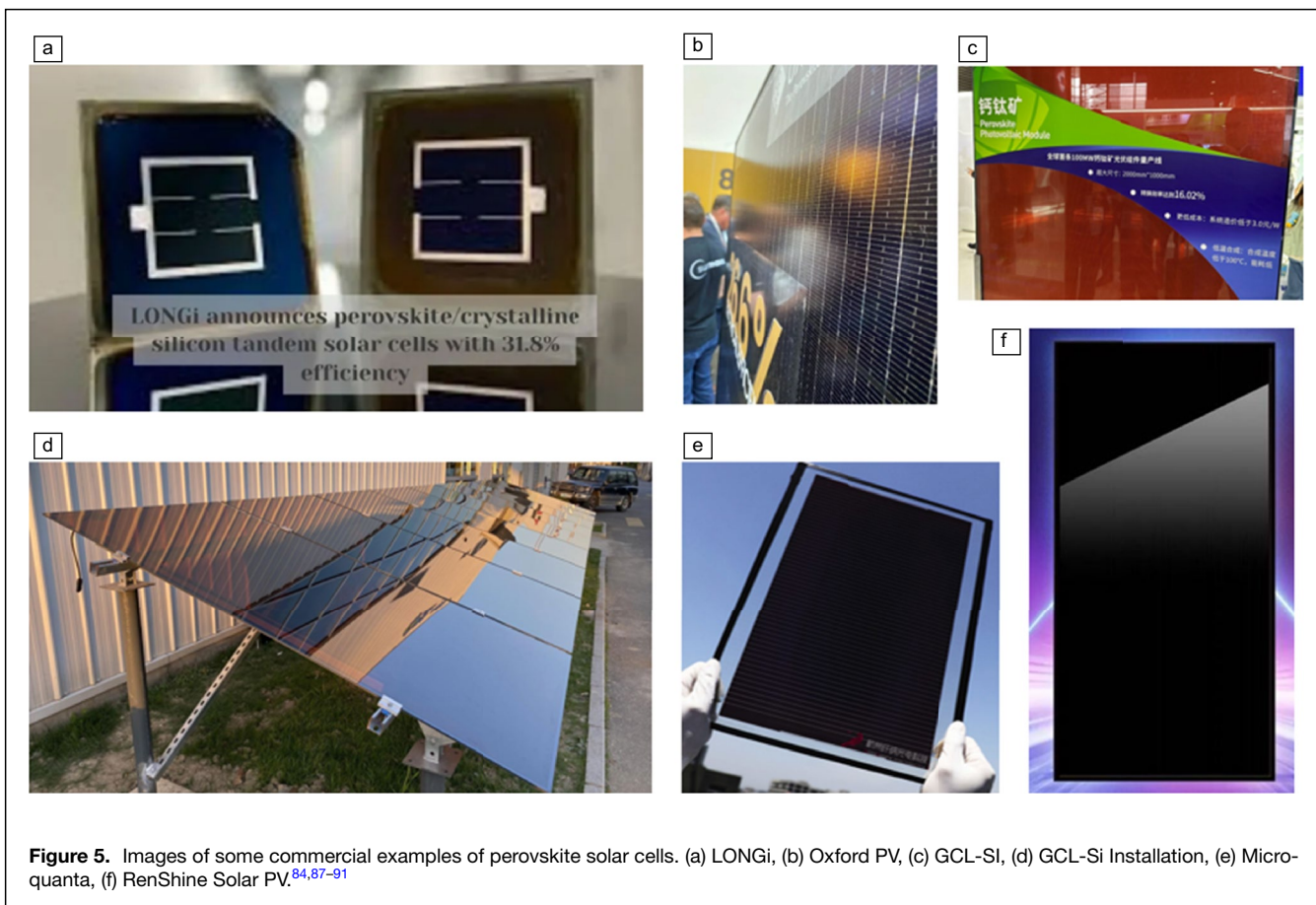


Figure 5. Images of some commercial examples of perovskite solar cells. (a) LONGi, (b) Oxford PV, (c) GCL-Si, (d) GCL-Si Installation, (e) Micro-quanta, (f) RenShine Solar PV.^{84,87–91}

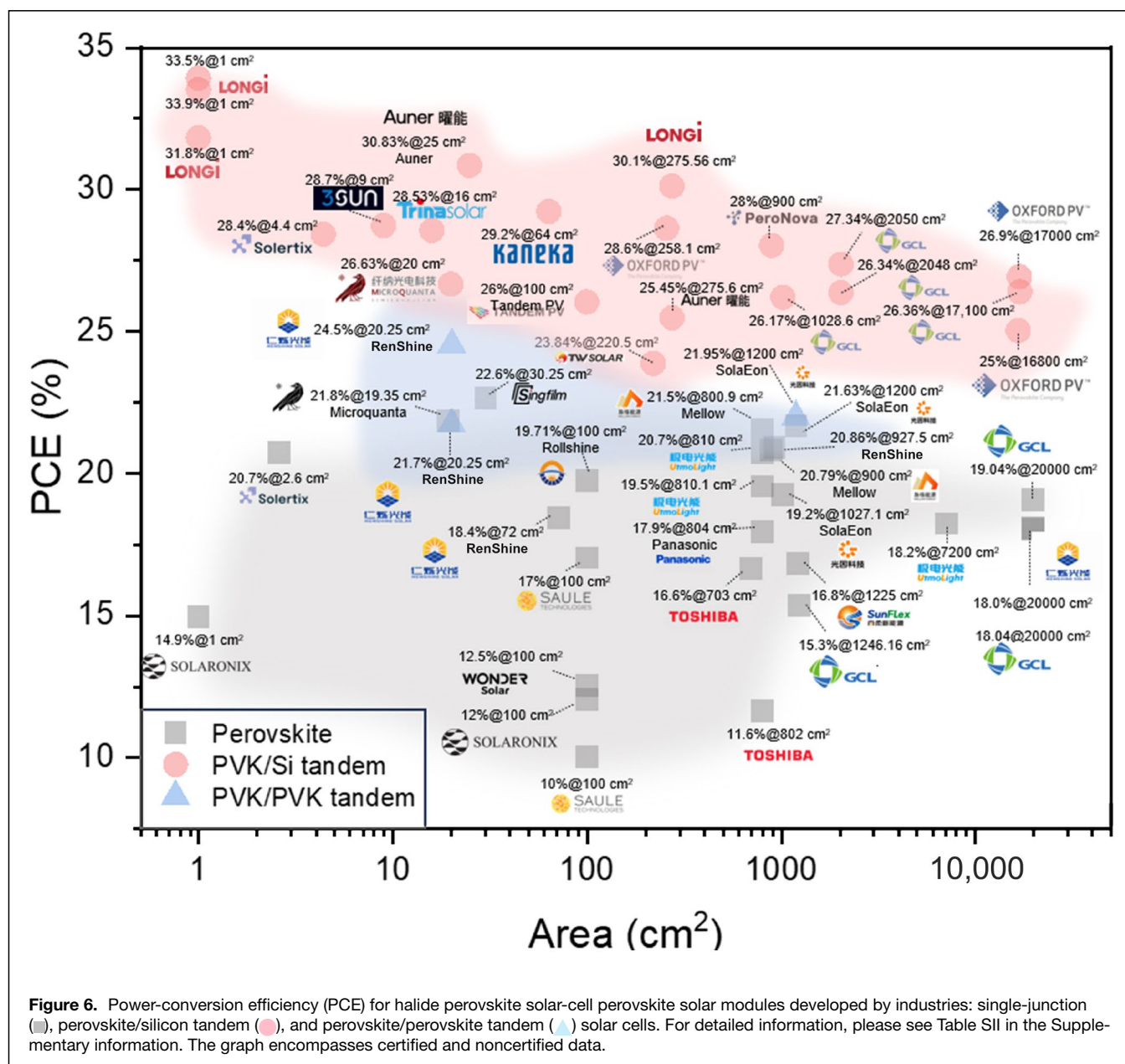
represent the maximum or the steady-state efficiency value or if these are obtained in reverse or forward scans. Especially certified values obtained by recognized laboratories usually result in lower PCEs.

Although many companies are not disclosing their stability analysis results and PSC lifetime, a few have done so, especially for single-cell modules, with very promising outcomes. For single-cell devices, Utmo Light (China) reported the positive result of their PSM passing the IEC testing, which can withstand a 2300-h UV bath at 1000 W/m² and 60°C, and predicted 12 years of operation without degradation.⁹³ GCL's perovskite solar panel had passed the IEC 61215 and IEC 61739 certification tests employed for silicon solar cells. The company guarantees 90% of the nominal output power after 10 years, which can decrease to 80% after 25 years.⁸⁴ Rayleigh Solar Tech has announced zero degradation for their 15 cm × 15 cm glass solar module after seven months (>5,000 h) of outdoor testing and T_{80} of 1200 h for their flexible module of the same size under damp heat test.⁹⁴

RenShine solar, a spinoff company led by T. Hai ren from Nanjing University, China, reported that their PSCs are capable of retaining greater than 90% of their initial performance after 600 h of continuous operation.⁹⁵ Their company has finalized the construction of a 1.2 MW perovskite rooftop distributed power station, which was connected

to the grid on September 2024. It encompasses 9,300 commercial PSM (1.2 m × 0.6 m, average power of 130 W). It has reported that its commercial modules have achieved a power-conversion efficiency of 18.4 percent. RenShine Solar has signed an agreement for a CNY 1 billion investment in PSCs.⁹⁰

In 2024, tandem silicon/perovskite solar cells exceeded, for the first time, the single-junction Shockley–Queisser limit of 33.7 percent. The work was developed through an academy/industry collaboration and involving LONGi Green Energy Technology Co. in collaboration with Soochow University and eight other institutions in China and Hong Kong (Figure 7). These two-terminal monolithic perovskite/silicon tandem solar cells were produced by a holistic approach⁹⁶ with a bilayer-intertwined passivation. The authors applied a lithium fluoride ultrathin layer followed by an additional deposition of diammonium diiodide molecule (LiF/EDAI bilayer) enhancing electron charge extraction and suppressing nonradiative recombination. As a result, they obtained an independently certified stabilized PCE of 33.89% with an excellent FF of 83% and 1.97 V_{oc} .¹ The reported stability for their PSC applying the LiF/EDAI bilayer was T_{80} of 1200 h obtained under ISOS-L conditions of MPP tracking, continuous illumination under N₂ (Figure 7j). The later result emphasizes the importance



of employing a holistic approach to obtain highly efficient devices.⁹⁶

Accelerated aging. Accelerated aging testing, while technically challenging, is the key to rapid assessment of the operational lifetimes and elucidation of long-term degradation mechanisms. If effectively applied, it can help the technology to be derisked and its time to market can be expedited. However, could accelerated tests properly predict the real-world operational lifetimes or at least that measured with aging under the STCs?⁹⁷ If the PCE versus time curves exhibit a consistent mathematical form (e.g., linear, exponential decay) with increasing stress (for the intrinsic degradation, it can be heating or light exposure), the rate of existing degradation processes is likely being accelerated (Figure 8a–b). In contrast,

a notable change in the degradation curve shape indicates that new degradation modes are likely being activated (Figure 8c).

For data like those in Figure 8a, that exhibit a consistent functional form with increasing stress, an acceleration factor (AF) can be defined for each stress level by dividing the degradation rate of solar cells aging at each accelerated condition by the rate of those aging at the reference condition (STC or outdoor). In the case of Figure 8a, the data from different stress conditions can be plotted onto a unified “equivalent time at the reference condition” axis as shown in Figure 8b, where all data collapse onto a single unified curve—the hallmark of an effective accelerated aging test. Because the data in Figure 8c do not have the same shape, acceleration factors cannot be extracted.

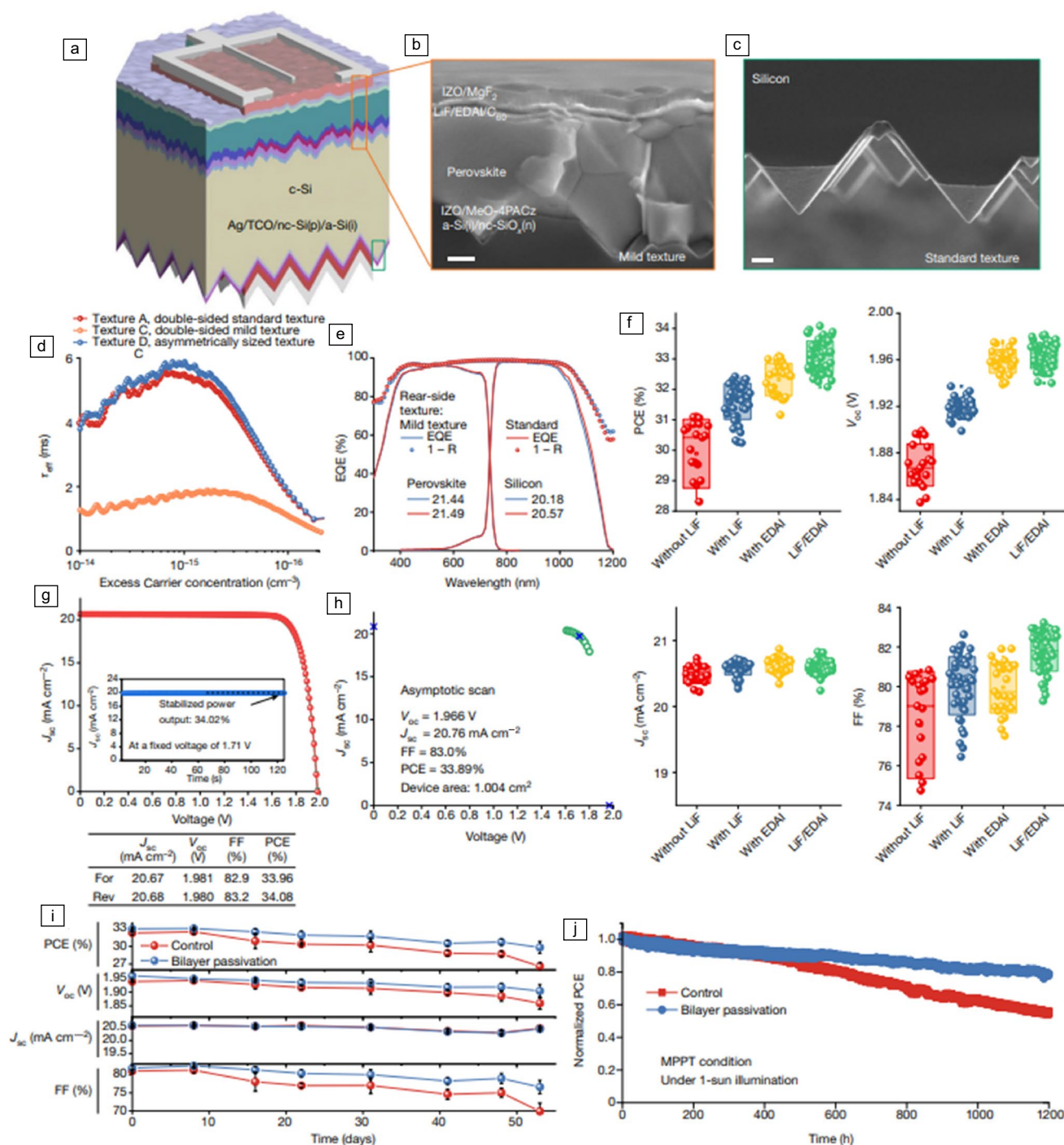
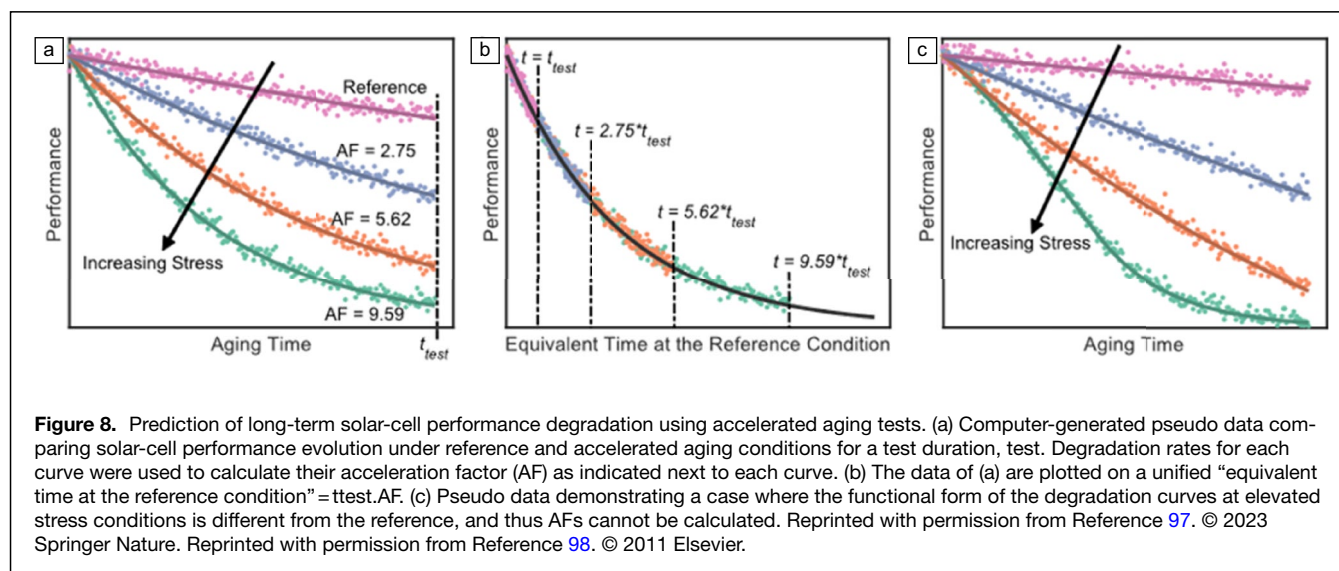


Figure 7. Tandem silicon/perovskite solar cells applying the LiF/EDAI bilayer. (a) Schematic of the monolithic perovskite/silicon tandem solar cell, (b) and standard-sized pyramid texture on the rear side (c). Scale bars = 200 nm (b) and 1 μm (c). (d) Effective minority carrier lifetime (τ_{eff}) measurements. (e) External quantum efficiency (EQE) comparison of the perovskite/silicon tandems using mild texture and standard texture on the rear side. (f) Photovoltaic performance parameter statistics for 1 cm² perovskite/silicon tandem. (g) In-house J-V curves. PCE, power-conversion efficiency. (h) J-V curve and the maximum power output point of one tandem cell, measured by the National Renewable Energy Laboratory. (i) Stability under ISOS-D protocol for the control (LiF treated) and bilayer passivated tandems. (j) Stability under ISOS-L protocol at room temperature. ¹ MPPT, maximum power point tracking, FF, fill factor. Reprinted with permission from Reference 1. © 2024 Springer Nature.



As previously stated, internal degradation mechanisms for PSCs can be thermally activated and/or photo-induced. This can be expressed as:⁹⁸

$$\frac{k_{\text{acc}}}{k_{\text{ref}}} = \text{AF}(T_{\text{acc}}, I_{\text{acc}}) = \left(\frac{I_{\text{acc}}}{I_{\text{ref}}} \right) \exp \left(\frac{E_a}{k_B} \left(\frac{1}{T_{\text{ref}}} - \frac{1}{T_{\text{acc}}} \right) \right), \quad 1$$

where E_a is the activation energy of degradation, k_B is the Boltzmann constant, T_{acc} , I_{acc} , and k_{acc} are the temperature, light intensity, and the rate of solar-cell degradation at the accelerated condition, and T_{ref} , I_{ref} , and k_{ref} are the temperature, light intensity, and the degradation rate at the reference condition.

This approach can properly predict the real-world operational lifetimes preferably for the most stable devices for which one degradation mechanism dominates and the stress factor is known. Recently, it was successfully demonstrated for PSC¹⁷ and PSM⁹⁹ with variation of temperatures in the ISOS-L aging as well as with aging under various intensities of concentrated sunlight.¹⁰⁰ In the latter case, light intensity and the cell temperature should be controlled independently.¹⁰¹

Conclusion

In summary, PSCs are just now entering the commercial stage. Enormous efforts are being dedicated to demonstrating the long-lifetime stability of laboratory-scale solar cells and commercial modules. Currently, outdoor stability analyses of laboratory-scale devices can prove above 20,000 h stability under ISOS-O protocol, and several thousand hours for ISOS-L under harsh temperatures of 85°C. Many commercial modules have passed the IEC standardization required for silicon solar cells, which gives a promising future for the technology. The answer to the question “Are we there yet?” will be solved in the next couple of years once this PV technology demonstrate its endurance and long lifespan.

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Author contributions

All authors contributed equally to the writing of this article. K.T.T. and Z.T. developed all the tables and corresponding graphs.

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Data availability

Not applicable.

Conflict of interest

No conflict of interest to be declared.

Supplementary information

The online version contains supplementary material available at <https://doi.org/10.1557/s43577-025-00863-5>.

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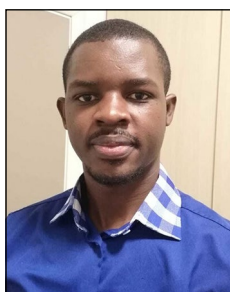
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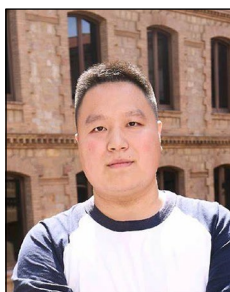
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