

Supporting Information

The Long Road to Outdoor Stability: Real-World Challenges for Controlling Perovskite Materials for Solar Cells

Juan José Patiño López^{a†}, Kelly Geraldine Rivera Botia^{a†}, Kevin Ballestas^a, Esteban Velilla^{ab}, Juan Felipe Montoya^{ac}, Franklin Jaramillo^a and Daniel Ramirez^{a*}

a. Centro de Investigación, Innovación y Desarrollo de Materiales – CIDEMAT, Universidad de Antioquia UdeA, Medellín, Colombia.

b. Grupo de Manejo Eficiente de la Energía - GIMEL, Departamento de Ingeniería Eléctrica, Facultad de Ingeniería, Universidad de Antioquia UdeA, Calle 70No. 52-21, Medellín, Colombia.

c. Grupo de Catalizadores y Adsorbentes-CATALAD, Instituto de Química, Facultad de Ciencias Exactas y Naturales, Universidad de Antioquia UdeA, Medellín, Colombia.

**Corresponding author: estiben.ramirez@udea.edu.co*

Supplementary Note 1

A literature search was conducted in the Scopus database using the search equation “perovskite AND solar AND cells AND outdoor,” carried out on September 9, 2024. This search yielded a total of 248 documents. The title, abstract, and keywords of each article were then carefully examined to identify those that explicitly reported stability evaluations under outdoor conditions. A second filter was subsequently applied to ensure that the selected studies specifically addressed perovskite solar cells single junction with outdoor stability evaluations, resulting in a total of 57 relevant publications. A summary of the reviewed articles evaluating device performance under real-world operating conditions employing ISOS protocols is presented in Table S1, which corresponds to accelerated tests associated with real-life operating conditions. The collected articles were extracted from the Perovskite Database and the table includes key information such as T100, T90 or T80 values, as well as the country in which the tests were performed. Table S2 reports key information extracted from Scopus database such as T₁₀₀, T₉₀, or T₈₀ values, as well as the country in which the tests were conducted.

Table S1. Summary table compiling the reviewed articles that report the use the norms ISOS-O1, ISOS-LC-1 and ISOS-T3 in the Perovskite database for labcell devices¹.

ISOS-O-1						
Year	T100	T90	T80	Total hours	Country	Reference
2017		6		20	India	2
2018		88		800	India	3
2019		45		400	India	4
		48		480	China	5
		432		720	China	6
ISOS-LC-1						
2016		9		10	China	7
		336		336	China	8
2019		1000		1000	China	9
ISOS-T-3						
2016	80			80	China	10
2023		T98=250		250	China*	11

* In this article they used mini modules.

Table S2. Summary table compiling the reviewed articles in the Scopus database that report the stability of devices evaluated under real operating conditions.

Labcell							
Year	T100	T90	T80	Total hours	Country	Reference	
2015	168			168	Saudi Arabia	12	
2016			360	432	China	13	
			846	846	Spain	14	
2017			560	1100	India	15	
			9	20	India	2	
2018			216	336	Israel	16	
			96	408	Israel	17	
			41	41	Israel	18	
2019	It was completely degraded			10	India	4	
			T60=1800	1800	Qatar	19	
			450	1000	Israel	20	
		T98=2250		2250	China	21	
2020			96	480	Israel	22	
			240	500	India	23	
2021		T95=1272		1272	China	24	
			550	1000	Spain	25	
			85	370	Germany	26	
2022	7200			7200	Germany	27	
			T83=720	720	Saudi Arabia	28	
			T84=1500	2160	India	29	
2023	4032		600	600	Spain	30	
		T95=3000		4032	4032	Japan	31
				3000	3000	China	32
			750	750	Cyprus	33	
		3700		3700	USA	34	
			8760	8760	Germany	35	
		3908	6570	France	36		
2024			Not Clear	1200	Spain and Israel	37	
			Unreported	432	Cyprus, Israel and	38	
					Germany		
			300	1000	Israel	39	
			17000	21900	Germany	40	
			19710	24090	Germany and	41	
				Slovenia			
		2000	2000	India	42		
2025	8760			8760	USA	43	
			T85=35040	35040	Germany	44	

Minimodule						
Year	T100	T90	T80	Total hours	Country	Reference
2017	720			720	China	45
2018			240	720	United Kingdom	46
2019	500			500	Colombia	47
				1900	2000	Colombia
2021			1442	2200	Colombia	49
2022		T91,6=2000		1200	Norway	50
				2000	China	51
			960	2160	Belgium	52
2023			1440	1440	Italy	53
		240		240	South Korea	54
		There is no stability graph		1488	USA	55
2024			528	2400	Japan	56
		T93=2000		2000	China	57

		1104	1800	South Korea	58
	864		864	China	59
		T70=8400	8400	Ukraine and Poland	60
	4000		4000	France	61
		T91=280	720	China	62
	4872		4872	USA	63

Submodule						
Year	T100	T90	T80	Total hours	Country	Reference
2024	720			720	South Korea	64

Module						
Year	T100	T90	T80	Total hours	Country	Reference
2017	3360			3360	China	65
2020	6			6	Australia	66
2022			5832	8760	Greece	67
2024			336	3600	Italy	68

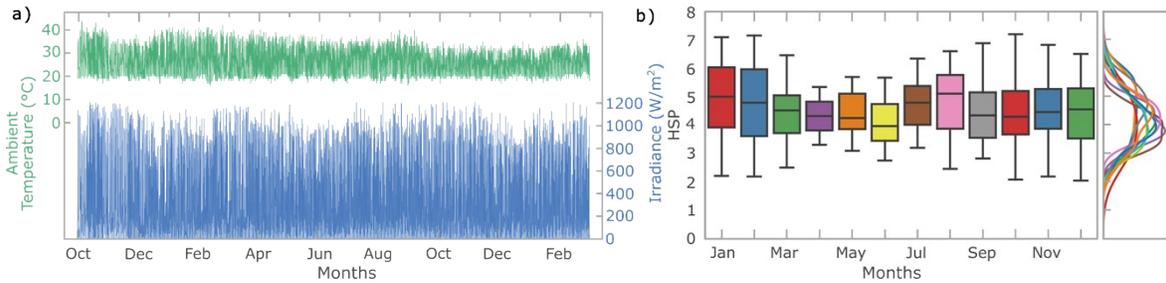


Figure S1. Weather variables conditions in tropical zones (Medellín, Colombia in the set-up showed in the Figure S2), **(a)** Continuous monitoring of irradiance (blue line) and ambient temperature (green line) over eighteen months, **(b)** Peak Sun Hours (PSH) monitoring over eleven months.



Figure S2. Assembly of a real-world solar station with its components and specifications. The station is installed at the University Research Center (SIU) of the Universidad de Antioquia ($6^{\circ}15'38''\text{N}$, $75^{\circ}34'05''\text{W}$) and is oriented south at a fixed tilt angle of 13° .

Supplementary Note 2

To enable a broader understanding of outdoor stability testing for perovskite solar cells (PSCs), we want to emphasize again that high-end infrastructure is not a must, and an acceptable and usable testing setup can be established with basic environmental sensors and inexpensive instrumentation. For irradiance: a class A pyranometer (eg Kipp & Zonen SMP11⁶⁹, or a calibrated reference silicon cell (eg PVPM Reference Cell by PV-Engineering⁷⁰ can be used depending on how strict you want to be. Basic temperature and humidity sensors, eg. Sensirion SHT85 or Bosch BME280, will produce good environmental data for not a lot of money, and microcontroller-based platforms will work well⁷¹.

When testing outdoors, you must also consider the difference between ambient temperature and actual device temperature, which can elevate by over 40°C from ambient temperature in full sun. Accurate monitoring of device temperature can be achieved by attaching NTC thermistors (e.g., EPCOS B57540G1⁷²) to the rear surface of the module and shielding them from direct solar exposure using reflective foil or ventilated enclosures⁷³. For mechanical positioning, low-cost single-axis solar trackers, such as those based on Arduino-controlled actuators or open-source designs like the Makersolar Sun Tracker v3⁷⁴ can significantly improve irradiance collection by maintaining optimal panel orientation throughout the day. Given the high V_{oc} typical of interconnected PSC modules, conventional Keithley-type potentiostats are often unsuitable due to their limited voltage capacity and high cost. As practical alternatives, we recommend programmable electronic loads (e.g., BK Precision 8600 series⁷⁵, compact source-measure units (e.g., Ossila SMU⁷⁶), or open-source IV curve tracer systems built around microcontroller architectures⁷⁷. These approaches enable scalable MPPT and are well aligned with the technical and economic constraints of long-term outdoor performance monitoring in PSC research.

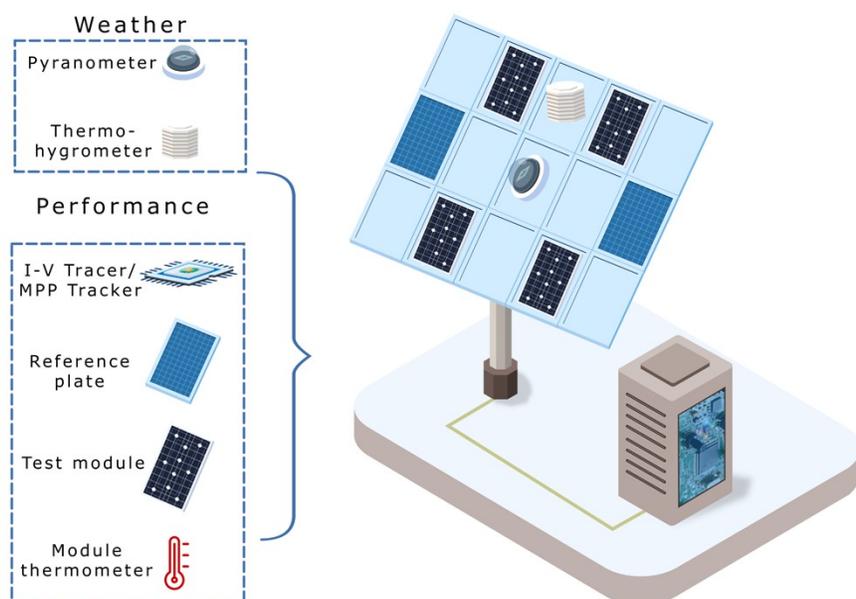


Figure S3. Simplified solar station and environmental monitoring setup to facilitate broader adoption of outdoor performance evaluation for perovskite solar cells under real-world conditions.

Supplementary Note 3

The research by Noor Titan et al advances a predictive model of aging for perovskite solar cells (PSCs) through the definition of a cycle yield ($\Phi(x)$) as the integral of power conversion efficiency (PCE) over time, normalized by the cycle length. The definition of cycle yield ($\Phi(x)$) allows references to temperatures when representing aging trends and is useful when defining temperature equivalent cycles. The use of the logarithmic-linear function along with cycle yield follows nonlinear modeling trends of degradation in PSCs as they transition through multiple cycles. The authors develop an equation based on time, for the equivalent cycle duration from a temperature (T_1) to a higher temperature (T_2), while minimizing the difference between the area under the cycle yield integrals at each temperature. This provides added confidence in the estimation of the degradation rate, as it relates to a projection of outdoor stability based on accelerated indoor testing of PSCs. Furthermore, the study suggests that equivalent cycle duration follows an Arrhenius-type equation, where the cycle duration exponentially decreases with temperature increase, while aging increases with the activation energy (E_a) and temperature (T). Correspondingly, the model thoughtfully outlines the use of accelerated aging protocols and in the case summarized, a six-month indoor test yielded predictions of up to that of 25 years of outdoor exposure. Consequently, there is increased confidence in the strength of estimates of PSC lifetimes.

References

- (1) The Perovskite Database. *The Perovskite Database Project*. <https://www.perovskitedatabase.com/> (accessed 2025-03-04).
- (2) Chauhan, A. K.; Kumar, P.; Pal, S. R.; Srivastava, S. K.; Muthiah, S. Air-processed organo-metal halide perovskite solar cells and their air stability. *J. Mater. Sci.* **2017**, *52* (18), 10886-10897. <https://doi.org/10.1007/s10853-017-1264-6>.
- (3) Chauhan, A. K.; Kumar, P. Photo-stability of perovskite solar cells with Cu electrode. *J. Mater. Sci. Mater. Electron.* **2019**, *30* (10), 9582-9592. <https://doi.org/10.1007/s10854-019-01292-2>.
- (4) Kumar, P.; Chauhan, A. K. Highly efficient flexible perovskite solar cells and their photo-

stability. *J. Phys. D. Appl. Phys.* **2020**, *53* (3), 035101. <https://doi.org/10.1088/1361-6463/ab4f07>.

- (5) Chen, Q.; Wang, W.; Xiao, S.; Cheng, Y.; Huang, F.; Xiang, W. Improved Performance of Planar Perovskite Solar Cells Using an Amino-Terminated Multifunctional Fullerene Derivative as the Passivation Layer. *ACS Appl. Mater. Interfaces* **2019**, *11* (30), 27145-27152. <https://doi.org/10.1021/acsami.9b07097>.
- (6) Zhang, F.; Yang, X.; Cheng, M.; Li, J.; Wang, W.; Wang, H.; Sun, L. Engineering of hole-selective contact for low temperature-processed carbon counter electrode-based perovskite solar cells. *J. Mater. Chem. A* **2015**, *3* (48), 24272-24280. <https://doi.org/10.1039/C5TA07507F>.
- (7) Liu, F.; Dong, Q.; Wong, M. K.; Djurišić, A. B.; Ng, A.; Ren, Z.; Shen, Q.; Surya, C.; Chan, W. K.; Wang, J.; Ng, A. M. C.; Liao, C.; Li, H.; Shih, K.; Wei, C.; Su, H.; Dai, J. Is Excess PbI₂ Beneficial for Perovskite Solar Cell Performance? *Adv. Energy Mater.* **2016**, *6* (7). <https://doi.org/10.1002/aenm.201502206>.
- (8) Huang, F.; Jiang, L.; Pascoe, A. R.; Yan, Y.; Bach, U.; Spiccia, L.; Cheng, Y.-B. Fatigue behavior of planar CH₃NH₃PbI₃ perovskite solar cells revealed by light on/off diurnal cycling. *Nano Energy* **2016**, *27*, 509-514. <https://doi.org/10.1016/j.nanoen.2016.07.033>.
- (9) Chen, C.; Zhuang, X.; Bi, W.; Wu, Y.; Gao, Y.; Pan, G.; Liu, D.; Dai, Q.; Song, H. Chemical inhibition of reversible decomposition for efficient and super-stable perovskite solar cells. *Nano Energy* **2020**, *68*, 104315. <https://doi.org/10.1016/j.nanoen.2019.104315>.
- (10) Liang, J.; Wang, C.; Wang, Y.; Xu, Z.; Lu, Z.; Ma, Y.; Zhu, H.; Hu, Y.; Xiao, C.; Yi, X.; Zhu, G.; Lv, H.; Ma, L.; Chen, T.; Tie, Z.; Jin, Z.; Liu, J. All-Inorganic Perovskite Solar Cells. *J. Am. Chem. Soc.* **2016**, *138* (49), 15829-15832. <https://doi.org/10.1021/jacs.6b10227>.
- (11) Yang, D.; Ma, M.; Li, Y.; Xie, G.; Ma, Y.; Wu, S.; Liu, C. FA cation replenishment-induced second growth of printed MA-free perovskites for efficient solar cells and modules. *Chem. Commun.* **2023**, *59* (11), 1521-1524. <https://doi.org/10.1039/D2CC06511H>.
- (12) Li, X.; Tschumi, M.; Han, H.; Babkair, S. S.; Alzubaydi, R. A.; Ansari, A. A.; Habib, S. S.; Nazeeruddin, M. K.; Zakeeruddin, S. M.; Grätzel, M. Outdoor Performance and Stability under Elevated Temperatures and Long-Term Light Soaking of Triple-Layer Mesoporous Perovskite Photovoltaics. *Energy Technol.* **2015**, *3* (6), 551-555. <https://doi.org/10.1002/ente.201500045>.
- (13) Dong, Q.; Liu, F.; Wong, M. K.; Tam, H. W.; Djurišić, A. B.; Ng, A.; Surya, C.; Chan, W. K.; Ng, A. M. C. Encapsulation of Perovskite Solar Cells for High Humidity Conditions. *ChemSusChem* **2016**, *9* (18), 2597-2603. <https://doi.org/10.1002/cssc.201600868>.
- (14) Reyna, Y.; Salado, M.; Kazim, S.; Pérez-Tomas, A.; Ahmad, S.; Lira-Cantu, M. Performance and stability of mixed FAPbI₃(0.85)MAPbBr₃(0.15) halide perovskite solar cells under outdoor conditions and the effect of low light irradiation. *Nano Energy* **2016**, *30*, 570-579. <https://doi.org/10.1016/j.nanoen.2016.10.053>.
- (15) Chauhan, A. K.; Kumar, P. Degradation in perovskite solar cells stored under different environmental conditions. *J. Phys. D. Appl. Phys.* **2017**, *50* (32), 325105. <https://doi.org/10.1088/1361-6463/aa7905>.
- (16) Khenkin, M. V.; K. M., A.; Visoly-Fisher, I.; Galagan, Y.; Di Giacomo, F.; Patil, B. R.; Sherafatipour, G.; Turkovic, V.; Rubahn, H.-G.; Madsen, M.; Merckx, T.; Uytterhoeven, G.;

- Bastos, J. P. A.; Aernouts, T.; Brunetti, F.; Lira-Cantu, M.; Katz, E. A. Reconsidering figures of merit for performance and stability of perovskite photovoltaics. *Energy Environ. Sci.* **2018**, *11* (4), 739-743. <https://doi.org/10.1039/C7EE02956J>.
- (17) Khenkin, M. V.; K. M., A.; Visoly-Fisher, I.; Kolusheva, S.; Galagan, Y.; Di Giacomo, F.; Vukovic, O.; Patil, B. R.; Sherafatipour, G.; Turkovic, V.; Rubahn, H.-G.; Madsen, M.; Mazanik, A. V.; Katz, E. A. Dynamics of Photoinduced Degradation of Perovskite Photovoltaics: From Reversible to Irreversible Processes. *ACS Appl. Energy Mater.* **2018**, *1* (2), 799-806. <https://doi.org/10.1021/acsaem.7b00256>.
- (18) Akbulatov, A. F.; Frolova, L. A.; Griffin, M. P.; Gearba, I. R.; Dolocan, A.; Vanden Bout, D. A.; Tsarev, S.; Katz, E. A.; Shestakov, A. F.; Stevenson, K. J.; Troshin, P. A. Effect of Electron-Transport Material on Light-Induced Degradation of Inverted Planar Junction Perovskite Solar Cells. *Adv. Energy Mater.* **2017**, *7* (19). <https://doi.org/10.1002/aenm.201700476>.
- (19) Ahmad, Z.; Shikoh, A. S.; Paek, S.; Nazeeruddin, M. K.; Al-Muhtaseb, S. A.; Touati, F.; Bhadra, J.; Al-Thani, N. J. Degradation analysis in mixed (MAPbI₃ and MAPbBr₃) perovskite solar cells under thermal stress. *J. Mater. Sci. Mater. Electron.* **2019**, *30* (2), 1354-1359. <https://doi.org/10.1007/s10854-018-0403-4>.
- (20) Siram, R. B. K.; Khenkin, M. V.; Niazov-Elkan, A.; K. M., A.; Weissman, H.; Katz, E. A.; Visoly-Fisher, I.; Rybtchinski, B. Hybrid organic nanocrystal/carbon nanotube film electrodes for air- and photo-stable perovskite photovoltaics. *Nanoscale* **2019**, *11* (8), 3733-3740. <https://doi.org/10.1039/C8NR09353A>.
- (21) Fu, Z.; Xu, M.; Sheng, Y.; Yan, Z.; Meng, J.; Tong, C.; Li, D.; Wan, Z.; Ming, Y.; Mei, A.; Hu, Y.; Rong, Y.; Han, H. Encapsulation of Printable Mesoscopic Perovskite Solar Cells Enables High Temperature and Long-Term Outdoor Stability. *Adv. Funct. Mater.* **2019**, *29* (16). <https://doi.org/10.1002/adfm.201809129>.
- (22) Khenkin, M. V.; Anoop, K. M.; Visoly-Fisher, I.; Di Giacomo, F.; Dogan, I.; Patil, B. R.; Turkovic, V.; Madsen, M.; Galagan, Y.; Ulbrich, C.; Katz, E. A. Peculiarities of perovskite photovoltaics degradation and how to account for them in stability studies. *Conf. Rec. IEEE Photovolt. Spec. Conf.* **2020**, *2020-June*, 0305-0308. <https://doi.org/10.1109/PVSC45281.2020.9300576>.
- (23) Nair, S.; Gohel, J. V. A study on optoelectronic performance of perovskite solar cell under different stress testing conditions. *Opt. Mater. (Amst.)* **2020**, *109*, 110377. <https://doi.org/10.1016/j.optmat.2020.110377>.
- (24) Chen, W.; Han, B.; Hu, Q.; Gu, M.; Zhu, Y.; Yang, W.; Zhou, Y.; Luo, D.; Liu, F.-Z.; Cheng, R.; Zhu, R.; Feng, S.-P.; Djurišić, A. B.; Russell, T. P.; He, Z. Interfacial stabilization for inverted perovskite solar cells with long-term stability. *Sci. Bull.* **2021**, *66* (10), 991-1002. <https://doi.org/10.1016/j.scib.2021.02.029>.
- (25) López-Vicente, R.; Abad, J.; Padilla, J.; Urbina, A. Assessment of Molecular Additives on the Lifetime of Carbon-Based Mesoporous Perovskite Solar Cells. *Energies* **2021**, *14* (7), 1947. <https://doi.org/10.3390/en14071947>.
- (26) Köbler, H.; Khenkin, M. V.; Roy, R.; Phung, N.; Emery, Q.; Remec, M.; Schlatmann, R.; Ulbrich, C.; Abate, A. The challenge of designing accelerated indoor tests to predict the outdoor lifetime of perovskite solar cells. agosto 17, 2021. <https://doi.org/10.21203/rs.3.rs-777413/v1>.
- (27) Emery, Q.; Remec, M.; Paramasivam, G.; Janke, S.; Dagar, J.; Ulbrich, C.; Schlatmann, R.;

- Stannowski, B.; Unger, E.; Khenkin, M. Encapsulation and Outdoor Testing of Perovskite Solar Cells: Comparing Industrially Relevant Process with a Simplified Lab Procedure. *ACS Appl. Mater. Interfaces* **2022**, *14* (4), 5159-5167. <https://doi.org/10.1021/acsmami.1c14720>.
- (28) Zheng, X.; Liu, J.; Liu, T.; Aydin, E.; Chen, M.; Yan, W.; De Bastiani, M.; Allen, T. G.; Yuan, S.; Kirmani, A. R.; Baustert, K. N.; Salvador, M. F.; Turedi, B.; Alsalloum, A. Y.; Almasabi, K.; Kotsovos, K.; Gereige, I.; Liao, L.-S.; Luther, J. M.; Graham, K. R.; Mohammed, O. F.; De Wolf, S.; Bakr, O. M. Photoactivated p-Doping of Organic Interlayer Enables Efficient Perovskite/Silicon Tandem Solar Cells. *ACS Energy Lett.* **2022**, *7* (6), 1987-1993. <https://doi.org/10.1021/acsenerylett.2c00780>.
- (29) Koiry, S. P.; Jha, P.; Sridevi, C.; Gupta, D.; Putta, V.; Chauhan, A. K. Improved water repellency and environmental stability of perovskite solar cells by encapsulating with paraffin wax. *Mater. Chem. Phys.* **2022**, *282*, 125954. <https://doi.org/10.1016/j.matchemphys.2022.125954>.
- (30) Karimipour, M.; Paingott Parambil, A.; Tabah Tanko, K.; Zhang, T.; Gao, F.; Lira-Cantu, M. Functionalized MXene/Halide Perovskite Heterojunctions for Perovskite Solar Cells Stable Under Real Outdoor Conditions. *Adv. Energy Mater.* **2023**, *13* (44). <https://doi.org/10.1002/aenm.202301959>.
- (31) Sekimoto, T.; Yamamoto, T.; Takeno, F.; Nishikubo, R.; Hiraoka, M.; Uchida, R.; Nakamura, T.; Kawano, K.; Saeki, A.; Kaneko, Y.; Matsui, T. Perovskite Solar Cell Using Isonicotinic Acid as a Gap-Filling Self-Assembled Monolayer with High Photovoltaic Performance and Light Stability. *ACS Appl. Mater. Interfaces* **2023**, *15* (28), 33581-33592. <https://doi.org/10.1021/acsmami.3c05215>.
- (32) Li, R.; Xu, Q.; Shi, B.; Wang, J.; Li, Y.; Chen, B.; Liu, J.; Ren, N.; Han, W.; Li, Y.; Sun, C.; Zhu, Z.; Zhang, Y.; Liu, P.; Han, X.; Dong, J.; Wang, X.; Huang, Z.; Gong, Y.; Xu, S.; Wang, P.; Huang, Q.; Zhang, D.; Du, X.; Ren, H.; Zhang, C.; Zhuang, H.; Zhao, Y.; Zhang, X. UV Encapsulated Monolithic Perovskite/Silicon Tandem Solar Cells for Hundred-Watt Power System. *ACS Energy Lett.* **2023**, *8* (5), 2414-2422. <https://doi.org/10.1021/acsenerylett.3c00275>.
- (33) Paraskeva, V.; Hadjipanayi, M.; Norton, M.; Aguirre, A.; Hadipour, A.; Song, W.; Fontanot, T.; Christiansen, S.; Ebner, R.; Georghiou, G. E. Long-Term Outdoor Testing of Perovskite Mini-Modules: Effects of FACl Additives. *Energies* **2023**, *16* (6). <https://doi.org/10.3390/en16062608>.
- (34) Jiang, Q.; Tirawat, R.; Kerner, R. A.; Gaulding, E. A.; Xian, Y.; Wang, X.; Newkirk, J. M.; Yan, Y.; Berry, J. J.; Zhu, K. Towards linking lab and field lifetimes of perovskite solar cells. *Nature* **2023**, *623* (7986), 313-318. <https://doi.org/10.1038/s41586-023-06610-7>.
- (35) Li, J.; Dagar, J.; Shargaieva, O.; Maus, O.; Remec, M.; Emery, Q.; Khenkin, M.; Ulbrich, C.; Akhundova, F.; Márquez, J. A.; Unold, T.; Fenske, M.; Schultz, C.; Stegemann, B.; Al-Ashouri, A.; Albrecht, S.; Esteves, A. T.; Korte, L.; Köbler, H.; Abate, A.; Töbrens, D. M.; Zizak, I.; List-Kratochvil, E. J. W.; Schlattmann, R.; Unger, E. Ink Design Enabling Slot-Die Coated Perovskite Solar Cells with >22% Power Conversion Efficiency, Micro-Modules, and 1 Year of Outdoor Performance Evaluation. *Adv. Energy Mater.* **2023**, *13* (33). <https://doi.org/10.1002/aenm.202203898>.
- (36) Medjoubi, K.; Dubois, A. M.; Castillon, J.; Guillemot, T.; Parra, J.; Provost, M.; Puel, J. B.; Rousset, J.; Medina Flechas, J. P.; Bainier, C.; Barrit, D.; Badosa, J.; Posada, J. Long Terms Stability and Metastable Behavior of Perovskite Solar Devices on Outdoor Conditions. *Conf. Rec. IEEE Photovolt. Spec. Conf.* **2023**, 1-3.

<https://doi.org/10.1109/PVSC48320.2023.10359985>.

- (37) Kouroudis, I.; Tanko, K. T.; Karimipour, M.; Ali, A. Ben; Kumar, D. K.; Sudhakar, V.; Gupta, R. K.; Visoly-Fisher, I.; Lira-Cantu, M.; Gagliardi, A. Artificial Intelligence-Based, Wavelet-Aided Prediction of Long-Term Outdoor Performance of Perovskite Solar Cells. *ACS Energy Lett.* **2024**, *9* (4), 1581-1586. <https://doi.org/10.1021/acsenerylett.4c00328>.
- (38) Erdil, U.; Khenkin, M.; Bernardes de Araujo, W. M.; Emery, Q.; Lauermann, I.; Paraskeva, V.; Norton, M.; VEDIAPPAN, S.; Kumar, D. K.; Gupta, R. K.; Visoly-Fisher, I.; Hadjipanayi, M.; Georghiou, G. E.; Schlatmann, R.; Abate, A.; Katz, E. A.; Ulbrich, C. Delamination of Perovskite Solar Cells in Thermal Cycling and Outdoor Tests. *Energy Technol.* **2025**, *13* (1). <https://doi.org/10.1002/ente.202401280>.
- (39) Gupta, R. K.; Kumar, D. K.; Sudhakar, V.; Beckedahl, J. M.; Abate, A.; Katz, E. A.; Visoly-Fisher, I. Seasonal Effects on Outdoor Stability of Perovskite Solar Cells. *Adv. Energy Mater.* **2025**, *15* (8). <https://doi.org/10.1002/aenm.202403844>.
- (40) Khenkin, M.; Köbler, H.; Remec, M.; Roy, R.; Erdil, U.; Li, J.; Phung, N.; Adwan, G.; Paramasivam, G.; Emery, Q.; Unger, E.; Schlatmann, R.; Ulbrich, C.; Abate, A. Light cycling as a key to understanding the outdoor behaviour of perovskite solar cells. *Energy Environ. Sci.* **2024**, *17* (2), 602-610. <https://doi.org/10.1039/D3EE03508E>.
- (41) Remec, M.; Tomšič, Š.; Khenkin, M.; Emery, Q.; Li, J.; Scheler, F.; Glažar, B.; Jankovec, M.; Jošt, M.; Unger, E.; Albrecht, S.; Schlatmann, R.; Lipovšek, B.; Ulbrich, C.; Topič, M. From Sunrise to Sunset: Unraveling Metastability in Perovskite Solar Cells by Coupled Outdoor Testing and Energy Yield Modelling. *Adv. Energy Mater.* **2024**, *14* (29). <https://doi.org/10.1002/aenm.202304452>.
- (42) Kr Rana, N.; Debata, S.; Kr Panda, S.; Pratap Singh, D.; Chander, N. Towards water-resistant perovskite solar cells: Electron-beam deposited SiO₂ layers for highly stable perovskite solar cells. *Sol. Energy* **2024**, *280*, 112874. <https://doi.org/10.1016/j.solener.2024.112874>.
- (43) Uličná, S.; Schall, J. W.; Hayden, S. C.; Irvin, N. P.; Silverman, T. J.; Fei, C.; Shi, X.; Arnold, R. L.; McDanold, B.; Parker, J.; Huang, J.; Berry, J. J.; Stein, J. S.; Kern, D. B.; Owen-Bellini, M.; Schelhas, L. T. Field-Relevant Degradation Mechanisms in Metal Halide Perovskite Modules. *Adv. Energy Mater.* **2025**. <https://doi.org/10.1002/aenm.202404518>.
- (44) Remec, M.; Khenkin, M.; Erdil, U.; Emery, Q.; Paramasivam, G.; Unger, E.; Schlatmann, R.; Albrecht, S.; Topič, M.; Ulbrich, C. Seasonality in Perovskite Solar Cells: Insights from 4 Years of Outdoor Data. *Adv. Energy Mater.* **2025**. <https://doi.org/10.1002/aenm.202501906>.
- (45) Hu, Y.; Si, S.; Mei, A.; Rong, Y.; Liu, H.; Li, X.; Han, H. Stable Large-Area (10 × 10 cm²) Printable Mesoscopic Perovskite Module Exceeding 10% Efficiency. *Sol. RRL* **2017**, *1* (2). <https://doi.org/10.1002/solr.201600019>.
- (46) Stoichkov, V.; Bristow, N.; Troughton, J.; De Rossi, F.; Watson, T. M.; Kettle, J. Outdoor performance monitoring of perovskite solar cell mini-modules: Diurnal performance, observance of reversible degradation and variation with climatic performance. *Sol. Energy* **2018**, *170*, 549-556. <https://doi.org/10.1016/j.solener.2018.05.086>.
- (47) Velilla, E.; Ramirez, D.; Uribe, J.-I.; Montoya, J. F.; Jaramillo, F. Outdoor performance of perovskite solar technology: Silicon comparison and competitive advantages at different irradiances. *Sol. Energy Mater. Sol. Cells* **2019**, *191*, 15-20. <https://doi.org/10.1016/j.solmat.2018.10.018>.

- (48) Ramirez, D.; Velilla, E.; Montoya, J. F.; Jaramillo, F. Mitigating scalability issues of perovskite photovoltaic technology through a p-i-n meso-superstructured solar cell architecture. *Sol. Energy Mater. Sol. Cells* **2019**, *195*, 191-197. <https://doi.org/10.1016/j.solmat.2019.03.014>.
- (49) Velilla, E.; Jaramillo, F.; Mora-Seró, I. High-throughput analysis of the ideality factor to evaluate the outdoor performance of perovskite solar minimodules. *Nat. Energy* **2021**, *6* (1), 54-62. <https://doi.org/10.1038/s41560-020-00747-9>.
- (50) Pitchaiya, S.; Eswaramoorthy, N.; Madurai Ramakrishnan, V.; Natarajan, M.; Velauthapillai, D. Bio-Inspired Graphitic Carbon-Based Large-Area (10×10 cm²) Perovskite Solar Cells: Stability Assessments under Indoor, Outdoor, and Water-Soaked Conditions. *ACS Appl. Mater. Interfaces* **2022**, *14* (38), 43050-43066. <https://doi.org/10.1021/acsami.2c02463>.
- (51) Feng, Q.; Huang, X.; Tang, Z.; Hou, Y.; Chang, Q.; Nie, S.; Cao, F.; Niu, X.; Yin, J.; Li, J.; Zheng, N.; Wu, B. Governing PbI₆ octahedral frameworks for high-stability perovskite solar modules. *Energy Environ. Sci.* **2022**, *15* (10), 4404-4413. <https://doi.org/10.1039/D2EE02162E>.
- (52) Paraskeva, V.; Hadjipanayi, M.; Norton, M.; Aguirre, A.; Hadipour, A.; Ebner, R.; Georghiou, G. E. Seasonal dependence of diurnal efficiency degradation and recovery in perovskite mini-modules during outdoor testing. *Conf. Rec. IEEE Photovolt. Spec. Conf.* **2022**, *2022-June*, 217-222. <https://doi.org/10.1109/PVSC48317.2022.9938726>.
- (53) Aime, G.; Ciocia, A.; Malgaroli, G.; Narbey, S.; Saglietti, L.; Spertino, F. Degradation Assessment for Prototypal Perovskite Photovoltaic Modules in Long Term Outdoor Experimental Campaign. *Proc. - 2023 IEEE Int. Conf. Environ. Electr. Eng. 2023 IEEE Ind. Commer. Power Syst. Eur. IEEEIC / I CPS Eur. 2023* **2023**, 1-5. <https://doi.org/10.1109/IEEEIC/ICPSEurope57605.2023.10194854>.
- (54) Lee, H.; Hong, S.; Lee, S.; Byun, K.; Kim, D.; Jang, J.; Kim, H. J. UV-Blocking and Transparent Polydimethylsiloxane Film for Improving Stability of Perovskite Photovoltaics. *ACS Appl. Opt. Mater.* **2023**, *1* (7), 1208-1216. <https://doi.org/10.1021/acsaoam.3c00002>.
- (55) Schall, J. W.; Glaws, A.; Doumon, N. Y.; Silverman, T. J.; Owen-Bellini, M.; Terwilliger, K.; Uddin, M. A.; Rana, P.; Berry, J. J.; Huang, J.; Schelhas, L. T.; Kern, D. B. Accelerated Stress Testing of Perovskite Photovoltaic Modules: Differentiating Degradation Modes with Electroluminescence Imaging. *Sol. RRL* **2023**, *7* (14). <https://doi.org/10.1002/solr.202300229>.
- (56) Tayagaki, T.; Hirooka, S.; Kobayashi, H.; Yamamoto, K.; Murakami, T. N.; Yoshita, M. Ion-migration analysis of degradation caused by outdoor exposure and accelerated stress testing in perovskite solar cells. *Sol. Energy Mater. Sol. Cells* **2024**, *272*, 112879. <https://doi.org/10.1016/j.solmat.2024.112879>.
- (57) Huang, C.; Tan, S.; Yu, B.; Li, Y.; Shi, J.; Wu, H.; Luo, Y.; Li, D.; Meng, Q. Meniscus-modulated blade coating enables high-quality α -phase formamidinium lead triiodide crystals and efficient perovskite minimodules. *Joule* **2024**, *8* (9), 2539-2553. <https://doi.org/10.1016/j.joule.2024.06.008>.
- (58) Yoo, J. J.; Lee, J.-W.; Ju, Y.; Kang, B. J.; Kim, Y.; Kim, B.-S.; Kim, Y. Y.; Shin, S. S.; Shin, T. J.; Jeon, N. J. Pyrophosphate interlayer improves performance of semi-transparent perovskite solar cells. *J. Mater. Chem. A* **2024**, *12* (20), 12126-12133. <https://doi.org/10.1039/D4TA00899E>.

- (59) Cao, F.; Zhan, S.; Dai, X.; Cheng, F.; Li, W.; Feng, Q.; Huang, X.; Yin, J.; Li, J.; Zheng, N.; Wu, B. Redox-Sensitive NiOx Stabilizing Perovskite Films for High-Performance Photovoltaics. *J. Am. Chem. Soc.* **2024**, *146* (17), 11782-11791. <https://doi.org/10.1021/jacs.4c00110>.
- (60) Babu, V.; Pineda, R. F.; Bizan, M.; Wojak, A.; Wierzowiecki, S.; Gervásio, J.; Szklarz, J.; Castriotta, L. A.; Carlo, A. Di. Perovskite Solar Module Enabled IoT Asset Tracking for Wildlife Conservation. *IEEE J. Photovoltaics* **2024**, *14* (2), 337-343. <https://doi.org/10.1109/JPHOTOV.2024.3355406>.
- (61) Chakar, J.; Oswald, F.; Dubois, A. M.; Stéphan, E.; Narbey, S.; Parra, J.; Puel, J.; Bonnassieux, Y. Six-Month Outdoor Performance Study of Stable Perovskite Solar Cells Under Real Operating Conditions. *Sol. RRL* **2024**, *8* (11). <https://doi.org/10.1002/solr.202400093>.
- (62) Zhang, G.; Zheng, Y.; Wang, H.; Ding, G.; Yang, F.; Xu, Y.; Yu, J.; Shao, Y. Shellac protects perovskite solar cell modules under real-world conditions. *Joule* **2024**, *8* (2), 496-508. <https://doi.org/10.1016/j.joule.2023.12.008>.
- (63) Fei, C.; Kuvayskaya, A.; Shi, X.; Wang, M.; Shi, Z.; Jiao, H.; Silverman, T. J.; Owen-Bellini, M.; Dong, Y.; Xian, Y.; Scheidt, R.; Wang, X.; Yang, G.; Gu, H.; Li, N.; Dolan, C. J.; Deng, Z. J. D.; Cakan, D. N.; Fenning, D. P.; Yan, Y.; Beard, M. C.; Schelhas, L. T.; Sellinger, A.; Huang, J. Strong-bonding hole-transport layers reduce ultraviolet degradation of perovskite solar cells. *Science* **2024**, *384* (6700), 1126-1134. <https://doi.org/10.1126/science.adi4531>.
- (64) Yun, H.; Seo, Y.; Seo, C.; Kim, H. S.; Yoo, S. Bin; Kang, B. J.; Jeon, N. J.; Jung, E. H. Surface Engineering of Tin Oxide Nanoparticles by pH Modulation Facilitates Homogeneous Film Formation for Efficient Perovskite Solar Modules. *Adv. Energy Mater.* **2024**, *14* (25). <https://doi.org/10.1002/aenm.202400791>.
- (65) Cai, L.; Liang, L.; Wu, J.; Ding, B.; Gao, L.; Fan, B. Large area perovskite solar cell module. *J. Semicond.* **2017**, *38* (1), 014006. <https://doi.org/10.1088/1674-4926/38/1/014006>.
- (66) Schwenzer, J. A.; Rakocevic, L.; Abzieher, T.; Rueda-Delgado, Di.; Moghadamzadeh, S.; Gharibzadeh, S.; Hossain, I. M.; Gehlhaar, R.; Richards, B. S.; Lemmer, U.; Paetzold, U. W. Toward Stable Perovskite Solar Cell Architectures: Robustness against Temperature Variations of Real-World Conditions. *IEEE J. Photovoltaics* **2020**, *10* (3), 777-784. <https://doi.org/10.1109/JPHOTOV.2020.2969785>.
- (67) Pescetelli, S.; Agresti, A.; Viskadourous, G.; Razza, S.; Rogdakis, K.; Kalogerakis, I.; Spiliarotis, E.; Leonardi, E.; Mariani, P.; Sorbello, L.; Pierro, M.; Cornaro, C.; Bellani, S.; Najafi, L.; Martín-García, B.; Del Rio Castillo, A. E.; Oropesa-Nuñez, R.; Prato, M.; Maranghi, S.; Parisi, M. L.; Sinicropi, A.; Basosi, R.; Bonaccorso, F.; Kymakis, E.; Di Carlo, A. Integration of two-dimensional materials-based perovskite solar panels into a stand-alone solar farm. *Nat. Energy* **2022**, *7* (7), 597-607. <https://doi.org/10.1038/s41560-022-01035-4>.
- (68) Bovesecchi, G.; Petitta, M.; Pierro, M.; Agresti, A.; Pescetelli, S.; Leonardi, E.; Di Carlo, A.; Cornaro, C. Outdoor Performance Monitoring Method for Degradation Studies of Perovskite Modules. *Prog. Photovoltaics Res. Appl.* **2025**, *33* (3), 445-461. <https://doi.org/10.1002/pip.3860>.
- (69) Kipp & Zonen. *Solar Radiation Measurement*. <https://www.kippzonen.com> (accedido 2025-07-25).

- (70) Engineering, P. *I-V Curve Tracers for the Photovoltaic Industry*. <https://pv-engineering.de/> (accedido 2025-07-25).
- (71) BOSCH. *We are Bosch Sensortec*. <https://www.bosch-sensortec.com> (accedido 2025-07-25).
- (72) TDK Corporation. *Temperature Sensors (NTC)*. <http://bit.ly/3HGLpbL> (accedido 2025-07-25).
- (73) Jordan, D. C.; Kurtz, S. R. Photovoltaic Degradation Rates—an Analytical Review. *Prog. Photovoltaics Res. Appl.* **2013**, *21* (1), 12-29. <https://doi.org/10.1002/pip.1182>.
- (74) Instructables (Autodesk, I. . *Solar tracker*. <https://bit.ly/4g0PMuX> (accedido 2025-07-25).
- (75) B&K Precision Corporation. *Model 8600B - DC Electronic Loads*. <https://bit.ly/3HPVKCf> (accedido 2025-07-25).
- (76) Ossila enabling Science. *Low Price Lab Equipment and Materials Worldwide*. <https://www.ossila.com/> (accedido 2025-07-25).
- (77) openpvtools. *Open Source Tools for PV Modeling*. <https://openpvtools.readthedocs.io/en/latest/> (accedido 2025-07-25).