Supplementary Information:

How to accelerate outdoor ageing of perovskite solar cells by indoor testing

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Supplementary Note 1: Cycled PCE function fitting

Supplementary Table S1 reports the number of solar cells used for accelerated aging tests.

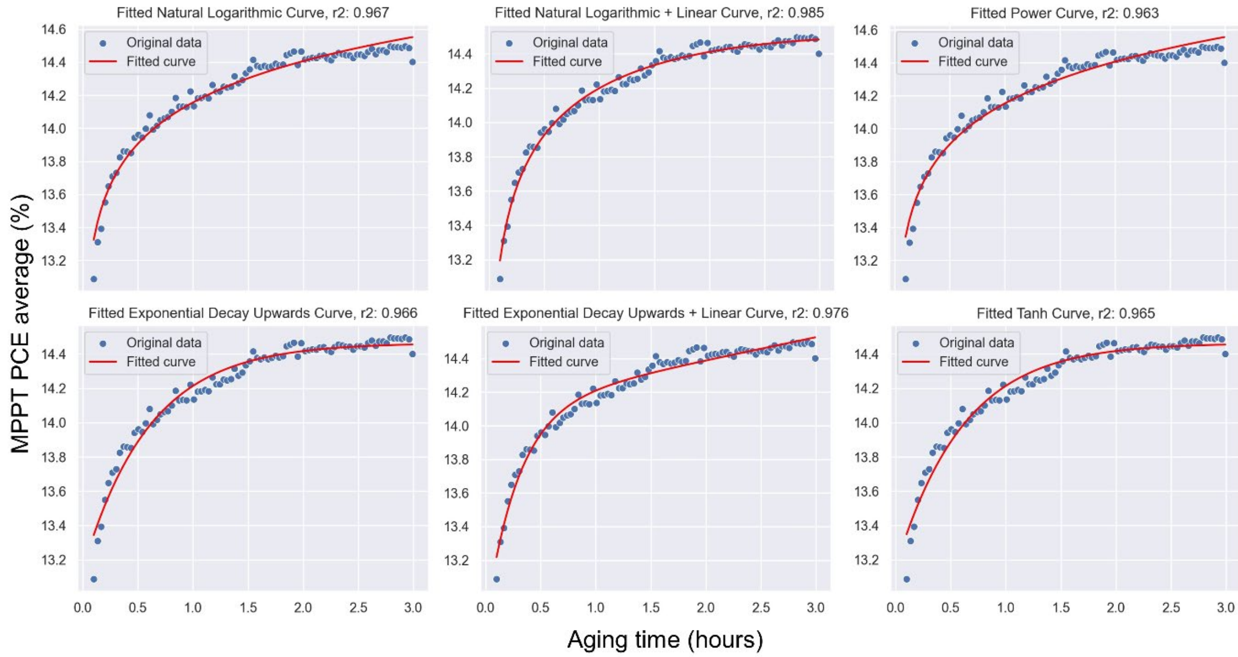
Temperature	**SAM-based total # cells**	**NiOx-based total # cells**	**NiO/SAM-based total # cells**
25°C	19	11	11
45°C	16	11	11
55°C	23	6	12

Supplementary Table S1. The table for the number of cells for SAM-, NiOx, and NiOx+SAM - based cells for a specific temperature.

To fit the PCE MPP curve over cycle length time, there are 6 possible functions that could "describe" this shape: exponential (**Supplementary Eq. 1**), logarithmic (**Supplementary Eq. 2**), exponential linear (**Supplementary Eq. 3**), logarithmic linear **Eq. 2**), power (**Supplementary Eq. 4**), and tanh (**Supplementary Eq. 5**), where T_1 is specific temperature/ cycle length, and t is the time for a specific cycle.

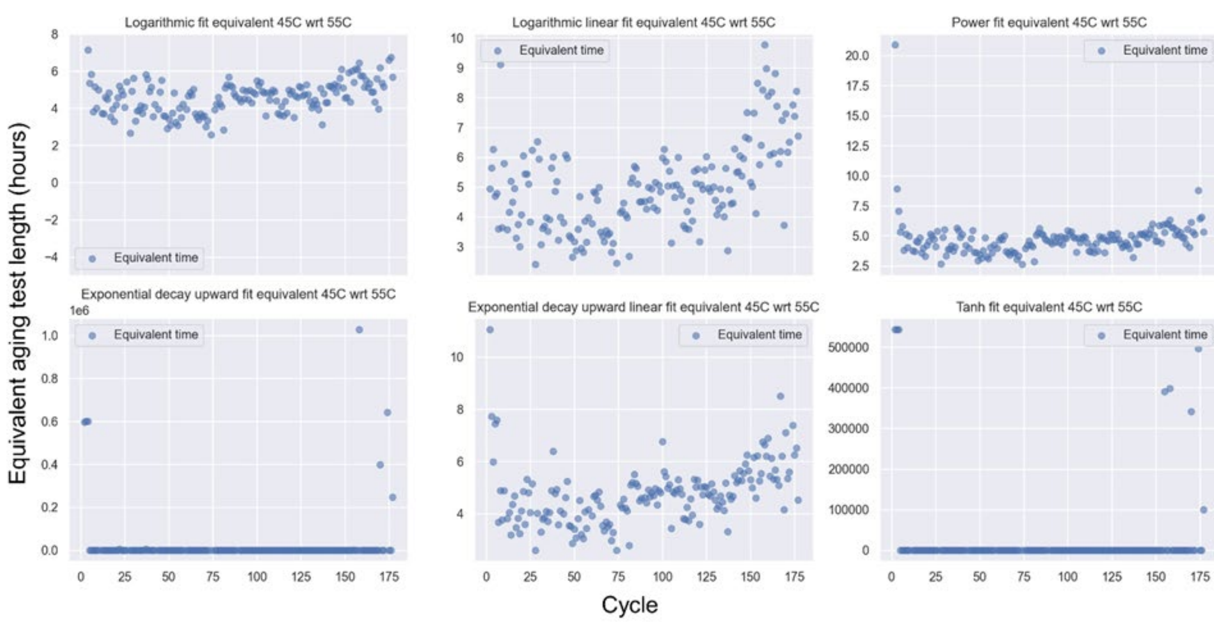
$f_{T1}(t) = ae^{-bt} + c$ (**Supplementary Eq. 1**)
$f_{T1}(t) = a(ln(bt)) + c$ (**Supplementary Eq. 2**)
$f_{T1}(t) = ae^{-bt} + ct + d$ (**Supplementary Eq. 3**)
$f_{T1}(t) = at^b$ (**Supplementary Eq. 4**)
$f_{T1}(t) = a(tanh(bt - c))$ (**Supplementary Eq. 4**)

The example of the various function fittings is shown in **Supplementary Fig. 1**, for SAM-based cells at 45°C, cycle 8. The r^2, indicating how good the fit is, is also shown in the figure. In this case, the logarithmic linear function has the best fit with the highest r^2 value, however that is not always the case across different temperatures and cycles.

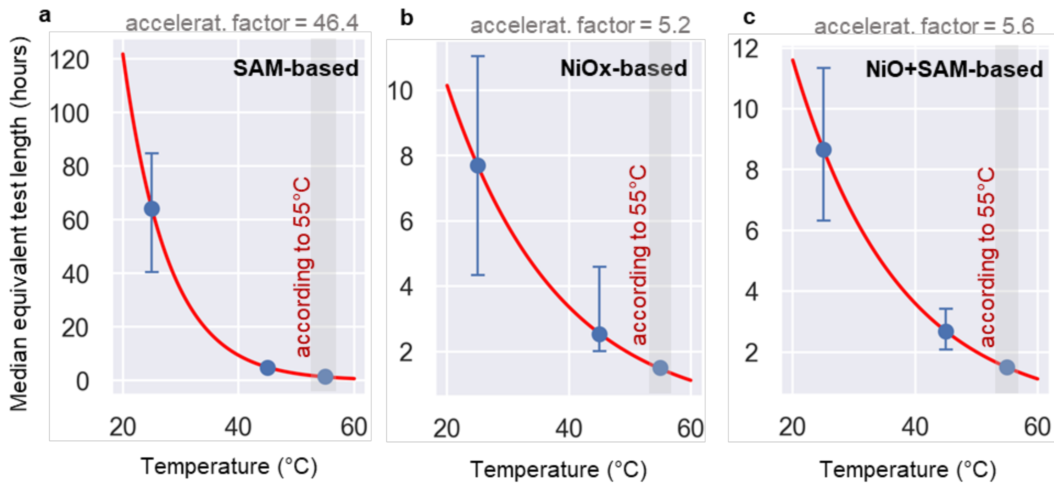


Supplementary Fig. 1. Example of various function fittings for SAM-based cells, at 45°C, cycle 8.

The choice to focus on logarithmic linear function stems from the fact that after backcalculation to find the equivalent test aging length based on data from specific temperature, the reasonable result comes from logarithmic linear or exponential linear function. For the others, the equivalent aging test length either goes to zero or negative values, or blows up to a really high number, with no physical meaning behind it (see **Supplementary Fig. 2**).



Supplementary Fig. 2. The fit examples for equivalent aging test at 25, 45°C based on 55°C ageing test length across cycles for SAM, based cells for different fitting functions.



Supplementary Fig. 3. Exponential function fitting on equivalent test length for SAM-, NiO, and NiO+SAM based cells. The median equivalent test lengths and acceleration factor are calculated across different temperatures, for 55 °C (131 °F) base temperature. Then, an exponential function is fitted, showing exponential reduction in equivalent test length as test temperature increases. The shaded points indicate the base temperatures, the red line indicates the exponential fit, and the error bars indicate 25th and 75th percentiles.

Supplementary Note 2: Arrhenius equation analysis

We have also performed Arrhenius analysis on the dataset; however, due to the multiple complex reaction processes during degradation of solar cells, the temperature and the rate constant of chemical reaction relationship is not as straightforward.

Arrhenius equation is often used to estimate the activation energy, E_a, of the PSC degradation process[11] (https://doi.org/10.1038/s41586-023-06610-7). We also performed an Arrhenius analysis to estimate E_a. We found that acceleration factor analysis does not directly align with the Arrhenius equation, which typically correlates the rate constant of a chemical reaction with temperature. On the other hand , it exhibits an analogous exponential decay trend. Although an Arrhenius analysis was conducted on the dataset (**Supplementary Note 2: Arrhenius equation analysis, Supplementary Fig. 5**), the complex nature of the degradation processes in solar cells complicates the straightforward relationship between temperature and the rate constant of chemical reactions. This complexity is in contrast to continuous MPPT aging tests, where the relationship is more obvious[11] (https://doi.org/10.1038/s41586-023-06610-7). In our study, the cycled light aging test introduces transient processes at the start of each cycle, adding layers of complexity. Moreover, multiple parameters, including energy yield (as explored in this work), maximum or average power conversion efficiency (PCE) at the maximum power point (MPP), and maximum or average voltage at MPP (V_{MPP}), among others, need evaluation in the accelerated cycle test setup. Our research presents a streamlined approach to explore this relationship, extract the acceleration factor, and systematically reduce the cycled aging test length. This practical framework provides researchers with an efficient means to assess the stability of perovskite solar cells at an accelerated pace.

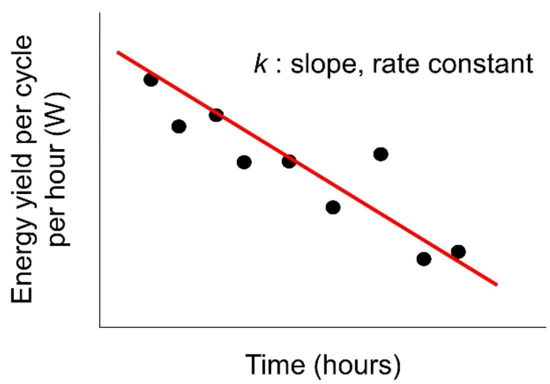
Supplementary Eq. 4 shows the Arrhenius equation, where k is the rate constant, A is the pre-exponential factor, E_a is the activation energy, R is the universal gas constant, and T is the absolute temperature. We can also rearrange the equation to fit a linear equation, where m is the slope, that depends on the activation energy, and the constant c that depends on the pre-exponential factor.

$$k = Ae^{\frac{-E_a}{RT}}$$

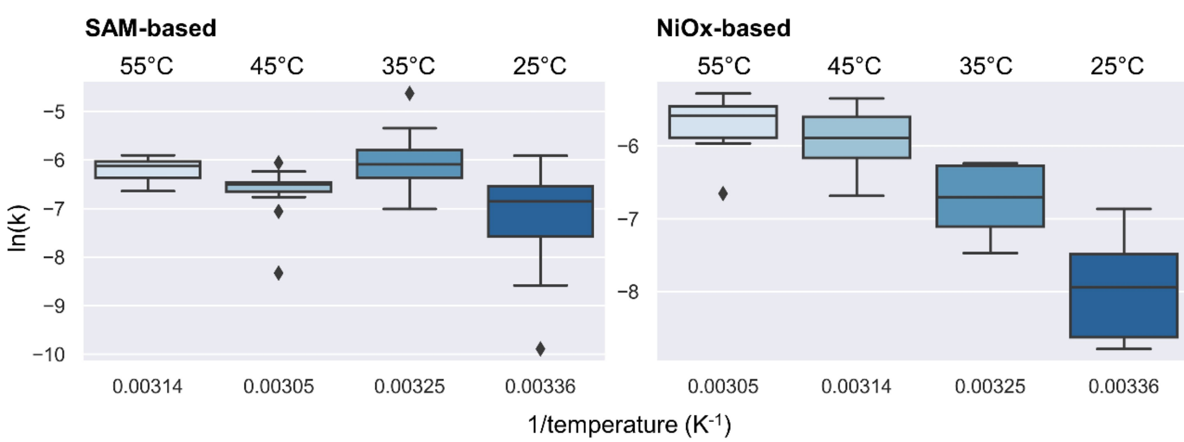
$$ln(k) = -\frac{E_a}{R}\left(\frac{1}{T}\right) + ln(A)$$

$ln(k) = m\left(\frac{1}{T}\right) + c, where\ m = -\frac{E_a}{R}, c = ln(A)$ (**Supplementary Eq. 5**)

In our dataset, the rate constant can be extracted from the slope of the aging time against energy yield per cycle per hour (see schematic example in **Supplementary Fig. 4**). This is similar to **Fig. 2b**, however, in the case of **Fig. 2b**, the *x*-axis is cycle, not time, which leads to a similar rate constant (hence, similar degradation rate across cycles for different temperatures). After the slope, i.e. the rate constant (k) is extracted, $ln(k)$ is calculated, to see the Arrhenius relationship, as shown in **Supplementary Fig. 5**, that shows as the temperature increases, we observe a higher rate constant for the degradation process. Based on this result, we can extract the m and c values, allowing us to know the activation energy E_a.



Supplementary Fig. 4. The schematic of how rate constant is extracted from the slope of the energy yield per cycle per hour across time, similar to **Fig. 3b**. However, note that in **Fig. 3b**, the *x*-axis is cycle, not time, which leads to a similar rate constant in that case.



Supplementary Fig. 5. Fitting the Arrhenius equation with the data for both SAM- and NiOx-based solar cells. Generally, the Arrhenius relationship hold, where higher temperature leads to higher rate constant ($ln(k)$).

Supplementary Note 3: Default testing condition

We also performed a test to look at the default testing condition, when there is no set temperature/ active cooling in the sample holder, and is under 1-sun illumination. The ambient temperature is (25±0.5)°C. **Supplementary Table S2** shows the recorded data in the sample holder over time.

Time (minutes)	Temperature of sample holder (°C)
0	24.2
4	29.0
12	29.7
40	29.1
100	28.5
200	28.5

Supplementary Table S2. The temperature of the sample holder when ambient temperature is (25±0.5)°C, no active cooling, and under 1-sun illumination.

Supplementary Note 4: fitted parameters

The exponential reduction of equivalent length is depicted through the exponent fitting parameters, which are presented in **Table S3**. The corresponding acceleration factors are provided alongside.

Cells type	base T, °C	a_fit	b_fit	r_squared	25°C eq. cycle time	55°C eq. cycle time	Acceleration factor_25C_55C
SAM	25	45.71	-0.053	0.95	11.88	2.36	5.03
SAM	45	1232.16	-0.126	0.99	52.29	1.17	44.32
SAM	55	1573.80	-0.127	0.99	64.24	1.38	46.44
NiOx	25	71.85	-0.071	0.98	11.94	1.38	8.60
NiOx	45	112.3	-0.076	0.99	16.62	1.67	9.89
NiOx	55	37.35	-0.058	1	8.65	1.49	5.77
NiO+SAM	25	57.28	-0.062	0.99	11.96	1.82	6.54
NiO+SAM	45	108.45	-0.075	0.99	16.26	1.66	9.74
NiO+SAM	55	30.58	-0.055	0.99	7.70	1.47	5.23

Supplementary Table S3. Exponent fitting parameters and corresponding acceleration factors