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Solar Cells Reporting Summary

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Experimental design

Please check: are the following details reported in the manuscript?

1. Dimensions

Area of the tested solar cells	☒ Yes ☐ No	The active area of perovskite modules is 12 cm2. The information can be found in the Methods and Supplementary Fig. 2.
Method used to determine the device area	☒ Yes ☐ No	No shadow mask was used for measurement of the perovskite solar modules. The active area of the perovskite modules is 12 cm2, determined by the overlap areas of top and bottom electrodes. The information can be found in the Methods and Supplementary Fig. 2.

2. Current-voltage characterization

Current density-voltage (J-V) plots in both forward and backward direction	☐ Yes ☒ No	The main object of this work is to realistically assess the environmental impact of toxic lead leaked from damaged perovskite solar modules and to report a new encapsulation method that can prevent Pb leakage. We used our reported recipe to prepare the perovskite solar modules. (Jiang, Y. et al. Combination of Hybrid CVD and Cation Exchange for Upscaling Cs-Substituted Mixed Cation Perovskite Solar Cells with High Efficiency and Stability. Adv. Funct. Mater. 28, 1703835, (2018).) In that work, we showed the current-voltage (J-V) plots in both forward and backward direction. For example, a perovskite solar module showed a power conversion efficiency of 14.6% from forward to backward scan and 12.4% from backward to forward scan.
Voltage scan conditions *For instance: scan direction, speed, dwell times*	☒ Yes ☐ No	The J-V curves were scanned in the forward to backward direction at a speed of 0.2 V/s. The information can be found in the Methods.
Test environment *For instance: characterization temperature, in air or in glove box*	☒ Yes ☐ No	The J-V curves were measured at ~25 deg. C in ambient (relative humidity ~60%) without encapsulation. The information can be found in the Methods.
Protocol for preconditioning of the device before its characterization	☒ Yes ☐ No	10 s pre-illumination and no pre-bias were applied for the the J-V measurements. The information can be found in the Methods.
Stability of the J-V characteristic *Verified with time evolution of the maximum power point or with the photocurrent at maximum power point; see ref. 7 for details.*	☐ Yes ☒ No	The main object of this work is to realistically assess the environmental impact of toxic lead leaked from damaged perovskite solar modules and to report a new encapsulation method that can prevent Pb leakage. We used our reported recipe to prepare the perovskite solar modules. (Jiang, Y. et al. Combination of Hybrid CVD and Cation Exchange for Upscaling Cs-Substituted Mixed Cation Perovskite Solar Cells with High Efficiency and Stability. Adv. Funct. Mater. 28, 1703835, (2018).) In that work, we showed the steady-state measurement at the solar cell maximum power point condition. For example, when the measurement was performed in a N2-filled glovebox with relative humidity of 5%, the solar cell showed a stabilized power conversion efficiency of 14.0% in 1200 min with negligible decay.

3. Hysteresis or any other unusual behaviour

Description of the unusual behaviour observed during the characterization	☐ Yes ☒ No	The main object of this work is to realistically assess the environmental impact of toxic lead leaked from damaged perovskite solar modules and to report a new encapsulation method that can prevent Pb leakage. We used our reported recipe to prepare the perovskite solar modules. (Jiang, Y. et al. Combination of Hybrid CVD and Cation Exchange for Upscaling Cs-Substituted Mixed Cation Perovskite Solar Cells with High Efficiency and Stability. Adv. Funct. Mater. 28, 1703835, (2018).) In that work, we showed the hysteresis behavior in the current-voltage (J-V) plots from the forward and backward scan directions. For example, a perovskite solar module showed a power conversion efficiency of 14.6% from forward to backward scan and 12.4% from backward to forward scan. To accurately access the device performance, we performed the steady-state measurement at the solar cell maximum power point condition.
Related experimental data	☐ Yes ☒ No	The main object of this work is to realistically assess the environmental impact of toxic lead leaked from damaged perovskite solar modules and to report a new encapsulation method that can prevent Pb leakage. We used our reported recipe to prepare the perovskite solar modules. (Jiang, Y. et al. Combination of Hybrid CVD and Cation Exchange for Upscaling Cs-Substituted Mixed Cation Perovskite Solar Cells with High Efficiency and Stability. Adv. Funct. Mater. 28, 1703835, (2018).) In that work, we showed the experimental data reflecting the J-V hysteresis behavior. For example, a perovskite solar module showed a power conversion efficiency of 14.6% from forward to backward scan and 12.4% from backward to forward scan.

4. Efficiency

External quantum efficiency (EQE) or incident photons to current efficiency (IPCE)	☐ Yes ☒ No	The main object of this work is to realistically assess the environmental impact of toxic lead leaked from damaged perovskite solar modules and to report a new encapsulation method that can prevent Pb leakage. We used our reported recipe to prepare the perovskite solar modules. (Jiang, Y. et al. Combination of Hybrid CVD and Cation Exchange for Upscaling Cs-Substituted Mixed Cation Perovskite Solar Cells with High Efficiency and Stability. Adv. Funct. Mater. 28, 1703835, (2018).) In that work, we showed the EQE results. For examples, EQE is higher than 80% at wavelength between 400-700 nm.
A comparison between the integrated response under the standard reference spectrum and the response measure under the simulator	☐ Yes ☒ No	The main object of this work is to realistically assess the environmental impact of toxic lead leaked from damaged perovskite solar modules and to report a new encapsulation method that can prevent Pb leakage. We used our reported recipe to prepare the perovskite solar modules. (Jiang, Y. et al. Combination of Hybrid CVD and Cation Exchange for Upscaling Cs-Substituted Mixed Cation Perovskite Solar Cells with High Efficiency and Stability. Adv. Funct. Mater. 28, 1703835, (2018).) In that work, we compared the integrated EQE and the current measured under the simulator. The two values match very well with a variation of less than 2.0%.
For tandem solar cells, the bias illumination and bias voltage used for each subcell	☐ Yes ☒ No	Perovskite solar modules investigated in this work are not tandem solar cells.

5. Calibration

Light source and reference cell or sensor used for the characterization	☒ Yes ☐ No	Xenon-lamp (USHIO, UXL-150SO) based solar simulator (Oriel Sol 1A) was used for J-V characterizations. The solar simulator illumination intensity was calibrated using a calibrated silicon detector (Oriel Instruments Model 91150V). The information can be found in the Methods.
Confirmation that the reference cell was calibrated and certified	☒ Yes ☐ No	The reference silicon detector (Oriel Instruments Model 91150V) was calibrated and certified by NREL. The information can be found in the Methods.
Calculation of spectral mismatch between the reference cell and the devices under test	☐ Yes ☒ No	No spectral mismatch calculation was performed.

6. Mask/aperture

Size of the mask/aperture used during testing	☐ Yes ☒ No	No mask/aperture was used during the test.
Variation of the measured short-circuit current density with the mask/aperture area	☒ Yes ☐ No	The perovskite solar modules without encapsulation showed short-circuit current density (Jsc) from 3.65 to 3.66 mA/cm2. The information can be found in the Supplementary Table 1.

7. Performance certification

Identity of the independent certification laboratory that confirmed the photovoltaic performance	☐ Yes ☒ No	We did not send our perovskite solar modules to a certification laboratory for performance certification. The performance is achieved in our lab using a solar simulator with intensity calibrated to 1 sun.

A copy of any certificate(s)
Provide in Supplementary Information

☐ Yes
☒ No

We did not send our devices to a certification laboratory for performance certification.

8. Statistics

Number of solar cells tested

☒ Yes
☐ No

A total of 12 perovskite solar modules were tested.

Statistical analysis of the device performance

☒ Yes
☐ No

J-V measurements were performed on a total of 12 encapsulated modules (3 perovskite solar modules for each encapsulation method) to study the effect of encapsulation methods on the module performance. The current density (Jsc), photovoltage (Voc), FF and power conversion efficiency (PCE) are shown in the Supplementary Table 1.

9. Long-term stability analysis

Type of analysis, bias conditions and environmental conditions
For instance: illumination type, temperature, atmosphere humidity, encapsulation method, preconditioning temperature

☐ Yes
☒ No

The main object of this work is to realistically assess the environmental impact of toxic lead leaked from damaged perovskite solar modules and to report a new encapsulation method that can prevent Pb leakage. We used our reported recipe to prepare the perovskite solar modules. (Jiang, Y. et al. Combination of Hybrid CVD and Cation Exchange for Upscaling Cs-Substituted Mixed Cation Perovskite Solar Cells with High Efficiency and Stability. Adv. Funct. Mater. 28, 1703835, (2018).) In that work, we showed the steady-state measurement at the solar cell maximum power point condition. For example, when the measurement was performed in a N2-filled glovebox with relative humidity of 5% at ~25 deg. C under 1 sun, the solar cell without encapsulation showed a stabilized power conversion efficiency of 14.0% in 1200 min with negligible decay.