Supporting Information

Challenging Conventional Assumptions in PV: A High-Throughput Open-Air Approach to Low-Cost Perovskite Module Production

Austin C. Flick and Reinhold H. Dauskardt*

Device Fabrication Experimental References

Conventional Perovskite Module Fabrication: sputtered ITO substrates reference the performance and thickness of 10 Ω sq^{-1} commercially available ITO from Xin Yan Technology, Ltd. Poly(triaryl amine) (PTAA) films for the HTL were based on the procedures by Ouyang *et al.*, Küffner *et al.*, Wu *e al.*, and Fei *et al.*[1]–[5] Perovskite deposition followed blade-coating recipes adapted from Ouyang *et al.*, Küffner *et al.*, Wu *e al.*, and Fei *et al.*[2]–[5] Electron transport layers consisting of a 40 nm layer of C_{60} followed by a 7.5 nm layer of bathocuproine deposited by thermal evaporation followed the recipes outlined in Scheideler *et al.*[6], Rolston *et al.*[7], and Flick *et al.*[8] A 150 nm thick Ag metal electrode deposited by thermal evaporation references the recipes in Scheideler *et al.*, Rolston *et al.*, and Flick *et al.* For module integration, P1, P2, and P3 scribes are based on the average direct ablative scribes outlined in Flick *et al.*[8]

Open-Air Spray-Deposited Perovskite Module Fabrication: The front ITO electrode utilizes spray-deposited and combustion oxidation with rapid plasma (CORP) chemistry employing an Impact ultrasonic spray system (Sonotek) to deposit the CORP precursor solution followed by a N_2 blown-arc discharge with an Ar-forming gas shrouded plasma cure (Plasmatreat). The NiO_x HTL references the ultrasonic spray deposition recipe in Scheideler *et al.* The perovskite layer references the rapid spray plasma process (RSPP) developed in Hilt *et al.*[9] The ETL bilayer utilizes spray-deposition with an identical Impact ultrasonic spray system and annealed with a near infrared rapid thermal processing (NIR-RTP) unit (Adphos). Lastly, the rear electrode utilizes spray-deposition with an Impact spray system and silver nanowires (Asahi Singapore).

Optoelectronic Characterization: The open-air manufactured perovskite devices modeled were measured in ambient conditions (≈45% RH, 25 °C) under 1 sun, AM 1.5G illumination from a 300 W xenon lamp (Oriel PV) solar simulator. The lamp intensity was calibrated based on an NREL-calibrated KG5 filtered Si reference cell. *J*–*V* curves were collected with a Keithley Model

2400 digital multimeter measured between −0.1 and 1.4 V for the control devices with an increment of 0.01 V and a delay of 0.1 s between points. For the spin-coated modules, the voltage ranged from -0.1 and 4.8 V with an increment of 0.04 V and a delay of 0.1 s between points. For the RSPP modules, the voltage ranged from -0.1 and 20 V with an increment of 0.2 V and a delay of 0.1 s between points.

Equipment Costs

Equipment costs include quoted prices modified by tool depreciation and 7% taxes, shipping, and tariffs (r_{tst}). A conservative equipment scaling factor of 0.9 is employed to account for GW-scale manufacturing where the amount of equipment far exceeds the original quoted volume. Facilitation (electrical connections, waste, etc.) is fixed at $50k for each process. Commissioning and training for each process is fixed at $50k.

$$Depreciation\ (years) = \frac{5}{\left(Runtime_{tool} / Runtime_{factory} \right)^{n}},\ 0 < n < 1 \qquad \text{(Equation S1)}$$

$$Equipment\ Cost = \frac{Cost_{quote}}{Depreciation} \times (1 + r_{tst}) \qquad \text{(Equation S2)}$$

The depreciation discount factor *n* modifies the tool depreciation by the relative runtime of each tool to account for large variations in processing throughputs. The average open-air spray process throughput is 87 mod/hr, resulting in an average spray process uptime of 36%. The average vacuum-based process (e.g., sputter, thermal evaporation) throughput is 25 mod/hr, resulting in an average process uptime of 90%. A depreciation discount factor, *n*, of 0.5 results in a minimum depreciation period of 5 years (sputtered ITO, 11 mod/hr throughput) and a maximum depreciation period of 15 years (RSPP perovskite, 306 mod/hr throughput).

Number of tools per process, *i*: $$N_{tools,i} = \frac{N_{mod/year}}{N_{\frac{mod}{tool}/year}},\ \text{round up} \qquad \text{(Equation S3)}$$

Annual number of modules per process, *i*: $$N_{\frac{mod}{tool}\frac{}{year},i} = \frac{v_i}{L_{mod}} \times t_{\frac{on}{year},i} \qquad \text{(Equation S4)}$$

For process *i*, throughput v_i, module processing length L_{mod}, and factory runtime per year $t_{on/year}$.

Facilities

Facilities floor space per processing station is assumed as 50 m^2 for the equipment and walkways, 50 m^2 for module handling and logistics, and 25 m^2 for office and maintenance staff.

Production Yield

Factory yield losses are assumed globally as 5%. Individual yields per process were not considered.

Labor

Wages are provided from the 2022 California Bureau of Labor Statistics. Additional compensation and benefits is assumed as 35% on top of the baseline wages. The model assumes 1 direct operator per shift per tool and 0.25 first-line supervisors per shift per tool.

Maintenance

Maintenance costs per tool are assumed as 4% of the initial capital investment. Individually catered maintenance costs were not calculated based on the specific process. Maintenance personnel are assumed as 2 people per shift pert tool across 4 shifts per week during 6 weeks per year.

Utilities

$$C_{util,i} = E_{elec,i} \times C_{elec} \quad \text{(Equation S5)}$$

$$E_{elec,i} = P_{elec/nozzle,i} \times N_{nozzles,i} \times t_{on/year,i} \quad \text{(Equation S6)}$$

$$t_{on/year,i} = t_i \times N_{mod/year} \quad \text{(Equation S7)}$$

For electricity costs *C* per process *i*, the electricity required per process $E_{elec,I}$, and the power used by each individual component or nozzle *P*, and the number of components or nozzles *N*.

Materials Costs

Salts and Solvents

Materials Cost per material, j: $C_{mat,\,j,per\ unit} = \left\{ \$/g \right\}_j \times X_j$ (Equation S8)

Scaling Multiplier: $$X_j = \left(\frac{V_{prod,j} / f_{shipment}}{V_{quote,j}} \right)^{(\alpha_i - 1)}$$ (Equation S9)

Production Volume: $V_{prod,j} = N_{mod/year} \times c_j \times LD_j$ (Equation S10)

Liquid Dose: $$LD_j = \left(FR_{sol,j} \times N_{nozzles,parallel,j} \times t_j \right) \left(\frac{1}{UF_j} \right)$$ (Equation S11)

Number of Parallel Nozzles: $N_{nozzles,parallel,j} = \left(\frac{W_{mod}}{W_{nozzle,j}}\right) + N_{nozzles,excess,j}$ (Equation S12)

Processing Time per process, i: $t_i = \frac{N_{passes} \times L_{mod}}{v_i}$ (Equation S13)

Materials Costs per material:
$C_{mat,j,\,per\,year} = C_{mat,j,\,per\,unit} \times c_i \times LD_j \times N_{mod/year} \times (1 + r_{taxes})$ (Equation S14)

Materials Costs per step i and material j: $C_{i,per\,year} = \sum_j C_{j,\,per\,year}$ (Equation S15)

For materials shipment frequency f, concentration c, flow rate FR, and utilization factor UF to account for wasted processing materials.

Process Gases

Gas Demand: $GD_j = (FR_{gas,j} \times N_{nozzles,parallel,j} \times t_j)\left(\frac{1}{UF_j}\right)$ (Equation S16)

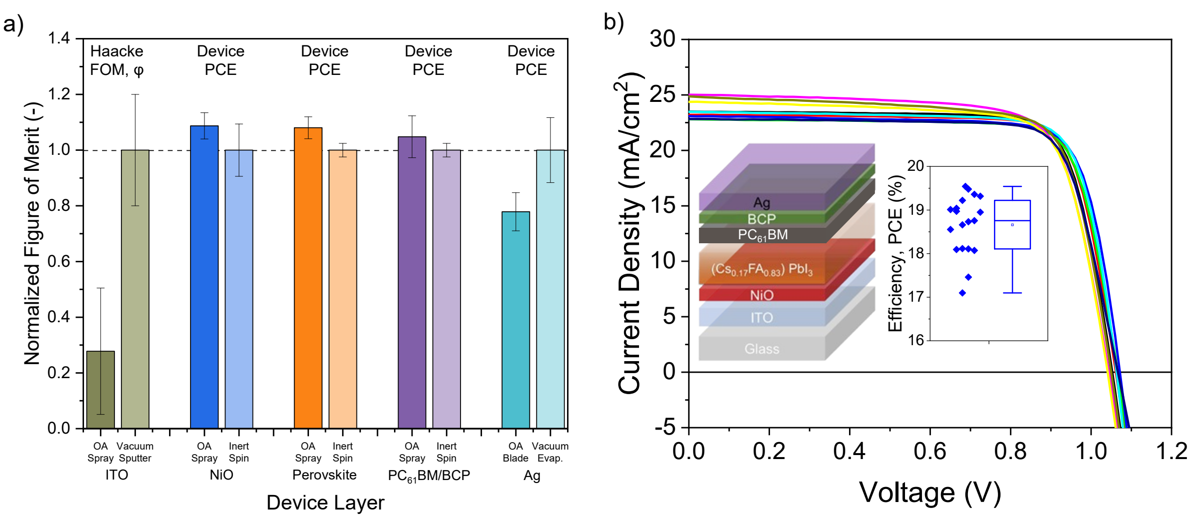


Figure S1: a) Figure of Merit (FOM) performance of modeled open-air perovskite device fabrication techniques against conventional fabrication alternatives for identical materials. OA refers to open-air deposition, Vacuum refers to deposition at ~1E-6 torr, and Inert refers to deposition in an N_2 glovebox. Spray refers to ultrasonic spray coating, Sputter refers to magnetron sputter deposition, Spin refers to spin-coating, Blade refers to blade-coating, and Evap. refers to thermal evaporation. b) Reference open-air manufactured perovskite device performances used in the module design calculations.

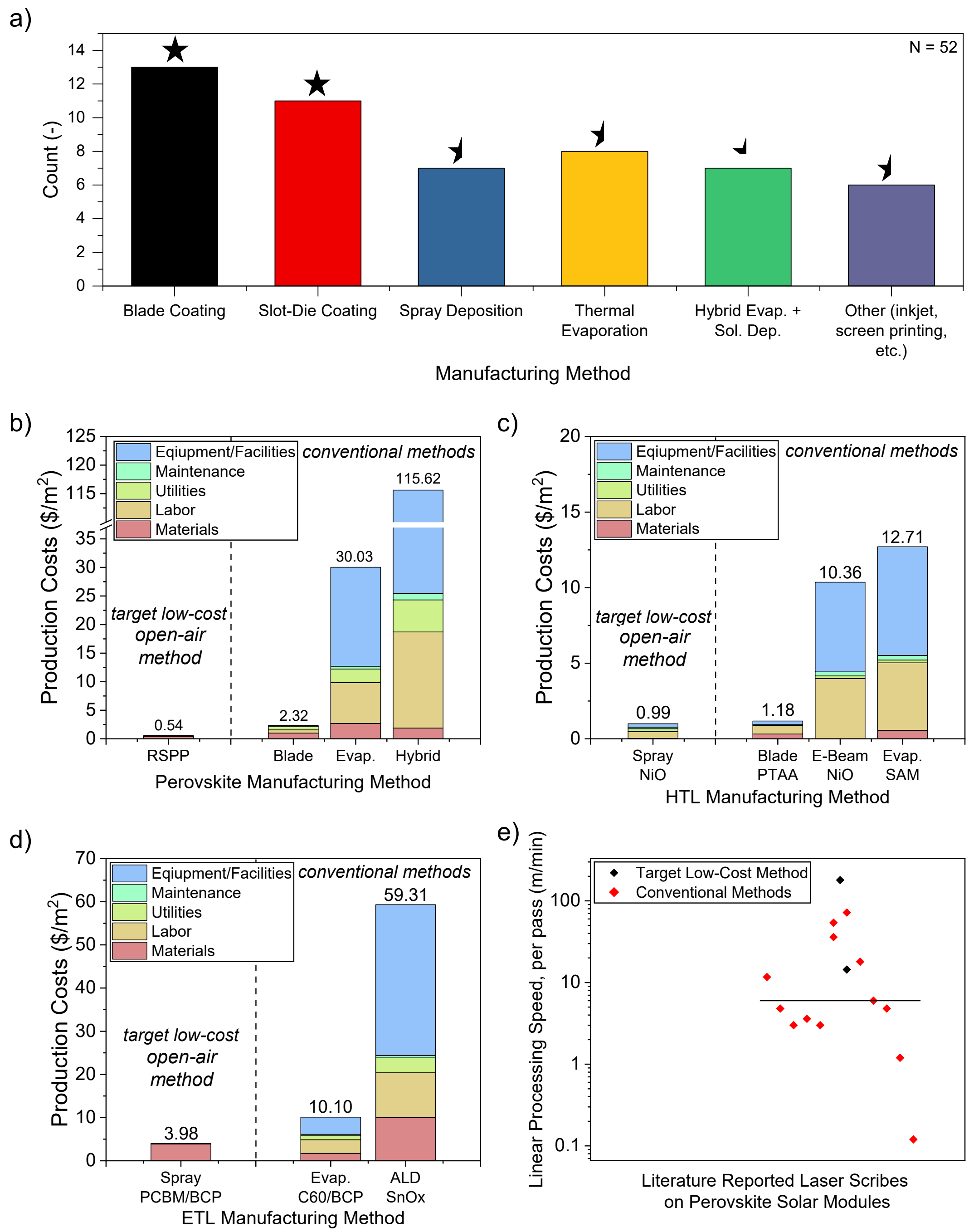


Figure S2: a) Recent publication relevance of popular perovskite manufacturing methods selected based on Google Search ranking. Stars indicate module/large-area emphasis for each method: Full star = strong module representation; half star = mix of devices and mini-modules, quarter star = few dedicated module papers. b-e) Down selection analysis for the b) perovskite, c) HTL, and d) ETL layers, alongside e) the laser scribing mechanisms. Horizontal line in (e) represents the global median.

Figure S2 references for Blade Coating[S10]–[S22], Slot-Die Coating[S23]–[S33], Spray Deposition[S34]–[S40], Thermal Evaporation[S41]–[S48], Hybrid Evaporation + Solution Deposition[S31][S44][S49]–[S53], and Other[S54]–[S59]

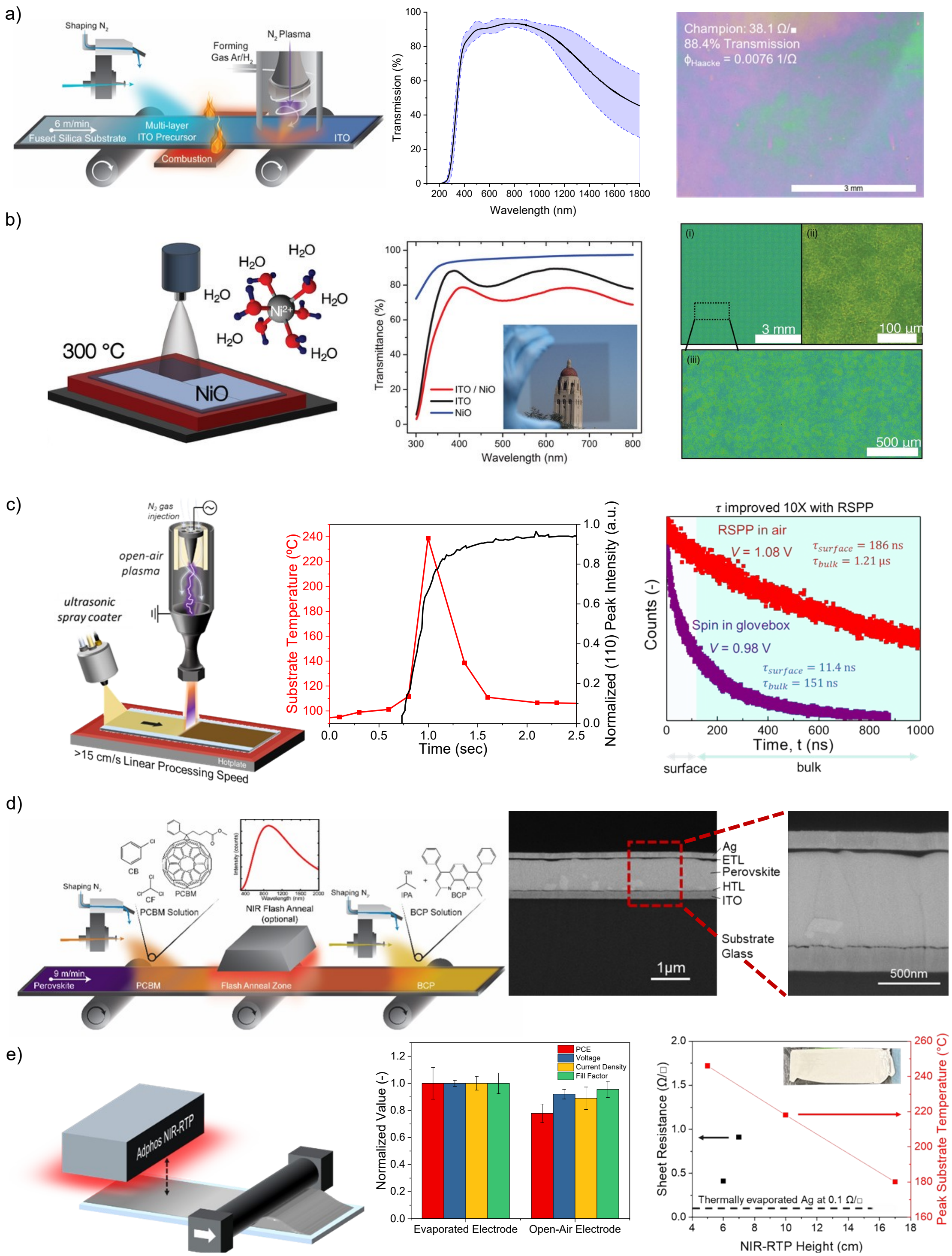


Figure S3: a) Combustion Oxidation with Rapid Plasma (CORP) processing of ITO front electrodes with >85% transmittance and Haacke Figure of Merit (FOM) above 0.005 1/Ω. b) Aqueous spray pyrolysis of NiO hole transport layers with considerable transparency and high uniformity across 100 cm^2. c) Rapid Spray Plasma Processing (RSPP) of perovskite absorber films with ultrafast <1 sec curing and elevated carrier lifetimes. d) Ultra-thin spray deposition with Near Infrared Rapid Thermal Processing (NIR-RTP) for $PC_{61}BM$/BCP electron transport bilayers demonstrating planarizing effect on underlying film roughness seen in backscatter SEM of polished cross sections. e) Blade coating with NIR-RTP for Ag rear electrodes with >90% maintained fill factor and low sheet resistance approaching that of thermally evaporated films.

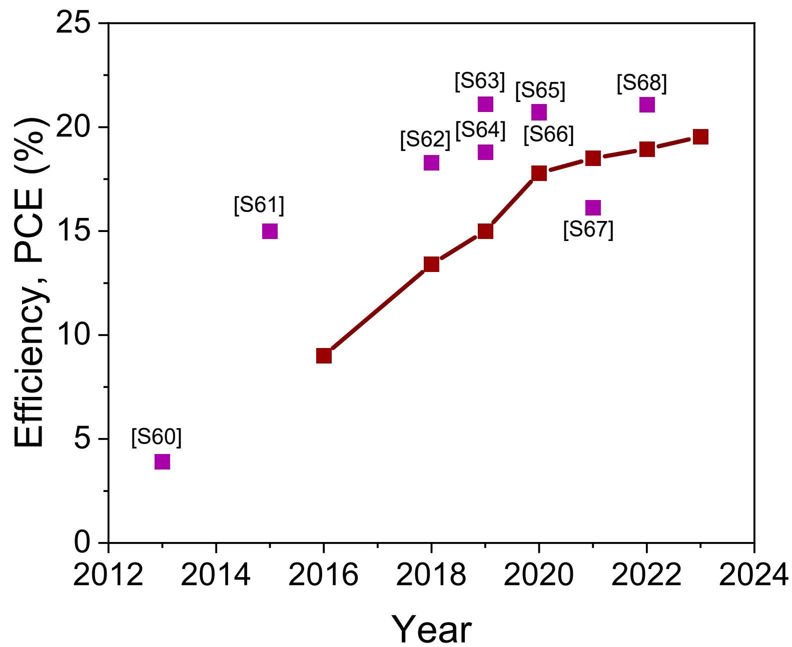
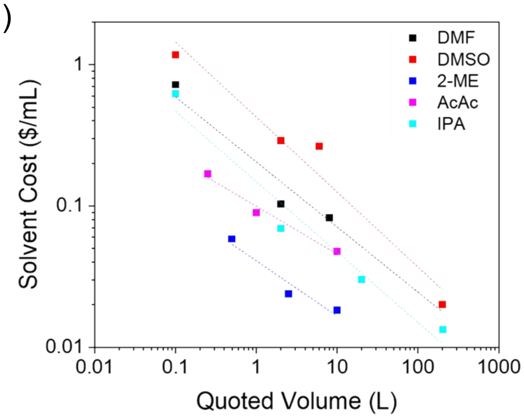


Figure S4: Record inverted p-i-n perovskite device performances since 2013 using conventional deposition methods (purple) and open-air techniques (red) without additional additives or interlayers within or between the p, i, and n materials.

Table S1: CapEx and throughputs for each analyzed thin-film fabrication technique.

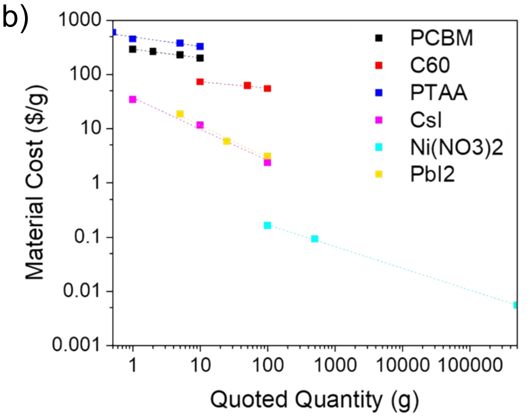
Processing Technique (Open-Air)	Throughput (mod/hr)	Parallel Processing Stations* (#)	Cost per Tool	Cost per Station (Millions of Dollars)	References
Ultrasonic Spray	180 – 306	1 – 4	$ 317,835.00	$ 0.32 – 1.28	[S6][S7][S69]
Atmospheric Pressure Plasma	306	1	$ 750,000.00	$ 0.75	[S7]
Shrouded Plasma	11	3	$ 2,304,000.00	$ 6.91	
NIR-RTP	270	1	$ 200,000.00	$ 0.20	
Hotplate Anneal	12	3	$ 20,000.00	$ 0.06	[S6]
Laser Liftoff	72 – 180	1	$ 1,000,000.00	$ 1.00	[S8]
Processing Technique (Conventional)	**Throughput (mod/hr)**	**Parallel Processing Stations* (#)**	**Cost per Tool**	**Cots per Station (Millions of Dollars)**	**References**
Sputter	18	2	$ 5,884,425.00	$ 11.77	[S7]
Blade Coater	36	1	$ 128,953.62	$ 0.13	[S1] – [S5]
Thermal Evaporation	9 – 11	3 – 4	$ 1,000,000.00	$ 3.00 – 4.00	[S7]
Hotplate Anneal	12	3	$ 20,000.00	$ 0.06	[S6]
Laser Ablation	7 – 17	2 – 5	$ 1,804,304.00	$ 3.61 – 9.02	[S8]

a)



Solvent	Discount Factor, γ	Scaling Factor, α
DMF	-0.46	0.54
DMSO	-0.53	0.47
2-ME	-0.39	0.61
AcAc	-0.34	0.66
IPA	-0.50	0.50

b)



Material	Discount Factor, γ	Scaling Factor, α
$PC_{61}BM$	-0.16	0.84
C_{60}	-0.12	0.88
PTAA	-0.18	0.82
CsI	-0.58	0.42
Ni(NO3)2	-0.58	0.60
PbI2	-0.60	0.40

Figure S5: Materials scaling factors for a) processing solvents, and b) metal salts and organic molecules.

Table S2: Comparison in module scribing techniques and methods.

Scribe Method	Ref	Authors	Year	Journal	Speed (m/min)	Laser Source (Wavelength (nm))
Conventional Direct Ablation Laser Scribing	[S70]	G. Mincuzzi…T. Brown	2015	ChemElectroChem	0.12	Nd:YAG (355, 1064), YAG (515)
	[S71]	H. Chen…L. Han	2017	Nature	1.2-4.8	(1064, 532)
	[S72]	E. Bi…L. Han	2019	Joule	3-6	(532, 1064)
	[S73]	F. Giacomo…A. Di Carlo	2020	Micromachines	11.7	(355)
	[S74]	A. Palma…A. Di Carlo	2017	IEEE J. Photovolt.	18	Nd:YVO_4 (355, 1064)
	[S75]	S.J. Moon…C. Ballif	2015	IEEE J. Photovolt.	36-72	(355, 532)
	[S76]	B. Turan…S. Haas	2017	Solar RRL	54*	Nd: YVO_4 (355, 532, 1064)
TCO-Based Indirect Liftoff Scribing	[S7]	N. Rolston…R.H. Dauskardt	2020	Joule	14.4	Nd:YVO_4 Fiber (1064)
	[S8]	Flick…R.H. Dauskardt	2024	Adv. Energy Mater.	180	Nd:YVO_4 Fiber (1064)

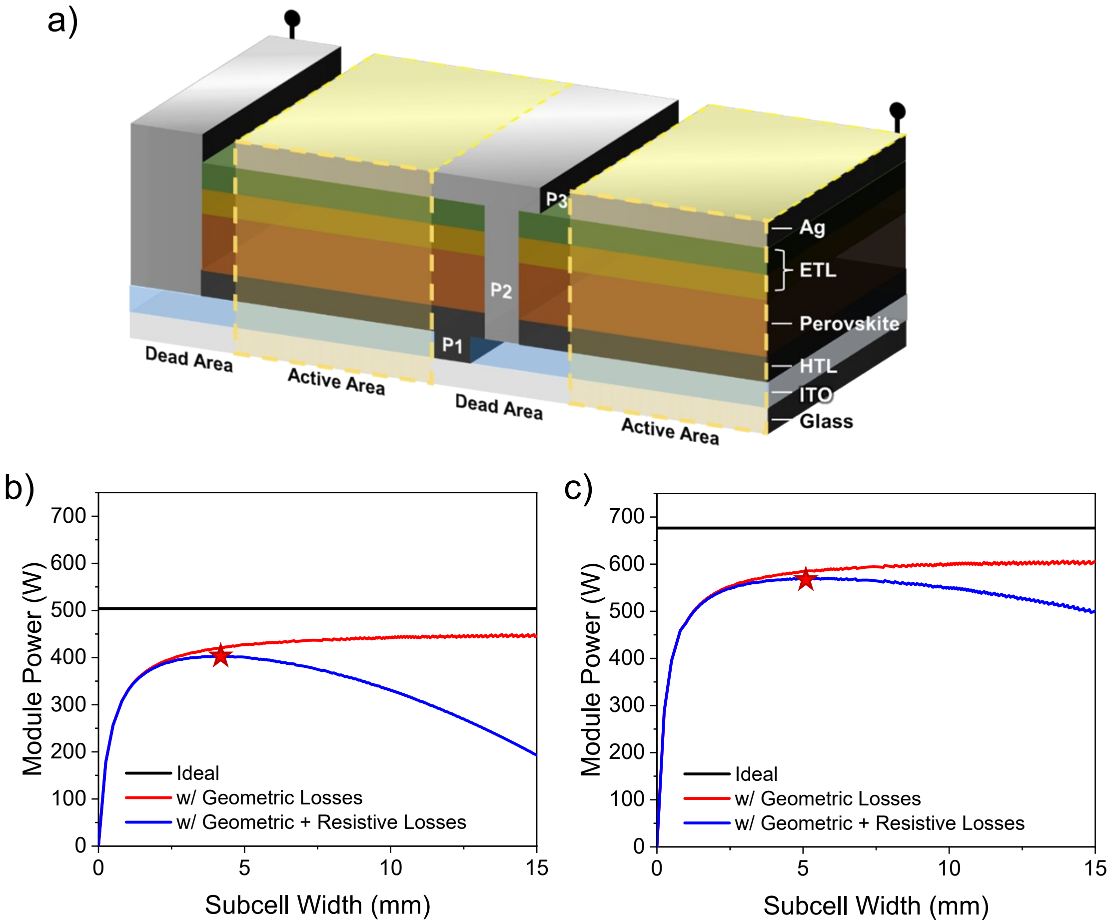


Figure S6: a) Thin-film serially interconnected module design used in Total Loss calculation. b) Open-air manufacturing subcell width optimization. c) Conventional manufacturing subcell width optimization.

Table S3: Module design and performance metrics for open-air and conventional manufacturing.

Metric	Open-Air Module	Conventional Module
Active Area Efficiency (%)	19.5	26.7
Aperture Area Efficiency (%)	17.9	25.3
Module Area Efficiency (%)	16.4	23.2
Module Wattage	402.14	570.49
J_{MPP}, per cell (mA/cm^2)	19.2	19.98
V_{MPP}, per cell (V)	0.80	0.97
ITO Sheet Resistance, R_{SH} (Ω/□)	35	10
P2 Contact Resistance, R_C (Ωcm)	0.32	1
Dead Width, W_D (mm)	0.4	0.3
Subcell Width, W_A (mm)	4.20	5.45
No. of Subcells (#)	250	200

Module Design

$$P_{mod,real}(W_A) = P_{mod,ideal}(W_A) \times [1 - TL_R(W_A)]$$ (Equation S17)

$$P_{mod,ideal} = N_{subcells}(W_A) \times A_{subcell}(W_A) \times 1000 {W}/{m^2}$$ (Equation S18)

$$A_{subcell} = [L_{mod} - 2 \times W_{ED}] \times W_A$$ (Equation S19)

$$N_{subcells} = \frac{[W_{mod} - 2 \times W_{ED}] - W_A}{W_A + W_D}$$, rounded down (Equation S20)

Levelized Cost of Energy Calculations

Nameplate power for the utility-scale perovskite PV power plant is 100 MW. Power output for the PV systems as a function of the module array power across the 30-year system lifetime is calculated based on the solar irradiation data for Blythe, CA within SAM.

$$LCOE = \frac{-C_0 - \sum_{n=1}^{N} \frac{C_n}{(1+d)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}}$$ (Equation S21)

$$N_{mod} = {P_{nameplate}}/{P_{mod}}$$ (Equation S22)

$$P_1 = N_{mod} \times P_{mod}$$ (Equation S23)

$$P_n = P_1 \times (1 - \frac{T80}{100})^{n-1}$$, for n > 1 (Equation S24)

Initial installation costs, C_0, based on the capital system costs and debt amount. Year costs C_n comprise Investment Tax Credit, state and federal taxes, principal and interest on the debt amount, reserves funding (debt, working capital, and equipment replacement), and interest on reserves.

Module Replacement Technology Improvement

$$PCE_n = PCE_0 + 2 \times (PCE_{max} - PCE_0) \times \left(\frac{1}{1 + e^{(-EIF \times (n-1))}} - 0.5\right)$$ (Equation S25)

$$C_n = C_0 - (C_0 - C_{min}) \times \left(1 - e^{(1-n)/CRF}\right) \quad \text{(Equation S26)}$$

Module replacement values used in this study include efficiency improvement factors (EIF) of 0.08 and cost reduction factors (CRF) of 15 (**Table S5**).

Table S4: Levelized Cost of Energy parameters fixed across all solar modules within the System Advisor Model.

System Power Output				Cash Flow				Earnings Before Interest, Taxes, Depreciation, and Amortization (EBITDA)	
LCOE Term	**Fixed Model Value**	**LCOE Term**	**Fixed Model Value**	**LCOE Term**	**Fixed Model Value**	**LCOE Term**	**Fixed Model Value**	**LCOE Term**	**Fixed Model Value**
Nameplate DC Capacity	100 MW	DC Losses, Module Mismatch	2%	Balance of Systems Costs, Equipment	$0.27/W_{DC}$	Land Costs	$1000/acre	Power Purchase Agreement Price	$0.04/kWh
Maximum AC Power, Inverter	3600	DC Losses, Diodes and Connections	0.5%	Balance of Systems Costs, Installation Labor	$0.13/W_{DC}$	Land Preparation and Transmission	$0.02/W_{DC}$	PPA Price Escalation	1%/year
Maximum DC Voltage, Inverter	500	DC Losses, DC Wiring	2%	Balance of Systems Costs, Margin and Overhead	$0.12/W_{DC}$	Debt Up-Front Fee	2.75%	IRR Target Year	25
Inverter Cost	$0.03/W_{DC}$	AC Losses, AC Wiring	1%	Permitting	$0.01/W_{DC}$	Debt Closing Costs	$450,000	Operation and Maintenance Costs	$15/DC kW-yr
DC/AC Ratio	1.34	Soiling Losses	5%	Engineer and Developer Overhead	$0.02/W_{DC}$	Tax Rate	5%	Inflation Rate	2.5%
Ground Coverage Ratio	0.3	Nominal Discount Rate	9.06	Grid Interconnection	$0.02/W_{DC}$				
Module Technology Improvement		**Equipment Replacement Reserves**		**Debt Amount**		**Taxes and Depreciation**			
LCOE Term	**Fixed Model Value**	**LCOE Term**	**Fixed Model Value**	**LCOE Term**	**Fixed Model Value**	**LCOE Term**	**Fixed Model Value**	**LCOE Term**	**Fixed Model Value**
Efficiency Improvement Factor (EIF)	0.08	Equipment Replacement Cost	$0.10/W_{DC}$	Term Interest Rate	4%	5-yr MACRS Allocations	90%	Investment Tax Credit	30%
Stability Improvement Factor (SIR)	0.1	Equipment Replacement Frequency	15 years	Tenure	18 years	15-yr MACRS Allocations	1.5%	State Tax Rate	7%
Cost Reduction Factor (CRF)	15	Reserves Interest	1.25%	Debt Service Coverage Ratio (DSCR)	1.3	15-yr SL Allocations	2.5%	Federal Tax Rate	21%
						20-yr SL Allocations	3%		

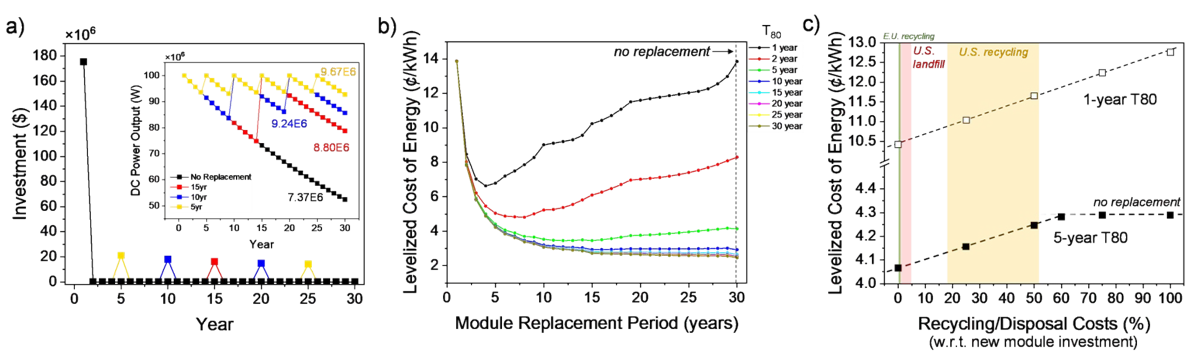


Figure S7: a) Module replacement with technology improvement across a 30-year PV system lifetime with an initial T_{80} of 10 years. b) Optimization of the module replacement period in reducing LCOE for varying initial T_{80} lifetimes. c) Module recycling rates.

Table S5: Manufacturing costs of the open-air perovskite module assembly.

	Open-Air Perovskite Manufacturing Costs at 100 MW Processing Scale ($/m^2)					
Open-Air Perovskite Device Processing Step	Materials	Labor	Utilities	Maintenance	Equipment /Facilities	Total
Glass Receipt	7.366	0.540	0.103	0.007	0.029	8.046
ITO CORP	4.450	1.005	0.760	0.613	2.572	9.400
P1 Scribe	0.000	0.032	0.010	0.078	0.176	0.296
NiO_x Spray Pyrolysis	0.068	0.451	0.185	0.123	0.166	0.993
Perovskite RSPP	0.734	0.065	0.009	0.084	0.151	1.042
PCBM/BCP Spray Deposition	5.279	0.073	0.010	0.044	0.091	5.497
P2 Scribe	0.000	0.080	0.025	0.079	0.273	0.458
Ag Paste Blade Coating	4.259	0.073	0.005	0.066	0.130	4.533
P3 Scribe	0.000	0.080	0.024	0.079	0.273	0.457
P4 Edge Deletion	0.000	0.032	0.010	0.078	0.176	0.296
Encapsulation	4.202	0.599	0.733	0.139	0.603	6.276
Junction Box /Testing	2.120	0.567	0.095	0.019	0.099	2.901
Cleanroom	0.000	0.000	1.41	0.000	0.301	1.715
Total	28.478	3.598	3.383	1.409	5.041	41.909

Table S6: Manufacturing costs of the conventional perovskite module assembly.

	Conventional Perovskite Manufacturing Costs at 100 MW Processing Scale ($/m^2)					
Conventional Perovskite Device Processing Step	Materials	Labor	Utilities	Maintenance	Equipment /Facilities	Total
Glass Receipt	7.366	0.764	0.103	0.010	0.038	8.281
ITO Sputter Deposition	0.382	2.634	5.176	1.249	5.984	15.424
P1 Scribe	0.000	0.470	0.151	0.395	1.814	2.830
PTAA Blade Coating	2.760	0.755	0.032	0.027	0.149	3.723
Perovskite Blade Coating	2.029	1.510	0.055	0.056	0.423	4.027
C_{60}/BCP Thermal Evaporation	4.322	2.874	0.967	0.453	2.161	10.777
P2 Scribe	0.000	0.470	0.145	0.395	1.814	2.824
Ag Thermal Evaporation	2.830	3.412	1.141	0.455	2.327	10.165
P3 Scribe	0.000	1.176	0.353	0.986	4.482	6.997
P4 Edge Deletion	0.000	0.103	0.034	0.193	0.628	0.958
Encapsulation	4.202	0.595	0.733	0.195	0.721	6.446
Junction Box /Testing	2.120	0.562	0.095	0.027	0.119	2.923
Cleanroom	7.366	0.000	0.603	0.000	0.142	0.745
Total	26.012	15.325	9.587	4.441	20.802	76.121

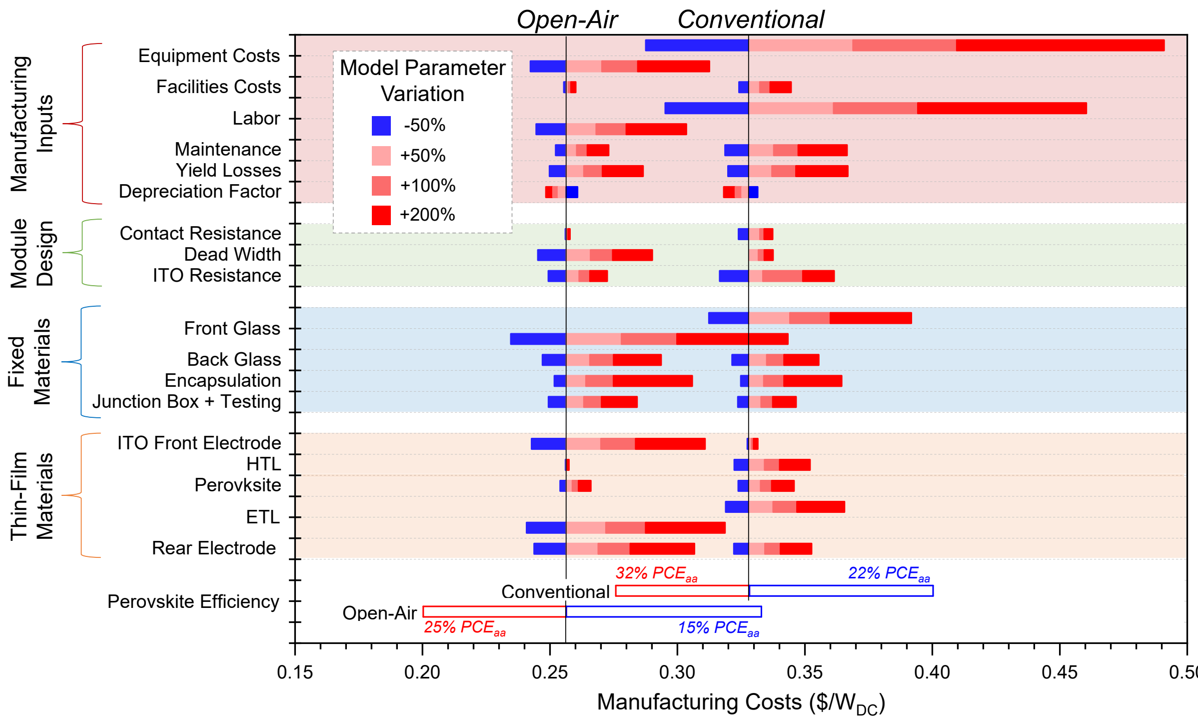


Figure S8: Sensitivity analysis for open-air and conventional manufacturing of perovskite solar modules. Parameters are analyzed within the cost model categories of Manufacturing Inputs, Module Design, Fixed Materials, and Thin-Film Materials. Open-air perovskite and conventional module manufacturing costs are centered around \$0.23/W_{DC} and \$0.33/W_{DC}, respectively.

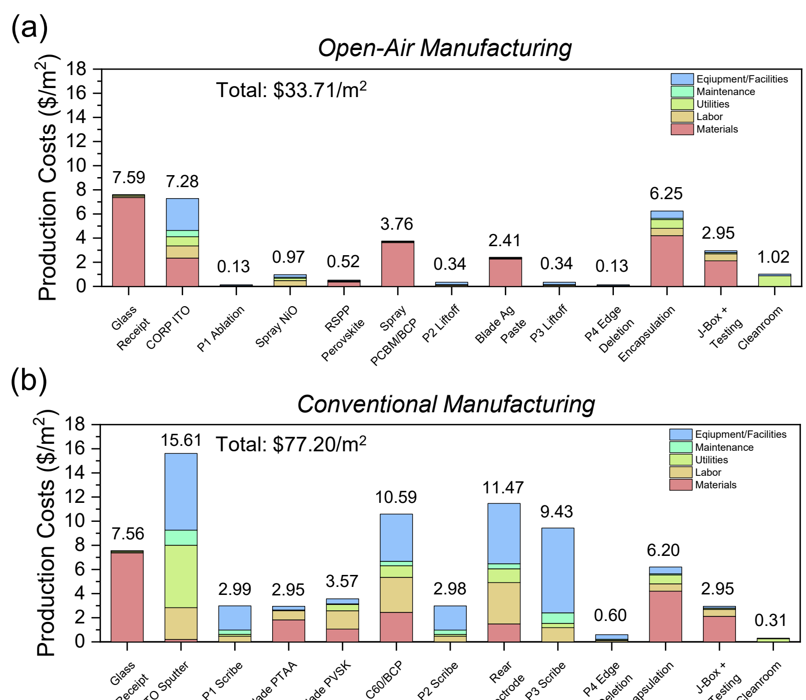


Figure S9: 12-step cost model at 1 GW production scale for a) open-air manufacturing and b) conventional manufacturing of perovskite solar modules.

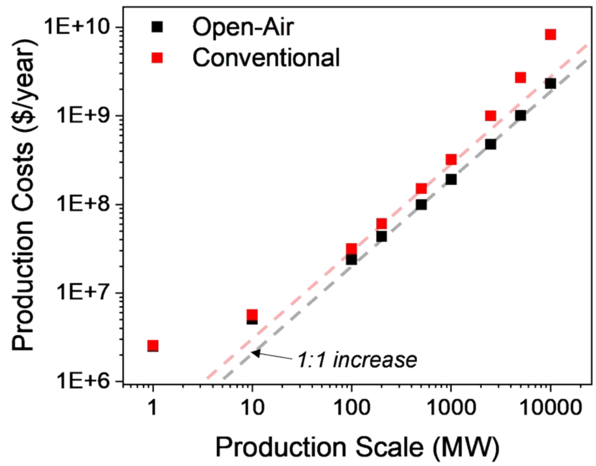


Figure S10: Perovskite module production costs as a function of production scale. Production scale increases that approach a 1:1 increase demonstrate economies of scale. Production scale increases that deviate from the 1:1 increase demonstrate diseconomies of scale.

Table S7: Minimum Sustainable Price (MSP) module costs for the perovskite, silicon, and tandem technologies across efficiencies and suppliers modeled in **Figure 5**.

Module	Minimum Sustainable Price, MSP ($/module)		
	16%	*19%*	*22%*
Perovskite - Open-Air	97.96	98.47	99.30
Perovskite - Conventional	241.73	233.33	227.61
	SE Asia	*EU*	*US*
Silicon	127.59	251.96	636.87
4T Tandem	323.76	448.13	833.05
2T Tandem	371.60	495.97	880.88

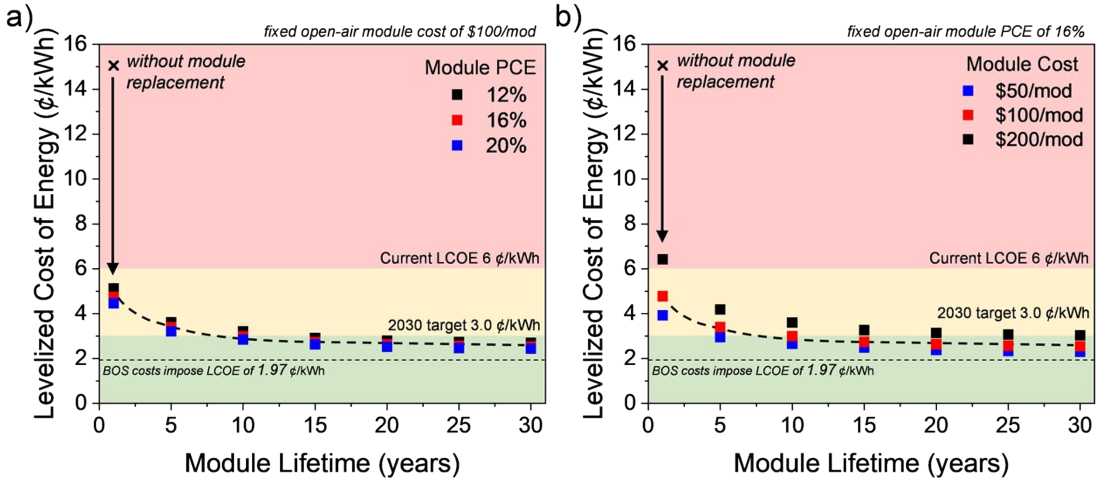


Figure S11: LCOE calculations for open-air module assemblies with a) variable module PCE and b) variable module manufacturing costs.

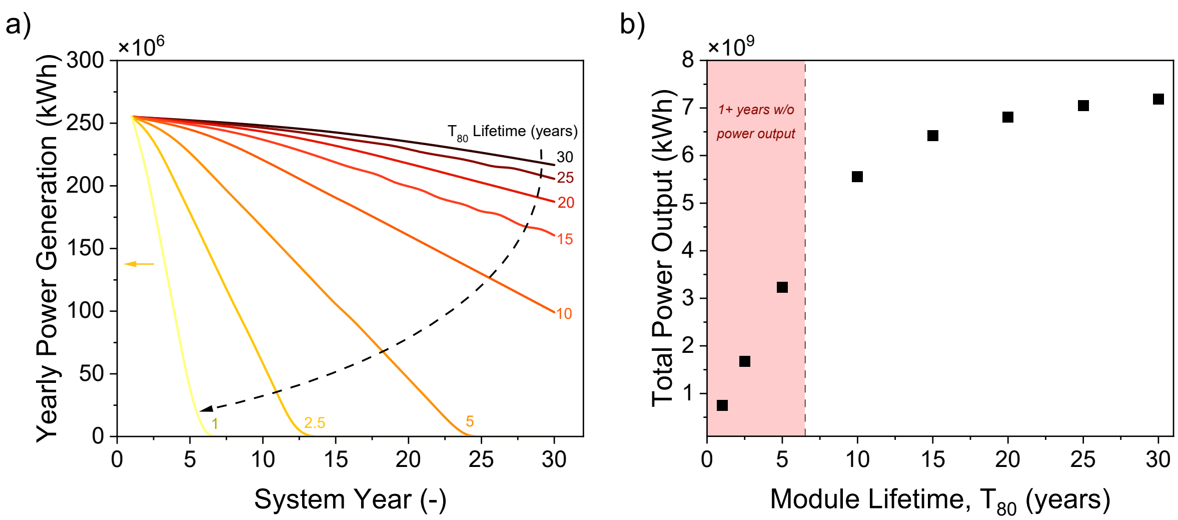


Figure S12: a) Yearly system power output for a 100 MW power production facility used to calculate LCOE and NPV as a function of module lifetime. b) Total system power output for the model in (a) integrated over the 30-year system lifetime. Red regime denotes <6.5-year T_{80} lifetimes where 1+ years have zero system power output.

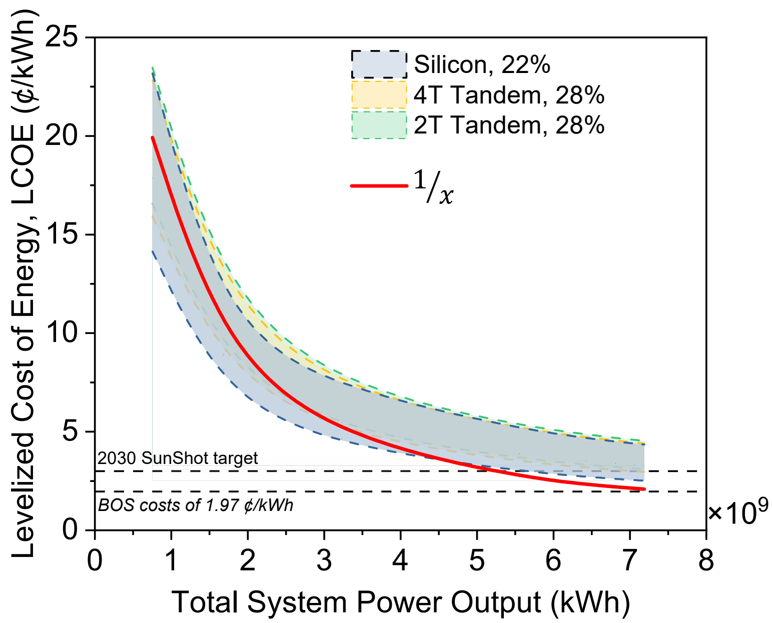


Figure S13: LCOE for silicon and tandem modules as a function of total system power output. Red line denotes a 1/x relationship.

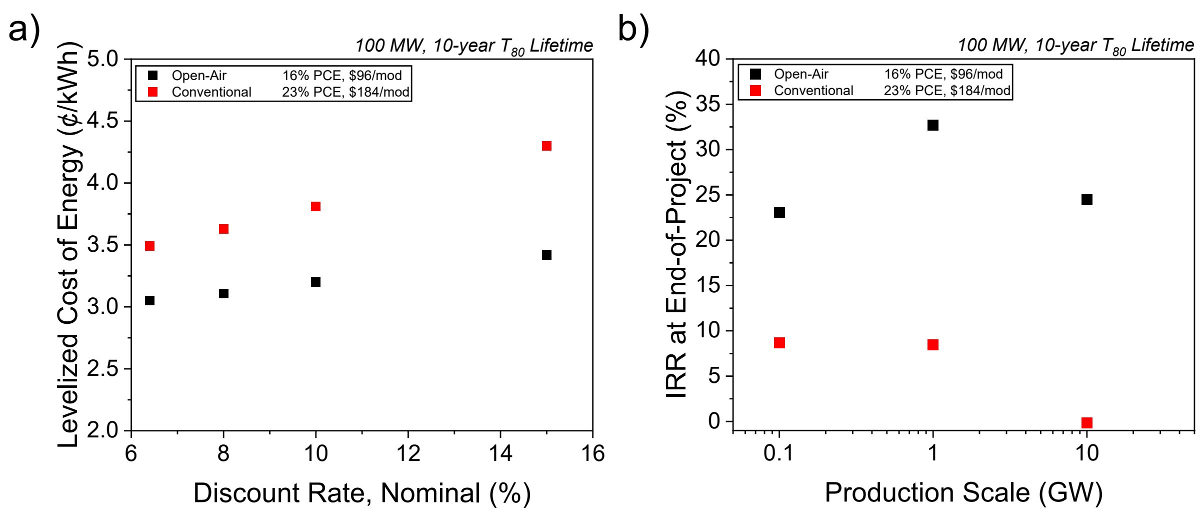


Figure S14: a) LCOE for the perovskite module assemblies with varying discount rates. b) Internal Rate of Return (IRR) for the perovskite module assemblies at varying production scales.

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