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Supplementary Information

A technoeconomic analysis of the manufacturing and levelized cost of energy for perovskite solar modules made with low-cost materials and techniques

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1. Basic Assumptions for perovskite module manufacturing

1.1. The perovskite PV manufacturer locates at Toledo, OH.

1.2. The module dimension is 1.2 m x 0.6 m (0.72 m^2), which is available in the market.[1]

1.3. Front glass is 3.2 mm heat strengthened with anti-reflective coating. Back glass is 3.2 mm tempered.

1.4. The reference module consists of 200 cells that are monolithically integrated.

1.5. The reference module efficiency is assumed to be 16%. The corresponding nominal power output is 115 W per panel.

1.6. To simplify the depreciation of physical properties owned by the manufacturer, we assume the linear depreciation for 20 years.

1.7. The total plant operation time is defined as 3520 h/year, corresponding to 16 h per day, 5 days per week, and 44 weeks per year.

1.8. The default deposition throughout is 0.5 min/module for each production line, corresponding to a production rate of 1.44 m^2/min or 230 W/min. The annual production capability of each production line is 0.49 MW/yr. If the production capacity of the manufacturer is ~200 MW/yr, 4 production lines are needed.

1.9. The footprint of 1 production line is estimated to be 5200 ft^2. The floor space cost is at \$3.63/(ft^2·yr).

1.10. Labor cost for manufacturing work, technical and scientific work in Ohio is $12 per hour.[2] We scale down the labor requirement of 100 workers for 200 MW/yr production based on the reported value.[3]

1.11. For utility costs in Ohio, the average price of electricity to industrial customers is $0.068 per kWh;[4] water and sewer rate is $8.63 per 1000 gallons.[5]

1.12. For the sputtering and screen printing deposition, we assume the material usage efficiency is 80%.

1.13. The maintenance costs for the facilities are set to be 20% of the annual equipment depreciation. The factory operating cost is assumed to be $0.03/W.

1.14. SG&A cost is assumed to be 15% of total revenue.

1.15. Considering the mature manufacturing process, R&D cost is set to zero be as it is expected to be negligible.

1.16. The federal corporate tax rate in the United States stands at 35% in 2016.

1.17. The expected internal return for investing 14%, which is the average WACC for a U.S. PV manufacturer.[3]

2. Detailed Processing Assumptions

Material, equipment, utilities costs are summarized in Tables S1 and S3. Cost inventory is acquired from surveys on manufacturers and suppliers from online trading website,[6] global value pricing database,[7] government report,[8] and literature.[3]

Table S1. Materials Costs for the reference module

Component	Raw material	Price ($/kg)	Weight (g/m^2)	Material cost ($/m^2)
Front glass	3 mm Glass (with AR)	0.8 – 1.1	7500	7.000
ITO	ITO	550 – 900	1.790	1.298
NiO	$Ni(NO_3)_2{\cdot}6H_2O$	38 – 60	2.597	0.127
NiO	$C_2H_6O_2$	0.85 – 1.35	12.426	0.014
NiO	$C_2H_8N_2$	2.3 – 2.9	0.671	0.002
$CH_3NH_3PbI_3$	$Pb(NO_3)_2$	1.8 – 2.3	0.226	0.005
$CH_3NH_3PbI_3$	KI	40 – 60	0.241	0.014
$CH_3NH_3PbI_3$	C_3H_7NO	0.8 – 1	0.787	0.001
$CH_3NH_3PbI_3$	CH_3NH_2	4.7 – 10.8	0.022	0.001
$CH_3NH_3PbI_3$	HI	44.6 – 200	0.093	0.043
$CH_3NH_3PbI_3$	$(CH_3)_2SO$	2.0 – 3.5	0.197	0.001
ZnO	ZnO	1.5 – 2.3	0.491	0.001
ZnO	C_6H_5Cl	1.2 – 2.6	30.680	0.058
Al	Al	2.0 – 2.3	0.338	0.001

Solder wire	Sn	8.0 – 12.0	1.065	0.011
Edge seal	Al	2.0 – 2.3	1555	3.888
Lamination	EVA	8.0 – 14.2	138.0	1.535
Edge sealant	butyl rubber	2.0 – 5.0	10.5	0.037
Back glass	2 mm Glass	0.4 – 0.8	5000	3.000
Junction box	-	-	-	7.500

Table S2. Equipment costs

No.	Equipment	footprint (m x m)	Unit price ($k)	Power (kW)	Operating time (min/module)
1	Ultrasonic bath	3 x 2	5 – 10	12 – 44	60
2	ITO sputtering	10 x 2.5	1000 – 3000	500	30
3	Screen Printing	6 x 2.5	20 – 80	10	3
4	Furnace	6 x 2.5	150 – 360	30	60
5	Al Sputtering	5 x 2.5	1200 –1500	80	15
6	Laser Scribing	6 x 2.5	30 – 90	2	2.5
7	Solar laminator	2.5 x 6	80 – 120	35	20
8	Soldering system	2.5 x 5	120 – 140	10	2
9	Testing table	2.5 x 1	10 – 15	0.5	1

Table S3. Distribution of direct manufacturing cost in each step.

Process	Utilities ($/m^2)	Labor ($/m^2)	Depreciation ($/m^2)	Maintenance ($/m^2)
Front Glass	0.259	0.231	0.158	0.011
Sputter ITO	0.394	0.116	0.900	0.232
Laser scribe (P1)	0.008	0.009	0.191	0.019
Print NiO	0.066	0.270	0.203	0.023
Print MAPbI3	0.062	0.502	0.236	0.032
Print ZnO	0.058	0.077	0.223	0.023
Laser scribe (P2)	0.008	0.009	0.191	0.019
Sputter Al	0.236	0.077	0.653	0.158
Laser scribe (P3)	0.008	0.009	0.191	0.019
Interconnection	0.008	0.019	0.200	0.023
Edge Seal	0.002	0.019	0.181	0.017
Lamination	0.028	0.077	0.190	0.020
Back Glass	0.259	0.231	0.158	0.011
Junction-box	0.002	0.019	0.158	0.010

Testing	0.000	0.008	0.163	0.011

3. LCOE calculation Assumptions

Parameters for Tables S4-S6 are adopted from the literature.[9]

Table S4. PV system installation cost inputs for the benchmark LCOE calculation

Input parameter	Value ($/$W_{DC}$)
Perovskite PV module	0.41
Inverter price	0.10
Balance of system equipment	0.25
Installation labor	0.10
Installer overheads	0.10
Permitting and environmental studies	0.03
Engineering and developer overheads	0.02
Grid interconnection	0.03
Land purchase	0.01
Land preparation and transmission	0.01
Sale tax (7% of direct cost)	0.06
Total installed cost	1.12

Table S5. PV system operating parameters for the benchmark LCOE calculation

Input parameter	Value
O&M annual cost	$7/(kW·yr)
Soiling loss	5.0%
DC-to-AC power ratio	1.4
DC power loss	4.5%
AC power loss	2.0%
Inverter lifetime	30 yr
Module degradation rate	0.5%

Table S6. Financial assumptions for LCOE calculation.

Financial input	Value
Construction debt, up-front fee on principle	4%, 1%
Project term debt	0%
Inflation	2.25%
Real discount	4.4%
Nominal discount	6.75%
WACC	7.00%

Federal income tax	35%
State income tax	7%
Insurance	0%
Property tax	0%
IRR target	7%
PPA escalation	2.5%/yr
Depreciation class	5-year MACRS
Incentives	0%

Table S7. Degradation rate assumption as a function of lifetime.

Lifetime (year)	Degradation rate (%)	Lifetime (year)	Degradation rate (%)
5	3.178	18	0.904
6	2.667	19	0.852
7	2.299	20	0.809
8	2.011	21	0.771
9	1.790	22	0.739
10	1.617	23	0.704
11	1.467	24	0.675
12	1.347	25	0.648
13	1.249	26	0.623
14	1.154	27	0.600
15	1.076	28	0.580
16	1.011	29	0.558
17	0.952	30	0.541

Table S8. Estimated LCOE values for the selected location in the U.S.

City	State	LCOE(¢/kWh)	City	State	LCOE(¢/kWh)
Alamosa	CO	4.93	Jackson	MS	6.2
Albany	NY	6.84	Jacksonville	NC	5.99
Albuquerque	NM	4.95	Kona	HI	5.84
Anchorage	AK	9.55	Las Vegas	NV	4.95
Atlanta	GA	6.01	Lincoln	NE	6.46
Augusta	ME	7.7	Louisville	KY	6.46
Baltimore	MD	6.53	Manchester	NH	7.25
Billings	MT	6.08	Medford	OR	6.29
Birmingham	AL	6.22	Minneapolis	MN	6.35
Bismarck	ND	6.09	Nashville	TN	6.29
Boise	ID	5.91	New Orleans	LA	6.27
Boston	MA	6.51	Newark	NJ	6.75
Burlington	VT	6.86	Oklahoma City	OK	5.73
Casper	WY	5.62	Orlando	FL	6.45
Charleston	WV	6.96	Pittsburgh	PA	7.14

Chicago	IL	6.75	Providence	RI	6.47
Columbus	OH	7.01	Rapid City	SD	5.83
Des Moines	IA	6.35	Richmond	VA	6.34
Dover	DE	6.73	Salt Lake City	UT	5.79
Flint	MI	7.03	San Antonio	TX	5.87
Fort Smith	AR	6.04	Seattle	WA	7.9
Green Bay	WI	6.68	St Louis	MO	6.36
Greenville	SC	6.11	Tucson	AZ	4.94
Hartford	CT	6.9	Wichita	KS	5.82
Imperial	CA	5	Average		6.456923
Indianapolis	IN	6.52			

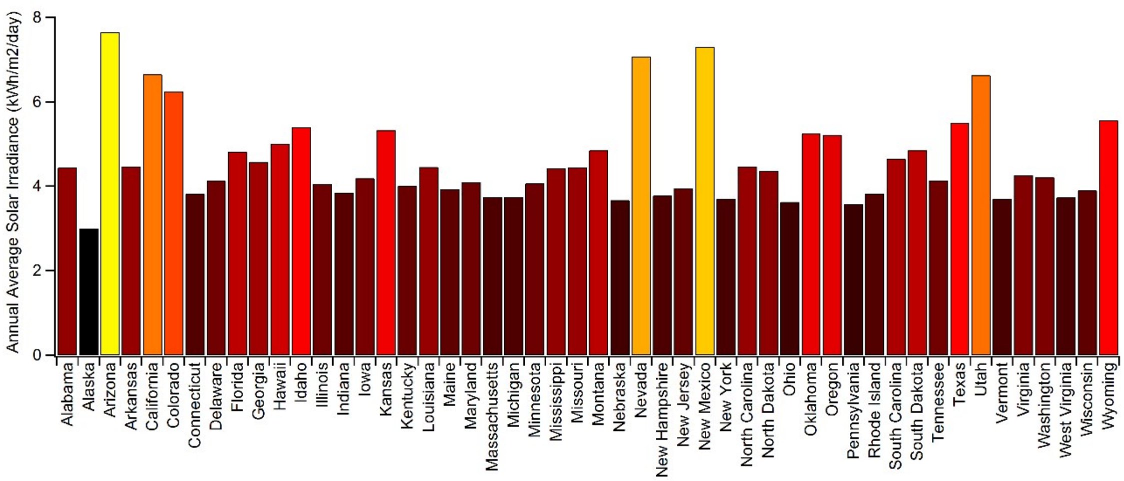

Figure S1. Average insolation in the United States.

4. Sensitivity Analysis

The inputs used in the model are the best estimates, but may still have significant errors. To determine how these possible errors that affect the LCOE values, we perform a sensitivity analysis on the manufacturing cost and LCOE modeling. Figure S1 shows the probability distributions of material, utilities, labor, maintenance, depreciation and manufacturing costs. The probability curves are plotted in the normal distribution function using the mean value and standard deviation from our market survey data. We estimated that manufacturing cost would be \$31.7/m^2 ± \$5.5/m^2.

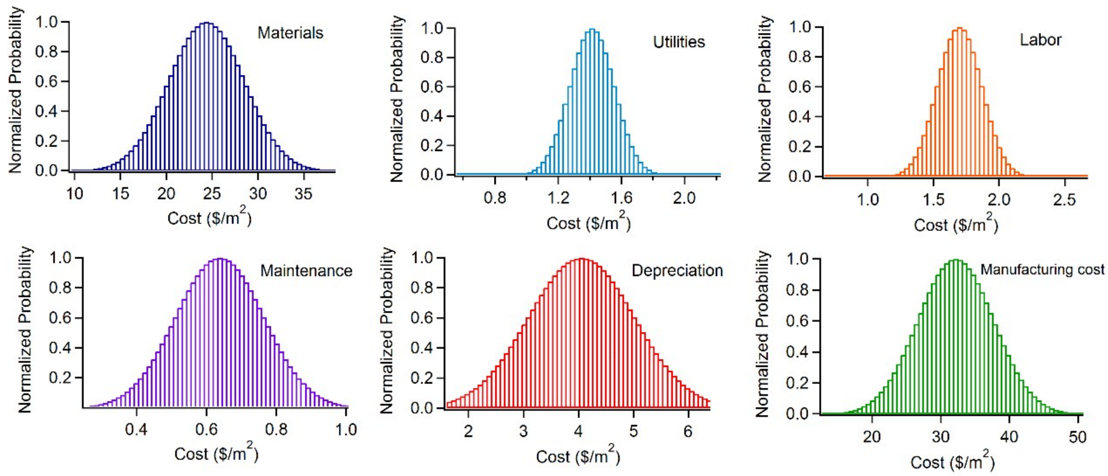

Figure S2. Probability distributions of material, utilities, labor, maintenance, depreciation and manufacturing costs.

Figure S3 shows the sensitivity of the baseline model to independent variations of +/- 10% of the module cost, degradation rate, BOS equipment, insolation, O&M, IRR, discount rate, and federal tax. The variation of insolation lead to ~10% uncertainties of total LCOE value, while others have impacts of less than 5%. As the result, the calculated LCOE for perovskite solar cells should be reasonably close to the actual value pending the assumptions are satisfied in real applications. When all the uncertainties are considered simultaneously, followed the propagation of uncertainty, the LCOE for PSCs falls in a 90% confidence interval of 4.9 to 7.9 ¢/kWh.

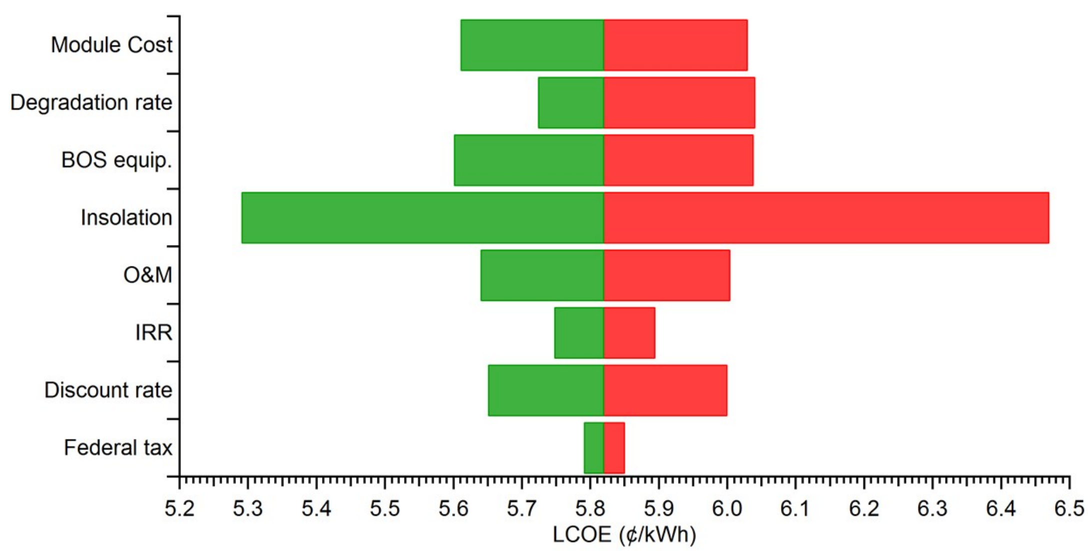

Figure S3. Sensitivity analysis of perovskite PV LCOE with respect to the increment (red) and decrement (green) of the selected inputs.

5. Energy Payback Time Calculation

Energy payback time calculation was done using approach of with the following equation:[10]

$$EPBT = \frac{PED \times \varepsilon}{I \times \eta \times PR \times CF} \quad \text{(Eqn.S1)}$$

where, EPBT is energy payback time (years), PED is primary energy demand (MJ/m^2), ε is electrical to primary energy conversion factor (35 %), PR is Performance Ratio (75 %), η is solar module Efficiency (16 %), I is insolation constant (kWh/m^2-yr), CF is Conversion factor, 3.6 MJ/kWh. The EPBT was found as ~3 months, which is consistent with the literature.[11]

Table S9. PED of perovskite PVs' components. These values are used in EPBT calculation.

Components	PED (MJ/m^2)
Al	2.11E+00
ZnO	4.03E+01
CH3NH3PbI3	3.48E+01
NiO	2.95E+00
ITO	8.75E+01
glass	7.24E+01
EVA	4.72E+01
frame	2.90E+02
Total	6.13E+02

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