Supplementary Information

Supplementary Section I. Module cost models

Supplementary Table 1. Module cost breakdowns and minimum sustainable price (MSP) for each single-junction and tandem considered: (a) Low-cost silicon SJ (PERC multi), (b) High-efficiency silicon single-junction (PERC mono), (c) Perovskite SJ, (d) Low-cost 4T tandem, (d) High-efficiency 4T tandem.

Supplementary Table 1a. Low-cost silicon single-junction module: mc-Si PERC single-junction

	Depreciation [$/m^2]	Maintenance [$/m^2]	Electricity [$/m^2]	Labor [$/m^2]	Materials [$/m^2]	Total (100% yield) [$/m^2]	Total (yield adjusted) [$/m^2]
Si wafer	$1.25	$0.21	$1.18	$0.73	$12.40	$15.78	$16.11
Si wafer to cell	$3.04	$0.92	$1.20	$0.74	$5.89	$11.78	$12.00
Tabbing and stringing	$0.22	$0.05	$0.09	$0.03	$1.74	$2.12	$2.15
Encapsulation	$0.30	$0.09	$0.38	$0.26	$10.51	$11.54	$11.64
Module wiring + testing	$0.27	$0.04	$0.25	$0.22	$3.32	$4.09	$4.11
R&D + SG&A	--	--	--	--	--	--	$5.00
						Total Cost	$55.64
						MSP	$63.33

Supplementary Table 1b. High-efficiency silicon single-junction module: mono-Si PERC single-junction

	Depreciation [$/m^2]	Maintenance [$/m^2]	Electricity [$/m^2]	Labor [$/m^2]	Materials [$/m^2]	Total (100% yield) [$/m^2]	Total (yield adjusted) [$/m^2]
Si wafer	$2.19	$0.65	$3.31	$1.46	$12.78	$20.40	$20.83
Si wafer to cell	$5.84	$1.41	$2.01	$1.01	$6.84	$17.11	$17.42
Tabbing and stringing	$0.22	$0.05	$0.09	$0.03	$1.74	$2.12	$2.15
Encapsulation	$0.30	$0.09	$0.38	$0.26	$10.51	$11.54	$11.64
Module wiring + testing	$0.27	$0.04	$0.25	$0.22	$3.32	$4.09	$4.11
R&D + SG&A	--	--	--	--	--	--	$6.26
						Total Cost	$68.36
						MSP	$79.31

Supplementary Table 1c. Perovskite single-junction module

	Depreciation [$/m²]	Maintenance [$/m²]	Electricity [$/m²]	Labor [$/m²]	Materials [$/m²]	Total (100% yield) [$/m²]	Total (yield adjusted) [$/m²]
FTO front glass cleaning	$0.16	$0.05	$0.26	$0.23	$6.60	$7.29	$7.54
Laser scribing	$0.25	$0.07	$0.07	$0.02	$0.25	$0.41	$0.42
Perovskite deposition	$0.66	$0.08	$0.19	$0.85	$0.27	$2.04	$2.10
ITO deposition							
Laser scribing	$0.25	$0.07	$0.07	$0.02	$0.25	$0.41	$0.42
Laser scribing	$0.25	$0.07	$0.07	$0.02	$0.25	$0.41	$0.42
interconnection	$0.20	$0.05	$0.01	$0.02	$0.01	$0.29	$0.30
Encapsulation	$0.30	$0.09	$0.38	$0.26	$10.51	$11.54	$11.64
Module wiring + testing	$0.27	$0.04	$0.25	$0.22	$3.32	$4.09	$4.11
R&D + SG&A	--	--	--	--	--	--	$2.85
						Total Cost	$31.57
						MSP	$36.18

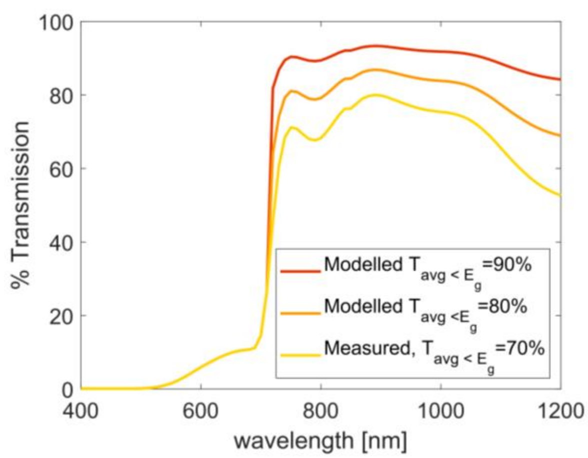
Supplementary Table 1d. Low-cost four-terminal tandem module: perovskite top cell on mc-Si PERC bottom cell

	Depreciation [$/m²]	Maintenance [$/m²]	Electricity [$/m²]	Labor [$/m²]	Materials [$/m²]	Total (100% yield) [$/m²]	Total (yield adjusted) [$/m²]
Si wafer	$1.25	$0.21	$1.18	$0.73	$12.40	$15.78	$16.11
Si wafer to cell	$3.04	$0.92	$1.20	$0.74	$5.89	$11.78	$12.00
Tabbing and stringing	$0.22	$0.05	$0.09	$0.03	$1.74	$2.12	$2.15
FTO front glass cleaning	$0.16	$0.05	$0.26	$0.23	$6.60	$7.29	$7.54
Laser scribing	$0.25	$0.07	$0.07	$0.02	$0.25	$0.41	$0.42
Perovskite deposition	$0.66	$0.078	$0.186	$0.849	$0.267	$2.04	$2.10
ITO deposition							
Laser scribing	$0.25	$0.07	$0.07	$0.02	$0.25	$0.41	$0.42
Laser scribing	$0.25	$0.07	$0.07	$0.02	$0.25	$0.41	$0.42
interconnection	$0.20	$0.05	$0.01	$0.02	$0.01	$0.29	$0.30
Encapsulation	$0.30	$0.09	$0.38	$0.26	$10.51	$11.54	$11.64
Module wiring + testing	$0.27	$0.04	$0.25	$0.22	$3.32	$4.09	$4.11
R&D + SG&A	--	--	--	--	--	--	$6.35
						Total Cost	$69.43
						MSP	$80.54

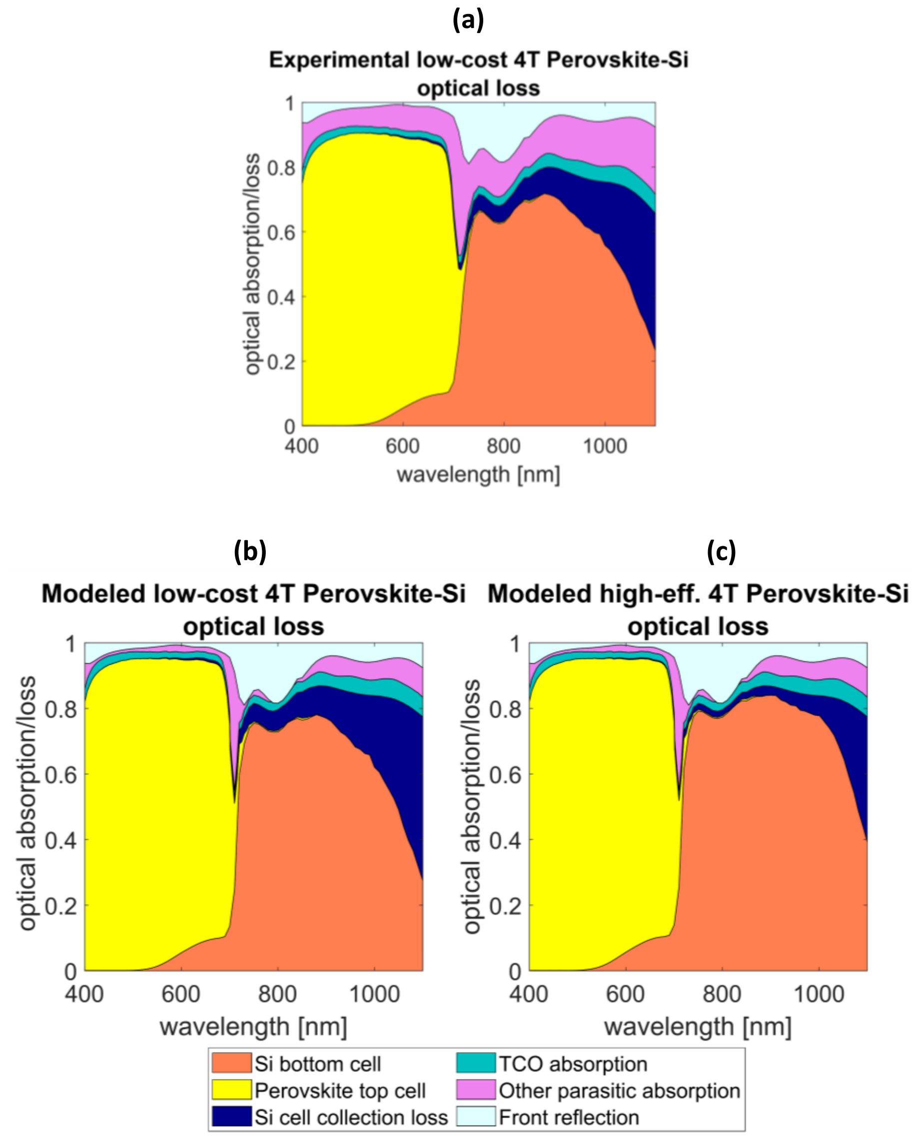
Supplementary Table 1e. High-efficiency four-terminal tandem module: perovskite top cell on mono-Si HIT bottom-cell

	Depreciation [$/m^2]	Maintenance [$/m^2]	Electricity [$/m^2]	Labor [$/m^2]	Materials [$/m^2]	Total (100% yield) [$/m^2]	Total (yield adjusted) [$/m^2]
Si wafer	$2.19	$0.65	$3.31	$1.46	$12.78	$20.40	$20.83
Si wafer to cell	$5.84	$1.41	$2.01	$1.01	$6.84	$17.11	$17.42
Tabbing and stringing	$0.22	$0.05	$0.09	$0.03	$1.74	$2.12	$2.15
FTO front glass cleaning	$0.16	$0.05	$0.26	$0.23	$6.60	$7.29	$7.54
Laser scribing	$0.25	$0.07	$0.07	$0.02	$0.25	$0.41	$0.42
Perovskite deposition	$0.66	$0.078	$0.186	$0.849	$0.267	$2.04	$2.10
ITO deposition							
Laser scribing	$0.25	$0.07	$0.07	$0.02	$0.25	$0.41	$0.42
Laser scribing	$0.25	$0.07	$0.07	$0.02	$0.25	$0.41	$0.42
interconnection	$0.20	$0.05	$0.01	$0.02	$0.01	$0.29	$0.30
Encapsulation	$0.30	$0.09	$0.38	$0.26	$10.51	$11.54	$11.64
Module wiring + testing	$0.27	$0.04	$0.25	$0.22	$3.32	$4.09	$4.11
R&D + SG&A	--	--	--	--	--	--	$7.51
						Total Cost	$80.71
						MSP	$95.16

Supplementary Section II. Tandem Performance Modeling



Supplementary Figure 1. Measure and modeled percent transmission versus wavelength of the perovskite semi-transparent top-cell with 70%, 80%, 90%.

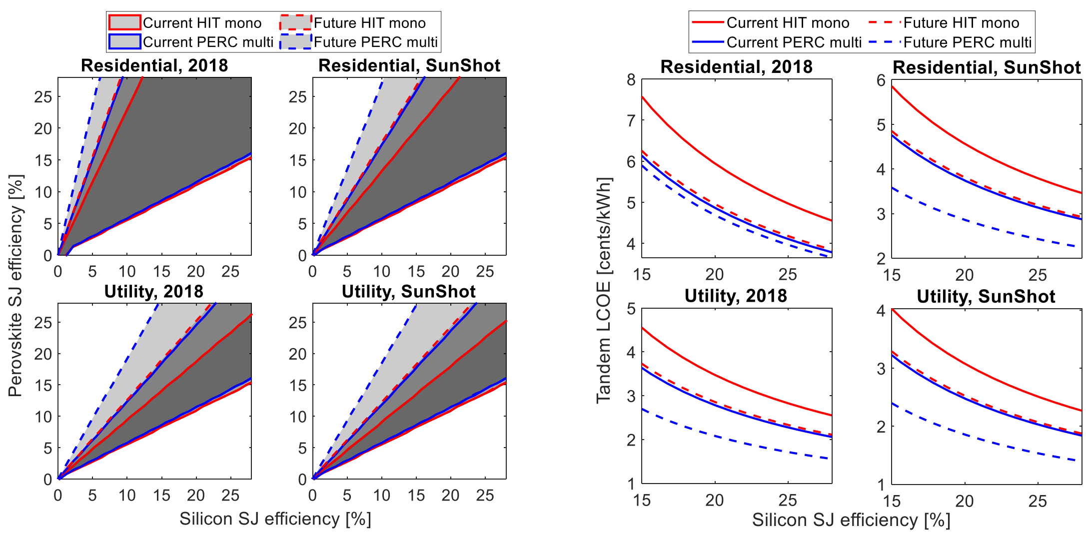


Supplementary Figure 1. Optical absorption/loss breakdown of the (a) experimental lo-cost tandem, (b) the modeled low-cost tandem, and (c) the modeled high-efficiency tandem

Supplementary Section III. Looking forward: Effect of increased sub-cell efficiency on tandem viability

To explore how tandem viability changes as all sub-cell efficiencies increase, we look at tandem viability over varied sub-cell single-junction module efficiencies, considering both current and expected future reduced costs of the two silicon cells types (Supplementary Figure 2). We see that the low cost tandem options allow for a much larger area over which tandem is the best option, again showing that the route employing a low-cost silicon bottom cell is more robust for tandems viability. As the cell cost decrease, the region over which the tandem is viable widens for both low-cost (PERC multi) and high-efficiency (HIT mono) tandems, however the low-cost option is always more flexible with a wider region than of viability than the high-efficiency tandem. This means that, as perovskite are developed and become higher efficiency, they are unlikely to achieve an LCOE lower than the low-cost tandem. This is not true for the high-efficiency tandem, and the perovskite single-junction will beat-out (or match) the tandem as is reaches module efficiencies above 20%.

Additionally, the wider range of viability allows for a lower LCOE to be achieved with a viable tandem than is possible with similar efficiency sub-cells using the high-efficiency tandem. The perovskite and silicon cell efficiencies tracked along the line bisecting the angle of the tandem viability region in Supplementary Figure 1a track the optimal tandem sub-cell combination (for the given costs). We plot the LCOE along this optimal line in Supplementary Figure 1b. This shows that the optimal tandem achieves a lower LCOE using the low-cost silicon cell than the high-efficiency cell, in all cases. These low LCOE cannot be achieved without either a significantly more efficiency silicon single-junction as a tandem or a significantly more efficiency perovskite cell as a single-junction. For example in 2018 residential systems, for the high-efficiency tandem to achieve the LCOE the low-cost tandem using a 20% efficiency silicon SJ cell and a ~20% efficiency perovskite cell, the high-efficiency silicon cell would need to be at least 25%. For both 2018 and future utility-scale systems given future expected silicon cell costs, to reach the LCOE of a tandem comprised of a 20% efficient low-cost silicon cell and 20% perovskite top-cell, the high-efficiency silicon module would have to reach about 28%. Though we expect the high-efficiency silicon to reach higher efficiencies, this efficiency gap is quite large and poses a great challenge.



(a) (b)

Supplementary Figure 2. (a) Plot showing where a tandem is viable versus the top and bottom single-junction module efficiency for the low-cost (PERC multi) (blue) and high-efficiency (HIT mono) (red) with current cell costs (solid) and future estimated reduced cell costs (dashed) (as used in Figure 5). The ratio of single-junction to bottom cell efficiency for each of the two silicon cell types is constant, as given in the rest of the paper. The region in parameters space where the tandem module has a lower LCOE than either sub-cell as a single junction module is shaded, and the region is marked by the outline with the associated color/style. The regions of the shaded areas that are overlapping are darker. (b) Plot of the tandem LCOE versus silicon SJ with perovskite SJ efficiency set by the line bisecting the angle of the viable tandem region in figure (a) (where tandem LCOE advantage is at an optimum) for each silicon cell type/cost scenario.