Economics of Tandem Flat Plate Photovoltaic Modules

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***Abstract* — Tandem modules, formed by stacking two PV cells, either monolithically or mechanically, can offer higher solar conversion efficiency than modules that use only one type of PV cell. Such modules necessarily cost more per unit area than either single-junction alternative, but the increased efficiency leverages area-related costs to potentially reduce system cost per watt. High-efficiency, low-cost tandems could arise if the cost of III-V cells is reduced to approach the cost of silicon cells, or if stable large-area perovskite cells are demonstrated with efficiency approaching that of today's best laboratory devices. Within the scope given by these optimistic assumptions, future costs and performance still have a substantial range of uncertainty. A probabilistic Monte Carlo model is presented that generates a large number of cost and performance scenarios based on a range of values for each input parameter. The results can be used to assign a probability, within the scope of the assumptions, that the tandem will be more cost-effective than either single-junction alternative. Four types of tandem modules are analyzed: (1) III-V on silicon, (2) III-V on thin film, (3) perovskite on silicon, and (4) perovskite on thin film. All of these tandems have a reasonable chance (>10%) of providing slightly lower cost per watt for residential systems, and the two thin-film options might also slightly benefit utility-scale systems. Achieving a substantial cost benefit is less likely. Only the perovskite on thin film tandem has a reasonable chance of reducing system cost per watt by more than 10% for residential systems, or of reducing system cost per watt by more than 5% for utility-scale systems.**

I. Input Parameters

Input parameters for cost and performance are selected to correspond to the 2020 – 2030 timeframe when it might be possible for III-V or perovskite cells to become suitable for mainstream one-sun PV applications. Table I lists the assumptions for the cost components [1-3]. A wide range is allowed for III-V cell cost, because issues regarding substrate reuse [4] and high-rate deposition are yet to be resolved. The BOS costs range from today's cost at the high end, to the 2020 SunShot targets at the low end [3]. Utility systems are fixed-tilt installations with their size constrained by power (or cost), whereas residential systems are a 50:50 mix of area-constrained and power/cost-constrained installations [5].

Table II lists the assumptions for performance. A wide range is allowed for perovskite efficiency, since substantial modifications to the cell chemistry and structure may be required to obtain stable large-area cells in production.

The 'tandem efficiency fraction' in Table II accounts for how a cell of a given technology performs in a tandem stack compared to how it performs by itself. For top cells, this factor is less than unity if the bandgap is increased for the tandem, and further reduced due to the need for a transparent rear surface. For bottom cells, this factor is one-half or less due to the optical filtering of the top cell, and further reduced if the bandgap of the bottom cell is decreased for the tandem.

Table I
Cost Parameters

Parameter	Low	Mid	High
Silicon Cell ($\$/m^2$)	50	60	70
III-V Cell ($\$/m^2$)	50	100	200
Thin-Film Cell ($\$/m^2$)	20	25	30
Perovskite Cell ($\$/m^2$)	10	20	30
Module Assembly ($\$/m^2$)	30	35	40
Tandem Module Added Cost ($\$/m^2$)	0	5	10
Utility Area-Related BOS ($\$/m^2$)	76	85	93
Utility Power-Related BOS ($/W)	0.32	0.40	0.50
Residential Area-Related BOS ($\$/m^2$)	125	176	228
Residential Power-Related BOS ($/W)	0.38	0.68	0.98

Table II
Performance Parameters

Parameter	Low	Mid	High
Silicon SJ Cell Efficiency	18%	20%	22%
Silicon Tandem Efficiency Fraction	0.40	0.45	0.50
III-V SJ Cell Efficiency	22%	24%	26%
III-V Tandem Efficiency Fraction	0.75	0.80	0.85
Thin-Film SJ Cell Efficiency	16%	18%	20%
Thin-Film Tandem Efficiency Fraction	0.35	0.40	0.45
Perovskite SJ Cell Efficiency	12%	16%	20%
Perovskite Tandem Eff Fraction	0.85	0.90	0.95
Cell to Module Efficiency Fraction	0.85	0.90	0.95

II. Results for III-V Top Cell

The cost model was run for a III-V top cell with either a silicon or thin-film bottom cell, for both utility-scale and residential systems.

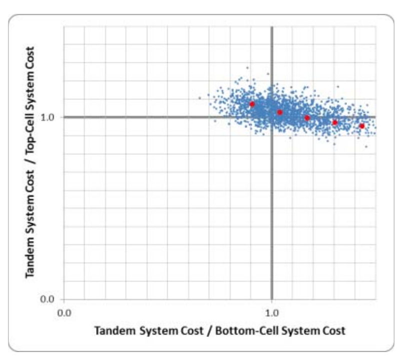

Fig. 1. Utility-scale system cost per watt for III-V/Si tandems relative to similar systems using single-junction Si cells (x-axis) or

single-junction III-V cells (y-axis). Red dots correspond to III-V costs in \$50/m^2 increments from \$50/m^2 (left) to \$250/m^2 (right), with all other input parameters set to their median value.

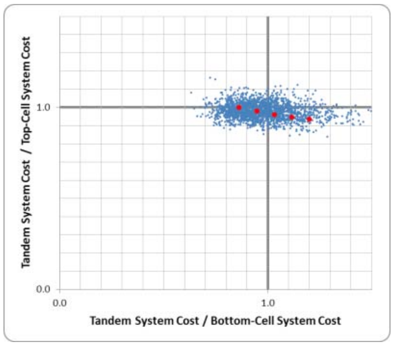

Fig. 2. Residential system cost per watt for III-V/Si tandems relative to similar systems using single-junction Si cells (x-axis) or single-junction III-V cells (y-axis). Red dots correspond to III-V costs in \$50/m^2 increments from \$50/m^2 (left) to \$250/m^2 (right), with all other input parameters set to their median value.

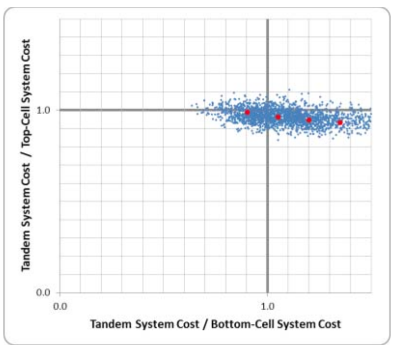

Fig. 3. Utility-scale system cost per watt for III-V/TF tandems relative to similar systems using single-junction TF cells (x-axis) or single-junction III-V cells (y-axis). Red dots correspond to III-V costs in \$50/m^2 increments from \$50/m^2 (left) to \$200/m^2 (right), with all other input parameters set to their median value.

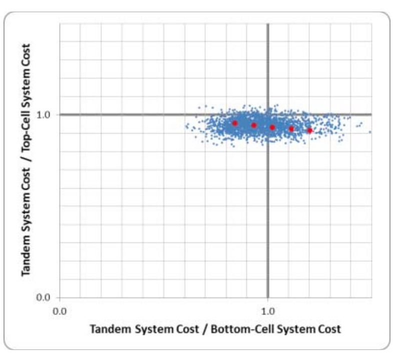

Fig. 4. Residential system cost per watt for III-V/TF tandems relative to similar systems using single-junction TF cells (x-axis) or single-junction III-V cells (y-axis). Red dots correspond to III-V costs in \$50/m^2 increments from \$50/m^2 (left) to \$250/m^2 (right), with all other input parameters set to their median value.

III. Results for Perovskite Top Cell

The cost model was run for a perovskite top cell with either a silicon or thin-film bottom cell, for both utility-scale and residential systems.

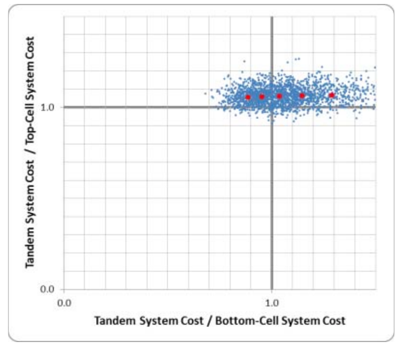

Fig. 5. Utility-scale system cost per watt for Perovskite/Si tandems relative to similar systems using single-junction Si cells (x-axis) or single-junction perovskite cells (y-axis). Red dots correspond to perovskite cell efficiency in 2% increments from 12% (right) to 20% (left), with all other input parameters set to their median value.

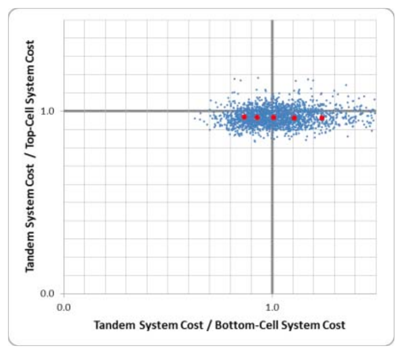

Fig. 6. Residential system cost per watt for Perovskite/Si tandems relative to similar systems using single-junction Si cells (x-axis) or single-junction perovskite cells (y-axis). Red dots correspond to perovskite cell efficiency in 2% increments from 12% (right) to 20% (left), with all other input parameters set to their median value.

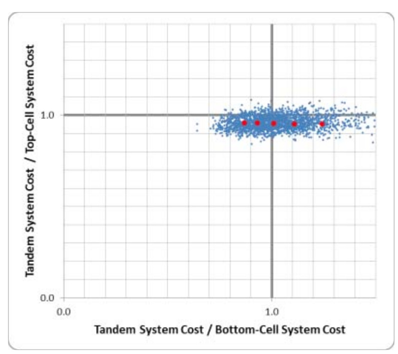

Fig. 7. Utility-scale system cost per watt for Perovskite/TF tandems relative to similar systems using single-junction TF cells (x-axis) or single-junction perovskite cells (y-axis). Red dots correspond to perovskite cell efficiency in 2% increments from 12% (right) to 20% (left), with all other input parameters set to their median value.

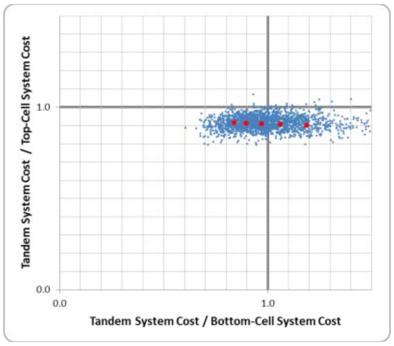

Fig. 8. Residential system cost per watt for Perovskite/TF tandems relative to similar systems using single-junction TF cells (x-axis) or single-junction perovskite cells (y-axis). Red dots correspond to perovskite cell efficiency in 2% increments from 12% (right) to 20% (left), with all other input parameters set to their median value.

IV. Discussion

For each of the applications depicted in Figs. 1-8, the fraction of the scenarios (blue dots) that lie within any given region of the plot can be determined by counting dots. Those dots that lie within the unit quadrant (both axes less than 1.0) correspond to cases where the tandem provides a lower system cost in \$/W relative to either of the two single-junction alternatives. Those dots that have both coordinates less than 0.95 represent cases where the tandem provides more than a 5% system cost benefit. Both coordinates less than 0.90 represents more than a 10% system cost benefit. Table III lists the fraction of scenarios that lie within each of these benefit regions. This fraction can be interpreted as the probability that the tandem will be preferred over the single-junction alternatives, within the scope of the assumptions reflected in the ranges given for the input parameters in Tables I and II.

Table III
Probability that Tandem Reduces System Cost

Tandem, Application	Tandem is better	5% better	10% better
III-V/Si, Utility-scale	5%	0%	0%
III-V/Si, Residential	41%	10%	1%
III-V/TF, Utility-scale	25%	6%	0%
III-V/TF, Residential	60%	29%	4%
Perovskite/Si, Utility-scale	4%	0%	0%
Perovskite/Si, Residential	38%	13%	1%
Perovskite/TF, Utility-scale	43%	17%	1%
Perovskite/TF, Residential	57%	38%	12%

V. Conclusions

Most of the rows in Table III offer a reasonable chance (>10%) of a slight reduction in system cost for the tandem (highlighted in blue). However, only the last row in Table III provides a reasonable chance that the tandem will provide at least a 10% system cost benefit (highlighted in green). That is Perovskite/TF in a residential system application. Several rows offer a reasonable chance that the tandem will provide at least 5% system cost benefit (highlighted in yellow). The only yellow cell for a utility-scale application is Perovskite/TF.

The small benefit of the tandem structure, despite the optimistic assumptions regarding III-V cost and perovskite efficiency, can be understood by noting that a tandem not only needs to be better than the silicon or thin-film bottom-cell technology, it also must be better than the top-cell technology. When III-V cells become sufficiently inexpensive, or when stable perovskites become sufficiently efficient, a single-junction module based on these materials is likely to be a better choice than forming a tandem with either silicon or a conventional thin-film bottom cell.

Acknowledgment

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An Excel calculator that implements the cost model described in this paper is available for download from the Archive tab on www.pvcolleagues.net.

References

[1] D.C. Bobela, L. Gedvillas, M. Woodhouse, K.A. Horowitz, and P.A. Basore, "Economic competitiveness of III-V on silicon tandem one-sun photovoltaic solar modules in favorable future scenarios," submitted to *Progress in Photovoltaics: Research and Applications*, 2016.

[2] S. Nanayakkara, K. Horowitz, M. Woodhouse, A. Kanevce, and P. Basore, "Evaluating the economic viability of CdTe/CIS and CIGS/CIS tandem photovoltaic modules," submitted to *Progress in Photovoltaics: Research and Applications*, 2016.

[3] R. Jones-Albertus, D. Feldman, R. Fu, K. Horowitz, M. Woodhouse, "Technology advances needed for photovoltaics to achieve widespread grid price parity," *Progress in Photovoltaics: Research and Applications,* 2016, DOI: 10.1002/pip.2755.

[4] S. Ward, T. Remo, K. Horowitz, M. Woodhouse, B. Sopori, K. VanSant, and P. Basore, "Techno-economic analysis of three different substrate removal and reuse strategies for III-V solar cells," *Progress in Photovoltaics: Research and Applications*, 2016, DOI: 10.1002/pip.2776.

[5] P.A. Basore, "Understanding manufacturing cost influence on future trends in silicon photovoltaics," *IEEE Journal of Photovoltaics*, **4**(6), Nov 2014, pp. 1477-1482.