ON COST-EFFECTIVENESS OF PEROVSKITE/C-SI TANDEM PV SYSTEMS

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ABSTRACT: The requirements to achieve cost reduction with perovskite/c-Si tandem PV systems relative to single-junction (SJ) perovskite or c-Si PV systems are modeled. Specific cases assume a perovskite band gap of 1.7eV in tandem use and 1.55 eV in SJ use, both having the same module efficiency expressed as a fraction of the Shockley-Queisser limit for the band gap. Compared to SJ perovskite PV systems, current and foreseen c-Si cell manufacturing costs are low enough to achieve cost reduction when adding c-Si cells to a perovskite module, if, in particular, additional loss (other than related to SQ limit as a function of band gap) of power conversion efficiency (PCE) of the perovskite module from SJ to tandem can be mostly avoided (it should be less than about 10-20%). Compared to SJ c-Si PV systems, requirements for cost-effective modification to tandem structure are, not suprisingly, a high PCE and low cost for the added perovskite stack. For example, for reasonable parameter assumptions, a semi-transparent perovskite PCE of 16.4% and a stack fabrication cost of about 35 €/m^2 would result in 10% cost reduction, the same PCE with a stack fabrication cost of 17€/m^2 in 16% cost reduction, for tandem PV systems relative to the c-Si technology. In both tandem-SJ comparisons, if there is a significant increase of module manufacturing cost for, e.g., more expensive junction box, power optimizer, additional encapsulant materials, etc., or balance-of-system costs these should be included in the c-Si cell or perovskite stack costs (translated to the m^2 cost), respectively.
Keywords: hybrid tandem, perovskite, silicon, economic analysis

1 INTRODUCTION

The rapid development of perovskite solar cells to achieving high efficiency, as well as increasingly more stable performance, has resulted in increased attention for hybrid perovskite/crystalline silicon tandem devices. 4-terminal hybrid tandems can potentially provide a unique combination of the attractive aesthetics of thin film (TF) PV, with an energy production that can be higher than the best performing crystalline silicon (c-Si) PV modules. Apart from stability, the cost and performance of such a tandem in comparison to the single junction (SJ) technologies are deciding factors.

This paper analyzes the potential for cost reduction of hybrid TF/c-Si tandem modules compared to the respective single junction modules. Sensitivities to module cost parameters and efficiency are investigated. While the comparison is aimed at perovskite, the framework is valid for other thin film technologies, so the general abbreviation TF will be used for the top submodule technology. The comparison is aimed at c-Si bottom cells, e.g. using the cost for a (156mm)^2 industrial cell as a metric, but with a simple conversion from that cell cost to a m^2 cost, the framework would be applicable to TF/TF tandems as well.

The Shockley-Queisser (SQ) efficiency limit increases from SJ to tandem by about a third. This would roughly be the cap for the cost reduction if the additional cell could be added to the SJ system for zero cost. For a tandem module that builds on a c-Si bottom cell, the potential efficiency increase is even larger than the SQ limit suggests, because c-Si has an Auger-limited efficiency limit significantly below the SQ limit. Therefore, a tandem with an ideal radiatively limited top cell can provide an even larger benefit (e.g., about 16 percentage points in [1]). However, the question is how far cost reduction can approach this potential value in practice. In earlier work, Peters et al.[2], Basore [3], and Bobela et al.[4] reported model analysis for tandem-enabled cost reductions, showing a likelihood of very small cost reductions.

One of the important things these papers pointed out, is that comparison of cost-effectiveness has to be with respect to both constituent single junction technologies, and that best results for the tandem may be expected when those single junction technologies are comparable in cost and performance. Since c-Si cell production presently costs about 1 €/cell which translates to about 35 €/m2, and the typical perovskite stack costs forecasts in literature are also around 30 €/m2 (of course with large uncertainty), and with perovskite module PCE in excess of 15% such comparability of cost and performance for both constituents of the future tandem seems to be a good possibility.

This paper attempts to analyze the cost reduction potential with minimized number and detail of assumptions where possible. It aims to use aggregated real-life numbers where possible. While the model is aimed at 4-terminal tandems (separately contacting TF and c-Si cells), consisting of a TF stack on a glass superstrate, laminated with strings of c-Si bottom cells), monolithically integrated 2-terminal tandems would not be very differently modeled.

At the end of this paper, possible changes in the relation between system cost and levelized cost of energy (LCOE) for SJ versus tandem technology are briefly considered.

2 COST COMPARISON MODEL

2.1 Reference system

The reference system in the model is the single-junction thin film (SJ TF) system. It is parameterized by a system installation cost *C*, and nominal module power output *P*. *C* is thus typically the system Capex, though it could be taken to include additionally an Opex-related term, for the purpose of LCOE calculations. The model assumes losses in inverter and cabling are percentage-wise the same for all technologies.

The relative cost reduction (in €/Wp) for a change from SJ TF to tandem PV system is

$$RCR \equiv -\left[(C+\Delta C)/(P+\Delta P) - C/P\right]/(C/P)$$

2.2 Tandem compared to SJ TF system

For the change from SJ TF to tandem, c-Si cells are added to the TF module, resulting in changes of cost and power:

$$\Delta C = C_{cell} + \Delta C_{str}$$
$$\Delta P = P_{cSi,T} + \Delta P_{TF}$$

C_{cell} is the cost of the c-Si cell (wafer and processing) and ΔC_{str} is the sum of all other changes in cost of any other aspect of the PV system, such as additional encapsulant, inverter electronics, cabling, etc (similar to [2]). $P_{cSi,T}$ is the additional power output from the added c-Si bottom cells. ΔP_{TF} is the change of power output from the TF top cell, e.g. due to change of contact materials from non-transparent to semi-transparent, or due to a change of bandgap of the absorber. All parameters are referred to the same (module) area, so area-dependent balance of system (BoS) costs do not change.

It is assumed that ΔC_{str} is composed of the following two parts:

Part 1. balance of system costs that are proportional to the added nominal power output, with a proportionality factor C_{Wp}. These extra costs are thus $\Delta P \cdot C_{Wp}$. This includes inverter and grid connection, as well as a small fraction of the costs of cabling, planning, infrastructure [5].

Part 2. the increased module manufacturing costs, specifically tabbing/stringing and extra encapsulant, as well as possibly increased costs for e.g. the junction box or a module-level power optimizer.

For Part 1 a value of C_{Wp}=0.1 €/Wp is used, which is reasonable for the present and some time into the future [5]. The sensitivity of the results to this value is very small. Part 2 can be combined with the cost per c-Si cell. For example, a change in module-level power optimizer that would add 20€ to the cost of a module would translate into 0.33 €/cell for a 60-cell module.

2.3 Tandem compared to SJ c-Si system

Because the TF system is the benchmark, the comparison of tandem to SJ c-Si system requires additional input parameters and assumptions.

In this paper's model the cost of the c-Si SJ system is related to the cost of the SJ TF system as

$$C_{cSi,SJ} = (1-f)\cdot C + \Delta C + \\ + \left[P_{cSi,SJ} - (1-f)\cdot P - \Delta P\right]\cdot C_{Wp}$$

In essence this means that the c-Si SJ generalized system cost is the sum of a fraction (1-*f*) of the generalized TF SJ system cost, plus the cost of the c-Si cells, with adjustments for the Wp-proportional costs according to the output power difference between TF and c-Si systems. In principle *f* thus roughly represents the cost of TF stack deposition and monolithic interconnection. Peters et al. [2] have already emphasized the importance of the parameter *f* for cost-effectiveness of tandems. $P_{cSi,SJ}$ is the power from the encapsulated c-Si cell in SJ use. The relative cost difference between the SJ c-Si and the tandem system, *RCR'*, follows from the difference between $C_{cSi,SJ}/P_{cSi,SJ}$ and $(C+\Delta C)/(P+\Delta P)$.

According to the ITRPV [6], the equivalent of *f* for c-Si systems is about 0.3 for utility scale PV systems (the c-Si cell cost is ~60% of the module cost, and module cost is slightly below 50% of the utility scale system cost). The most likely application of tandem modules will be in systems where balance of system costs are relatively high, which implies *f* is reduced below this value of ~0.3. In addition, we assume the perovskite stack production cost will be less than c-Si cell production cost, further reducing *f*.

3 RESULTS

3.1 Sensitivities

Table 1 shows the center values for the sensitivity analysis. Unless otherwise noted, these center values are also used in the sensitivity plots later in this paper.

Table I: Center values for sensitivity analysis.

Parameter	center value
f	0.15
c-Si PCE SJ	22%
c-Si PCE in tandem	11%
TF PCE SJ	17%
TF PCE in tandem	15.75%
TF PCE loss SJ→tandem	5%
SJ TF system cost	1 €/Wp
c-Si cell cost*	1.2 €/cell
C_{Wp}	0.1 €/Wp

*incl. tabbing/stringing and other extra module conversion costs when c-Si cells are added to the TF module

The c-Si SJ PCE is taken according to the ITRPV for PERx cell types in 2023. The filtered c-Si PCE in tandem is a feasible target for such cells under a perovskite stack with 1.7 eV bandgap [7]. Both c-Si PCEs are for encapsulated situation. The TF SJ aperture area module PCE of 17% is also a realistic target for perovskite of 1.55eV bandgap. The TF tandem PCE of 15.75% corresponds to the same fraction of the Shockley-Queisser efficiency limit (55% of SQ limit), for 1.7eV instead of 1.55 eV bandgap (1.7 eV is a more optimal band gap for application in tandem with c-Si). The TF PCE loss SJ→tandem of 5% is *on top of* this reduction from SJ to TF according to the SQ limit, and this value is probably one of the more challenging ones in this table. The c-Si cell cost can be thought of as composed of 1 €/cell for cell production costs (approximately the present industrial status), plus 0.2 €/cell for extra tabbing/string costs, encapsulant, etc. The value for C_{Wp} of 0.1 €/Wp is on the low end of today's range.

Fig. 1 shows the sensitivities for the cost reduction of tandems with respect to either single junction technology, for variation around these parameters. The sensitivity is calculated as the ratio of the relative variation of the *RCR* divided by the relative variation of the parameter. Note that the value of some parameters will vary by large amounts or have a large uncertainty (e.g. the parameter *f*, or the TF PCE loss SJ→tandem) while others are much better known or well predictable (e.g. the c-Si PCEs).

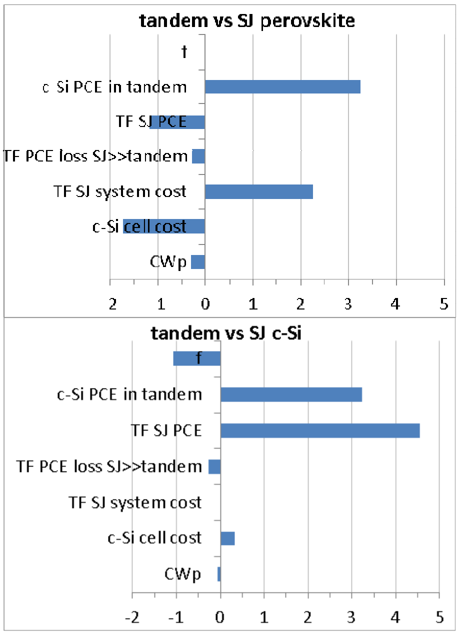

Figure 1: Sensitivities of the relative cost reduction of tandem compared to single junction, for key model parameters. Sensitivity is calculated as defined in the text.

Based on these sensitivities, it makes sense to plot the cost reduction for tandems relative to perovskite as a function of TF SJ system cost, and c-Si cell cost, for both of which the future values are quite uncertain (perhaps by a factor of 2), and the loss in TF PCE from SJ to tandem. The other two important parameters, c-Si PCE in tandem and TF SJ PCE are both relatively less uncertain (the first one more likely to be uncertain by ~10%, the second by perhaps ~30%, both leading to uncertainty in relative cost reduction of ~30%).

Likewise, based on these sensitivities, it makes sense to plot the cost reduction for tandems relative to SJ c-Si as a function of the parameter *f* (determined by the perovskite stack deposition&interconnection cost relative to TF system cost) and the TF PCE.

3.2 Tandems compared to SJ TF

Figure 2 shows the *RCR* for tandem PV systems compared to the bench mark SJ TF PV system, as a function of the cost of the added c-Si cells, the benchmark TF system cost, and the efficiency loss from SJ to tandem use.

Since the current production cost for c-Si cells is around 1 €/Wp, it can be seen that c-Si cells can be added cost-effectively. It should be noted though that all extra module costs, such as junction box, cables, connectors, encapsulant, and also system costs not included in the Wp-proportional costs, should be included in these c-Si cell costs. As an example, 10 €/module for e.g. junction box, connectors, cables, would correspond to 0.17 €/cell, which can be visualized as a left-shift of the curves (a lower cell cost is required to reach the same cost reduction).

Nevertheless, given the progress in reducing cell production costs, a *RCR* of about 10% or more could be achieved, in particular if the extra losses in the TF PCE from SJ to tandem can be largely avoided. The impact of area dependent costs is (implicitly) clearly visible: for expensive system locations, such as residential rooftop, the benchmark system costs will be relatively high, and the *RCR* for a tandem is therefore also high.

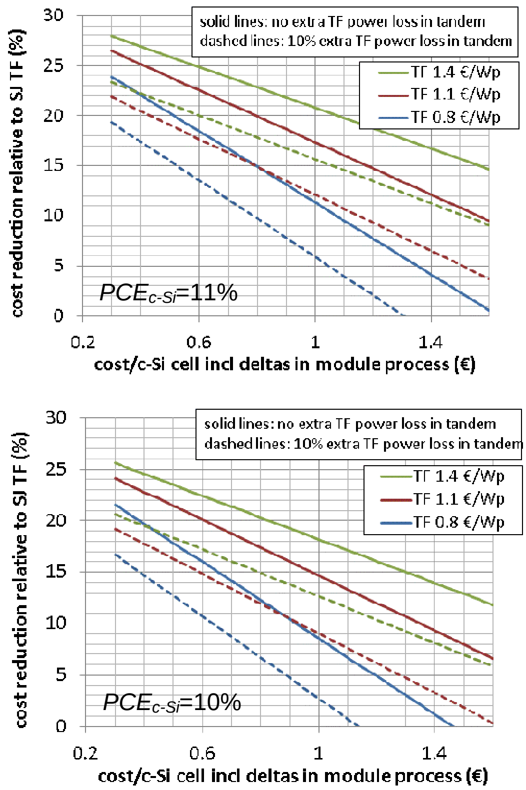

Figure 2: Relative cost reduction of tandem PV systems compared to SJ TF, as a function of the cost of the added c-Si cells. Other parameters as in Table 1, i.e., PCE of 17% for SJ, 15.75% in tandem (solid lines), and 14.2% in tandem (dashed lines). Top: c-Si filtered cell efficiency is 11%, bottom 10%.

3.3 Low cost low performance or high cost high performance c-Si cells?

The fact that the sensitivity to the filtered c-Si cell efficiency is not very large, is illustrated by the comparison of the top and bottom plots in Fig. 1, which are for 11% and 10% filtered c-Si efficiency, respectively. Conversely, this shows that spending c-Si processing costs for higher cell efficiency is less effective for tandem PV systems than SJ c-Si PV systems.

For example, Fig. 3 shows how c-Si cell cost increase for a high efficiency technology affects the system cost for c-Si SJ and TF/c-Si tandem PV systems, for the model parameters as in Table 1. Because the filtered c-Si cell efficiency is only half the SJ c-Si cell efficiency, the allowable cost increase for the high efficiency technology is also halved. In the example of Fig. 3, a SJ PCE increase of $2\%_{abs}$ allows 45% cell cost increase in case of SJ c-Si systems, versus 20% cell cost increase when used in tandems.

The notable exception to this rule of thumb is when changing from Al-BSF c-Si technology to PERx technology, which significantly improves the near-infrared response of the c-Si cells, and therefore has a relatively large benefit in tandem use. This situation should be modeled more precisely. However, a change from PERx to possibly significantly more expensive c-Si technology, e.g. SHJ or IBC, will have only roughly half the cost-effectiveness in tandem application

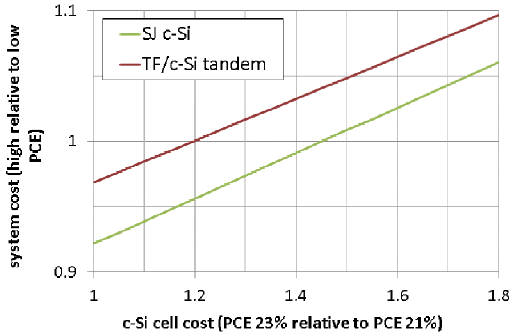

Figure 3: PV system cost for a 23% c-Si cell technology relative to a 21% c-Si cell technology, as a function of the c-Si cell processing cost, for both SJ systems and tandem systems. The break-even (relative system cost = 1) allows a ~2x higher c-Si cell cost increase for the 23% cells in SJ systems than in tandem systems.

3.4 Tandems compared to SJ c-Si

Fig. 4 shows the *RCR'* for tandem PV systems compared to the SJ c-Si PV system based on the same c-Si cells (22% efficiency, cf. Table 1), for two key parameters for the cost reduction: perovskite module efficiency, and fraction *f* of perovskite stack cost in total system cost. As described in section 2.3, since for c-Si cells used in utility scale systems the cell cost is a fraction of ~0.3 of the system cost, it can be expected that in the market segments relevant for tandems (with high BoS costs), for perovskite stacks *f* will be significantly below 0.3.

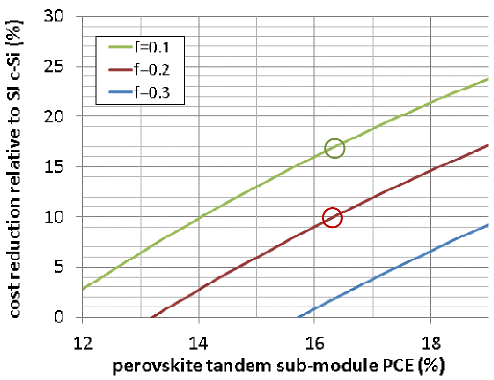

Figure 4: Relative cost reduction of tandems compared to SJ c-Si, as a function of the efficiency of the added semi-transparent TF submodule and the cost fraction of the perovskite stack in the SJ TF system cost. Other parameters as in Table 1.

When assuming a ball park system cost of 1 €/Wp, the parameter *f* can be translated into a perovskite stack cost (including monolithic interconnection, and all other module cost increases from c-Si to tandem). The green circle in Fig. 4 indicates a tandem cost reduction *RCR'*=17% when the stack cost is 18 €/m^2, and the red circle *RCR'*=10% when the stack cost is 35 €/m^2. Such perovskite stack costs seem to be feasible, based on recent literature attempting to estimate future perovskite production costs, e.g. [8], though other references estimate somewhat higher costs [9].

For lower system cost, the allowed perovskite stack cost will be reduced. Also, the increased costs for tandem module and system production (encapsulant, junction box, cabling, etc.) should be effectively included in this perovskite stack cost. Thus, it seems that to obtain cost reduction relative to c-Si SJ systems may be challenging for semi-transparent perovskite module efficiencies (at 1.7eV band gap) with PCE less than about 16%. On the other hand, it should be noted such module PCE is still far below the SQ limit and may have significant room for improvement.

3.5 Effect of module cost components specific for tandem

The previous sections have outlined how module and system costs specific for tandem PV have to be included in the sensitivity plots of Fig. 2-4: For Fig 2-3 (adding c-Si cells to a perovskite TF system) such costs have to be included at a rate of 0.17 €/cell per extra 10 €/module. For Fig. 4 (adding a perovskite stack to a c-Si system), since a standard c-Si module area is ~1.7 m^2, such costs have to be included in the costs for the perovskite stack at about 6 €/m^2 per extra cost of 10 €/module.

The largest part of such costs would probably be related to 4-terminal wiring structure, requiring extra cables, connectors, power optimizer circuits, etc. Therefore, there is significant potential benefit (in cost as well as market acceptance) to be expected from a 2-terminal module with internal voltage matching of the perovskite and c-Si submodules [1,10], if this can be realized at acceptable cost for suitably arranging the c-Si and perovskite submodule architecture.

4 FROM SYSTEM COST DIFFERENCES TO LCOE DIFFERENCES

4.1 LCOE

The levelized cost of electricity is given by

$$LCOE = \frac{Capex + M \cdot Opex}{U \cdot D}$$

where where *Capex* is the system installation cost and *Opex* the annual operational expenses (assumed to be constant), both in €/Wp. *M* is about 1/3 to 2/3 of the economic lifetime of the system in years, depending on the capital discount rate. For utility scale PV, a reasonable assumption is that $M \cdot Opex \approx 0.2$ €/Wp, which can be summed with the *Capex* to arrive at a generalized system cost. For residential rooftop, *Opex* may not be a parameter of interest (i.e., be effectively zero). *U* is the utilization of the system (specific energy yield in kWh/Wp), and *D* is a factor accounting for efficiency degradation as well as financial discount [5]:

$$D = \sum_{t=1}^{n} (1 - Degradation\,n)^t / (1 + WACC_{real})^t$$

where *n* is the economic lifetime of the system in years, *Degradation* the annual degradation of the nominal power of the system, and $WACC_{real}$ the real weighted annual average cost of capital.

LCOE should be a good guideline for the value (and therefore the price) of a high efficiency module, though it has been put forward that other factors, in particular constraints on available area, also play a role in this [11].

4.2 Utilization

Utilization may be a somewhat significant parameter in the cost/benefit evaluation of tandems. One aspect is the temperature coefficient TC of the PCE. The higher band gap top cell can be expected to have a better TC than c-Si [12], as is found for e.g. GaAs cells which have 2x lower TC than standard c-Si cells. For perovskite solar cells, TC is not well established. In addition to effect of differing TCs, also the module temperature in operation can be expected to be slightly less for tandems than for SJ systems because of the reduced thermalization losses. For example, for the parameters as in Table 1, the thermalization power input is reduced by 6%, and therefore the operating temperature increase over ambient temperature would likely be reduced by roughly the same percentage. This can amount to a few degrees in conditions such as for rooftop modules with little ventilation. If power output from perovskite solar cells would have a similar TC as that of GaAs solar cells (about -0.2%/K), this can correspond to an improvement in utilization of a few percents (e.g. 3% better utilization for tandem PV compared to c-Si PV, if a representative operating temperature difference relative to ambient is 25 K).

4.3 Degradation

The degradation rate of tandems incorporating perovskite, might be worse than for c-Si. This will affect the factor *D* in the LCOE. In Fig. 5 the relative LCOE is plotted as a function of degradation rate, for an economic lifetime of 30 years (the outlook for product warranty on c-Si modules in the ITRPV is 30 years). The curves in Fig. 5 will be slightly less steep for lower economic lifetime: the slope is roughly proportional to system lifetime. Whether or not a residual value after the economic lifetime is included, does not change the figure. The ITRPV outlook for degradation of c-Si systems is about 0.6%/year. Significant changes in degradation rate from c-Si PV system to tandem PV system, of order 1%/year, can negate part or all of an initial cost advantage for tandems.

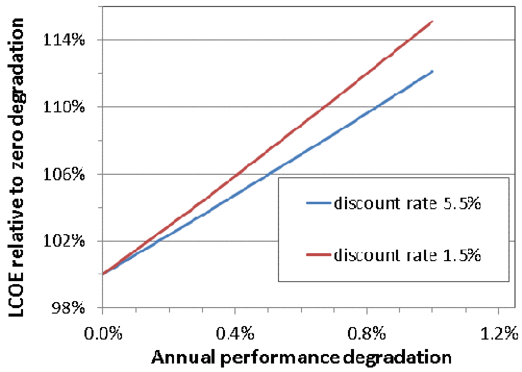

Figure 5: The effect of degradation on LCOE, for an economic lifetime of 30 years. The assumption of a residual value for the system after the economic lifetime does not change this plot. (discount rate = $WACC_{real}$)

5 CONCLUSIONS

This paper analysed under which conditions, using state of the art industrial c-Si production, a cost reduction of tandem systems relative to both SJ systems, of ~10-20% can be achieved.

If perovskite cell stacks can be deposited and interconnected for ~20-30 €/m^2, and achieve a (semi-transparent, 1.7eV band gap) efficiency of around 16-18%, such significant cost reduction can potentially be achieved when the benchmark PV system cost is around 1 €/Wp. For lower system costs the allowed perovskite stack costs should decrease proportionally. This does not allow much room for added module- or system-level tandem costs (junction box, connectors, MLPE cost increase, etc.) as these have to be included in these stack costs. Higher perovskite PCE improves cost-effectiveness and relaxes these constraints.

For cost-effectiveness of tandems relative to single-junction perovskite modules, PCE losses from non-transparent to semi-transparent perovskite cell will have to be effectively limited to about 10-20%. c-Si cell production costs do not seem to be a foreseeable bottleneck for the cost reduction of tandems with respect to future SJ perovskite modules.

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