Bifacial Four-Terminal Perovskite/Silicon Tandem Solar Cells and Modules

Ten years after the first paper[1] on the properties of metal halide perovskite solar cells, their efficiency and stability have increased tremendously.[2] It was quickly realized that their application goes beyond the single-junction use. Indeed, perovskite cell technology, by virtue of its tunable bandgap and low sub-bandgap absorption, offers new opportunities for stacking solar cells of different bandgap in a multijunction device to overcome the fundamental Shockley−Queisser (SQ) efficiency limit of a single-junction device. Under AM1.5 irradiation, this limit is 33.7% for the optimal bandgap, and for perovskite with a normally somewhat higher bandgap of 1.55 eV it drops to 31%. [3,4] It is not expected that perovskite will exceed 26% single-junction efficiency.[5] For crystalline silicon solar cells (c-Si), including Auger recombination, the theoretical SQ limit is 29.4%. [6,7]Currently, single-junction silicon solar cells reached an efficiency in the lab of 26.7%; [8,9] while in mass production, solar cells are produced with efficiencies up to about 25%,[10] with main stream efficiencies of about 22%. The latter have been increasing by 0.4%/year, and this trend is expected to continue for a number of years, but it will likely become overly costly to go beyond 24−25%. This efficiency increase has contributed significantly to the steep learning rate, which is the average reduction of Si PV module selling price for every doubling of cumulative shipment, of 39.8%[11] that has been experienced since 2006. Although the manufacturing cost 2 reduction also plays a major role, we expect that when the practical efficiency limits are being approached, the silicon PV industry will not be able anymore to maintain such a learning rate. Aside from module price, the further PV system costs (like installation) to a large extent depend on area and are reduced per unit of power output simply by higher module efficiency. It is because of the possibility that it can help overcome both these performance and cost limitations that metal halide perovskite-on-silicon tandem devices have been under development since 2015[12] and today lead to power conversion efficiencies of over 29%. [13,14]

In a similar vein, recently, bifacial PV silicon module technology has been rapidly gaining market share[11] because of their increased energy yield over conventional monofacial modules. Bifacial modules collect light falling onto their front as well as rear surfaces, thereby increasing carrier generation. The rear surface irradiance typically comes from diffuse sky radiation and reflected light from surrounding surfaces. The increase in generated power depends on the albedo of the surroundings and the configuration of the PV-system (e.g., height, orientation, tilt angle, ground coverage, etc.).[15] Typical increase of annual energy production thanks to bifaciality, for commercial systems, is 10−30%.[14] Tandem modules are expected to enter the PV market in 2023,[11] and by that time 16% of the modules are expected to be bifacial,[11] growing to 30% toward the end of the decade. To compete in the high-performance PV market, tandem modules therefore not only should be more efficient than conventional single-junction modules manufactured at that time but also will have to produce more energy than the best single-junction modules that would be available. For ground-based as well as commercial rooftop PV, the best single-junction modules in this sense are likely to be bifacial modules, which benefit from the extra energy collected at the rear. So why not combine the best of both technologies in a bifacial tandem module? This is the reasoning behind the approach that we propose in this Viewpoint. There have been early propositions of the use of the bifacial concept by several groups.16 In a bifacial tandem module the bottom solar cells (i.e., the silicon solar cells in this case) receive light from both sides. While the light received on the front of the bottom cell is "filtered" (short wavelengths removed) through the perovskite top cell, the light entering from the rear is not. Nevertheless, its spectrum is affected by atmospheric scattering and reflection from surrounding surfaces. The rear incident light can have a dramatic impact on the design and operation of the tandem device. Let us consider the two major configurations: four-terminal (4T) versus two-terminal (2T) tandems (see Figure 1).

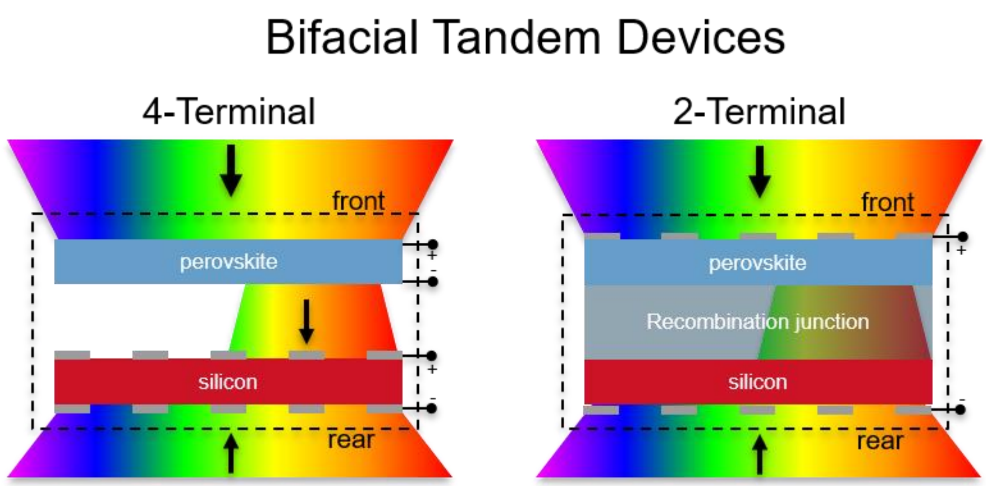

Figure 1. 4-terminal (left) versus 2-terminal (right) bifacial tandem configuration. Photons incident on the front, and of energy below the perovskite bandgap, reach the silicon bottom device and can be absorbed, while the entire photon spectrum incident on the rear is absorbed by the silicon bottom device. In a 4T tandem the extra rear incident light results linearly in extra power generated. Instead the 2T terminal tandem device needs to be redesigned in order to have current matching of both devices.

In a 4-terminal configuration the extra power generated by the bifacial bottom device scales linearly with the rear irradiance and comes at almost no extra cost compared to a monofacial bottom device. In a 2-terminal configuration, the power production is limited by the requirement for current matching of top and bottom cells. Therefore, the bifacial 2-terminal tandem device needs to be designed such that the top device absorbs more photons in order to match the extra current generated in the bifacial bottom device (more considerations are presented in the Supporting Information). Although this customization might be challenging in a production environment, we nevertheless think that a bifacial proposition for 2T tandem can be beneficial in terms of extra energy yield when the right technology adaptations (see the Supporting Information) are taken care of.16

Below, we report our recent experimental exploration of the performance of a 4T tandem device based on a stack of perovskite and bifacial c-Si solar cells. For this purpose, a semitransparent 17.0% perovskite “p-i-n stack” 17− 19 solar cell (3 × 3 mm2) with a record high near-infrared transmittance (average NIR transmittance of 95%20 was combined with a metal wrap through silicon hetero-junction (MWT-SHJ) 21,22 bifacial solar cell. The perovskite device is fabricated by TNO in the Solliance collaboration, whereas the bottom device resulted from a collaboration of TNO and Choshu Industry Co. The MWT-SHJ cell alone has a front (single-junction) efficiency of 22.8%. Thanks to the special design of the rear contacts it reaches a bifaciality factor of 84%. The 4T tandem efficiency is obtained by adding the top and bottom cell contributions. Considering front illumination only, this yields an efficiency of 26.5%, with the filtered bottom cell’s efficiency contribution being 9.5%-point. In Table 1 , the power densities relative to a front side illumination of 100 mW/cm2 of the semitransparent perovskite and crystalline silicon bottom cells either as single-junction or as part of a tandem device are reported. In the new IEC measurement norm23 to characterize bifacial PV devices, an additional rear irradiation of 20 mW/cm2 is defined as BiFi200. In Figure 2 the power output of both the single-junction c-Si and the 4T tandem bifacial cells are reported as a function of the rear irradiance, using a similar methodology.

Table 1. Overview of the efficiency of the semi-transparent PSC and c-Si bottom cells. The individual single-junction devices as well as the 4T tandem device is given at STC (viz. only front irradiance, 100mW/cm^2, AM1.5g) and at 20 mW/cm^2 of additional rear irradiance (AM1.5g). Similarly, MWT-SHJ bifacial bottom cell efficiencies are reported as single-junction devices and as bottom devices. Obviously these latter values include filtering by the perovskite top cell. IV data for both BiFi100 and BiFi200 are reported in SI.

Device	**Description**	**Power density relative to front-incident irradiance of 100 mW/cm^2 (%)**		
		Single-junction	Single-device for 4T tandem	4T tandem
ST-PSC Single-junction	Top cell – 5 min MPP tracking	17.0	17.0	
Bifacial MWT-SHJ Single-junction	Front illumination single-junction (BiFi0)	22.8		
	Rear illumination single-junction	19.1		
	Front illumination + rear 200W/m^2 (BiFi200)	26.8		
Bifacial 4T Tandem	Filtered bottom cell (BiFi0)		9.5	26.5
	Filtered bottom cell + rear 200W/m^2 (BiFi200)		13.5	30.5

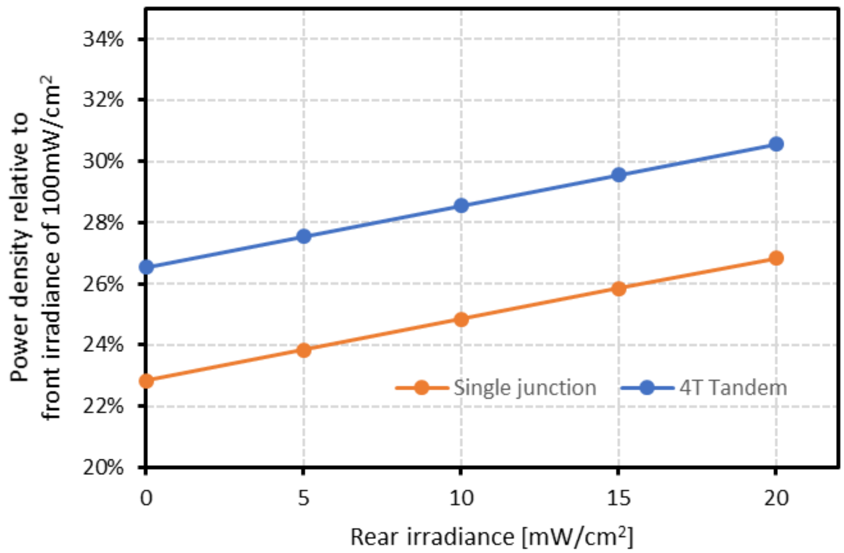

Figure 2. Experimentally determined power density relative to a front incident irradiation of 100 mW/cm^2, as a function of the additional rear irradiance, for the cells of Tab. 1. The intercept at zero rear irradiance represents the monofacial efficiency. The lines are a guide to the eye.

Based on BiFi200,23 the 4T tandem output power is 30.5 mW/cm2 or equivalently a 30.5% output normalized to 1 sun.24 The bifacial single-junction MWT-SHJ cell when characterized under the same BiFi200 conditions results in a power output of 26.8 mW/cm2 ,25 much less than the bifacial tandem output, but slightly greater than the monofacial tandem output, confirming the proposition to combine tandem with bifacial operation in order to achieve better energy production and competitiveness. To our knowledge, these are the first bifacial 4T tandem devices reported.

Annual energy yield calculation

In order to understand the potential of the bifacial and monofacial devices, we compare their energy yield in the same conditions using our bifacial PV simulation software BigEye.26 The relative contribution from the rear irradiance varies with many factors, related to the geographical location, albedo of the surrounding surfaces, atmospheric conditions, and factors related to the design of the PV installation (the module tilt, height, ground coverage ratio, etc.). An informative approach is to consider the efficiency of a hypothetical monofacial device that would generate the same amount of energy output as the bifacial device, under the same operating and location conditions. We define this as the “energy equivalent efficiency” or simply “equivalent efficiency”27 of the monofacial device. Although this equivalent efficiency will vary depending on the mentioned factors it does give clear metrics for a comparison of monofacial and bifacial systems under the same field conditions. Because, in our opinion, tandem devices will have to be competitive in a bifacial market, this comparison is useful to set tandem device efficiency targets. In Figure 3 , a summary of the outcome of the BigEye annual yield analysis for an albedo of 0.3 (indicatively corresponding to a concrete surface) and several ground coverage ratios (GCRs) at a constant total module area is included. The annual yield for the bifacial and monofacial tandem and the bifacial and monofacial single-junction c-Si systems are included for a typical meteorological year in Amsterdam (simulation results for Denver, CO, United States, and details on the simulation are given in the Supporting Information). Taking the monofacial single-junction (MWTSHJ) module asreference for an equivalent efficiency as described above, we find that a monofacial c-Sisingle-junction device with an efficiency of 30.5% would be needed to obtain the same energy yield as our bifacial 4T tandem device at the Amsterdam location, and 29.8% in Denver, for the smallest ground coverage ratio considered in the simulations. The lower fraction of diffuse irradiance at Denver lowers the equivalent efficiency compared to Amsterdam.

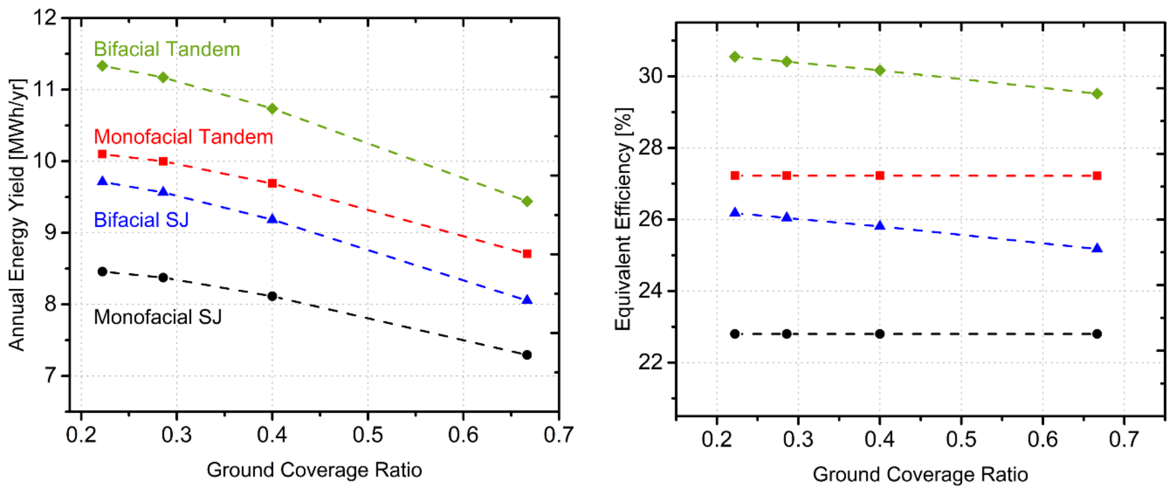

Figure 3. Left: Comparison of the modelled annual energy yield from the central row (22 modules of 1.65m² each) for the tandem PV plants as described in the text (details in the SI), obtained from the BigEye analysis using Amsterdam, the Netherlands as location, a ground surface albedo of 30% and a ground clearance of 1 m. For this simulation we used the device data reported in Table I. Right: When compared to the monofacial c-Si MWT-SHJ annual energy yield, an equivalent efficiency is determined. This equivalent efficiency varies with the GCR, and to match the bifacial tandem energy yield exceeds 30%.

Outdoor measurements

In order to also start a first experimental assessment of outdoor bifacial energy yield of perovskite/c-Si tandems, we manufactured a set of four 4T tandem minimodules for outdoor testing (Figure 4). Two were monofacial, and two were bifacial. The perovskite minimodules in these tandems measured 20 × 20 mm2 (cut from perovskite stacks processed on 6 in. superstrates) and were composed of 6 interconnected cells. Bifacial passivated emitter and rear cell (PERC+) silicon solar cells were cut down to 20 × 20 mm2 in order to provide bottom c-Si cells that match the area of the top minimodule.

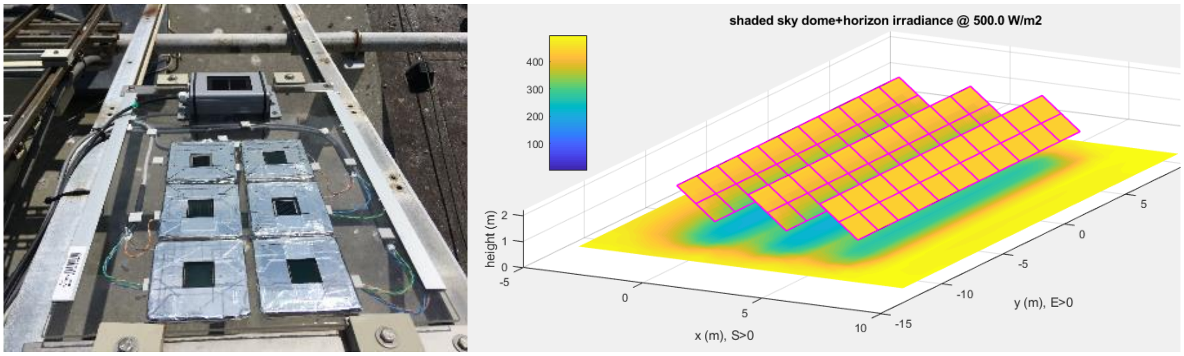

Figure 4. Left: Outdoor test station showing the monofacial and bifacial 4T tandem devices. Photo TNO Energy Transition, Solar Energy. Right: BigEye PV system configuration. Shed, South facing, 3 rows of 11x2 modules (1.65m2 each, not in scale in the figure).

The minimodules were placed on the concrete roof of our building, and the IV of all devices was recorded simultaneously every 10 min, while keeping both bottom and top devices at V mpp between the scans. In Figure 5 the power density as a function of the front irradiance is plotted for the initial 100 h of testing, which started on August 8, 2019. Only power densities above an irradiance level of 300 W/m2 are plotted. The 4T bifacial tandem module's power density is on average about 20% higher, agreeing very well to the energy yield calculations for an albedo of 30%. This is reasonable considering that concrete has an albedo of 20−40%.28 The monitoring is being continued to characterize degradation phenomena.

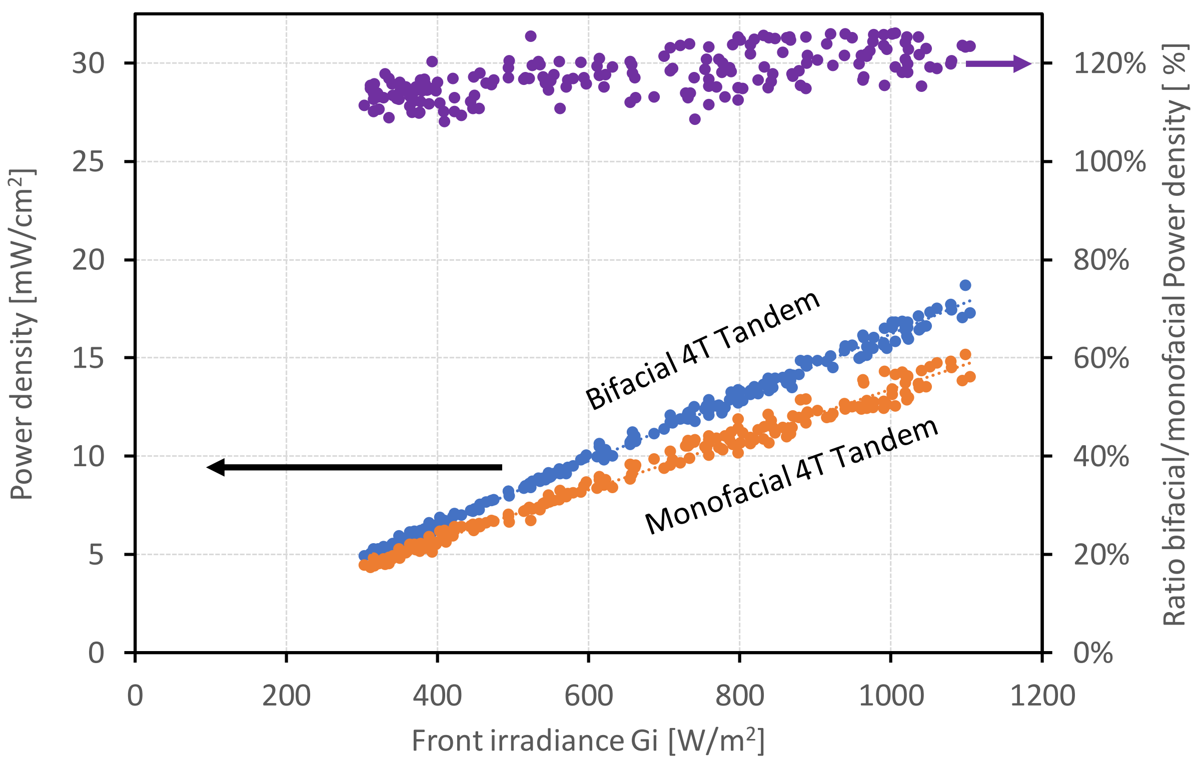

Figure 5. 4T tandem minimodule power density versus front irradiance (left). Ratio bifacial monofacial power versus front irradiance (right).

Cost considerations

So far, this Viewpoint has demonstrated the performance advantage of a bifacial configuration applied to 4-terminal tandem devices. However, performance alone is not sufficient to validate the competitiveness of a new technology with the incumbent (silicon single-junction) technology. In Figure 6 , the tandem efficiency required to reach a breakeven PV system cost (per equivalent power output) relative to monofacial single-junction crystalline silicon is shown, as a function of the add-on cost for the perovskite. The c-Si performance is taken from ITRPV,11 so the tandem efficiency is only a function of the perovskite efficiency. For example, in the case of monofacial devices, for a perovskite overall add-on cost of 20 $/m2 , 16.4% perovskite efficiency is needed to reach cost breakeven with the single-junction device (the breakeven tandem device needs to reach 25.6% efficiency). When we consider the bifacial configuration for the 4T tandem device, it can reach a breakeven with the single-junction silicon monofacial device at a significantly lower efficiency or higher add-on cost ($/m2). Equivalently, because of the bifacial feature, the cost benefit of the bifacial tandem is larger (compared to monofacial single-junction silicon). When the comparison is made with respect to a bifacial single-junction silicon technology, making the tandem bifacial will be practically essential to keep up with the reduced cost per energy output of the silicon single-junction technology. Notably, the breakeven efficiencies for perovskite shown in Figure 6 (right axis) are already achieved by several groups at cell or even module level. Hence, the long-term stability and cost (and related to cost, scaling up of technology) seem to become the main aspects to take into consideration for a positive business case for bifacial perovskite/c-Si-based tandem devices.

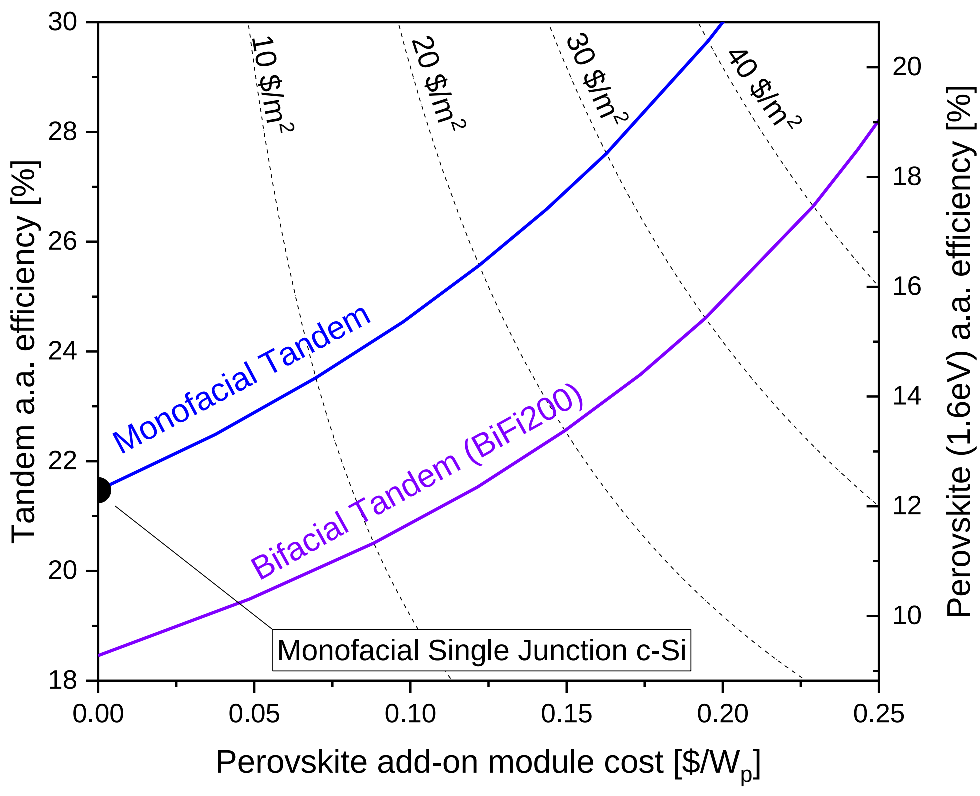

Figure 6. Iso-system-cost contours (solid lines) as a function of perovskite module cost in $/W_p$ and tandem (left axis) aperture area (a.a.) efficiency. Dash lines correspond to perovskite add-on module cost in $/m^2$. The blue and purple lines represent the aperture area tandem efficiency required for system-cost breakeven respect to single-junction monofacial silicon. The intercept

(at 0 $/W$_p$) of the monofacial tandem (blue line) shows the efficiency of the reference single-junction monofacial device (21.5% aperture area efficiency). The right axis represents the perovskite a.a. efficiencies required to reach the tandem efficiency, assuming a perovskite bandgap of 1.6 eV and the same transparency of the perovskite device as reported in this paper (see Supporting Information). State-of-the-art silicon module and system cost parameters from the ITRPV[Error! Bookmark not defined.] and, for BiFi200, 70% bifaciality were used.

Impact and future work

Challenges still remain. For example, a major challenge is to integrate the bottom and top devices in a module capable of lasting at least 25 years. This is the minimum requirement in order to compete with state-of-the-art bifacial silicon modules. The manufacturing of stable, large area, highly NIR-transparent, and high-efficiency perovskite solar modules is the main challenge for the top device. Perovskite, because of the low cost of the constituent materials and the processing (e.g., solution-processed slot die coating, ALD, and sputtering), is considered an ideal technology that can be produced at relatively low cost. When combined with the extra energy yield from bifacial configuration, the 4T bifacial tandem device can be considered as a natural evolution of the performance limit of single-junction silicon-based module technology.

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ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publication website at DOI: XXXX

Motivations, results and additional information on the device manufacturing; monofacial and bifacial characterization procedures; energy yield parameters and equivalent efficiency.

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Notes

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