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Review

A roadmap for tandem photovoltaics

Kirstin Alberi,[1,*] Joseph J. Berry,[1,2,3] Jacob J. Cordell,[1] Daniel J. Friedman,[1] John F. Geisz,[1] Ahmad R. Kirmani,[1,4] Bryon W. Larson,[1] William E. McMahon,[1] Lorelle M. Mansfield,[1] Paul F. Ndione,[1] Michael Owen-Bellini,[1] Axel F. Palmstrom,[1] Matthew O. Reese,[1] Samantha B. Reese,[1] Myles A. Steiner,[1] Adele C. Tamboli,[1] San Theingi,[1] and Emily L. Warren[1]

SUMMARY

Combining two or more junctions into a tandem solar cell promises to deliver a leap in power conversion efficiency that will help to sustain continued growth in installed photovoltaic (PV) capacity. Although tandems are now on the roadmaps of many PV manufacturers, much work remains before they are ready for mass deployment. Accelerating their development requires advances on many fronts. In this article, we outline the fundamentals and status of tandem PV, considering multiple PV technology pairings and architectures. We then present the challenges that must be overcome and a general timeline of activities that are required to translate tandems to commercial products. Our intent is to spur researchers and manufacturers to work together to address important aspects of tandem design, reliability, and scaling to enable more rapid progress toward mass production.

INTRODUCTION

Photovoltaics (PVs) is currently at an exciting point in its trajectory. Having recently passed the global milestone of 1 TW installed capacity, PV is beginning to deliver on its potential to supply the world with clean energy. To meet growing demand for both global human development and increased electrification of all energy sectors, multiple models suggest that 75 TW of PV would need to be installed by 2050.[1] This would require an installation rate of more than 1 TW per year by the end of this decade. In addition to significant growth in manufacturing, achieving this goal also calls for continued innovation to increase PV module efficiencies while reducing overall material and energy consumption. At the same time, single-junction solar cell efficiencies are asymptotically approaching what is practically achievable, limiting improved performance as a means for meeting this goal. Tandem solar cells, consisting of two or more junctions,[2] have therefore become increasingly attractive for their potential to reach much higher efficiencies (up to >40%) and lower their embodied carbon. These gains, in turn, become an important driver for lowering the total system cost by reducing the area of the system and the associated balance of systems (BOS) costs.[3–5] These linked benefits have placed tandem solar cells on the roadmaps of many PV manufacturers, and tandems are projected to reach 2% of market share by 2030.[6] In support of these goals, progress on lab-scale tandem demonstrations has been swift over the past several years, with record cell efficiencies now exceeding 30% for multiple technology pairings.[7–11] But much work remains to transfer this early success in the lab to commercial products.

Several advances are needed to enable the deployment of tandem PV at the TW scale. Record cell efficiencies must be increased through innovations in absorber

CONTEXT & SCALE

Photovoltaic (PV) technology not only promises to provide the world with clean energy but is also expected to be a necessary and significant component of our future energy infrastructure. Increasing solar cell efficiencies will aid widespread deployment, and combining existing PV technologies into tandem architectures (consisting of two or more junctions) offers a path toward cost-effective modules and systems. So-called hybrid tandems are still largely in the pre-commercialization stage, and the design considerations are currently being worked out. The objective of this review is to present the critical aspects that will come into play and encourage the PV community to work together to address them collectively.

technologies and their integration. Those efficiencies must then be translated to modules and high-volume manufacturing, where rigorous qualification testing must be carried out to ensure products are ready for market. In parallel, tandems must be designed for reduced embodied energy and enhanced sustainability before products are fully established. Both of these factors are essential to improving energy payback time (EPBT) and the greenhouse gas (equivalent CO_2e) return on investment at the cell, module, and system levels. Reliability and durability issues must also be identified and addressed to endow tandem modules with long lifetimes in support of deployment and reduced end-of-life waste objectives. Finally, the details of tandem PV system design must be worked out to speed deployment. It is critical that the PV community work together, as it has in the past, to achieve these advances on a timeline that will contribute to broader PV deployment goals necessary to enable the global clean energy transition.

The intent of this roadmap is to bolster the collective effort to develop tandem PV by providing a comprehensive view of the pathway to commercialization and the high-level challenges that must be overcome along the way. Here, we specifically focus on hybrid tandems with two junctions fabricated from a range of established and emerging PV technologies rather than high-efficiency, high-cost III–V multijunction cells. The first half of this article (sections "fundamentals of tandem solar cells," "materials for subcells," "fundamental tandem efficiency limits," "energy-harvesting efficiency," "cell and module demonstrations," "measurement," and "value proposition and associated metrics") provides foundational knowledge on tandem PVs as a primer for the subsequent roadmap discussion. It includes information about how devices and modules are configured, progress in cell-level efficiencies, a discussion about their value propositions, and an overview of and recommendations for the metrics, measurements, and models necessary for their further development. Those who are already well-versed in tandem PV technologies may want to skip ahead to the second half of the article (starting at section "a roadmap for future development"), where we discuss the road ahead, including addressing cell-level challenges and opportunities, scaling to modules and manufacturing, solving reliability issues, evaluating the cost competitiveness of tandem PV, planning for their environmental impact, and contending with risks to commercialization.

FUNDAMENTALS OF TANDEM SOLAR CELLS

A single-junction solar cell is limited by two major fundamental losses: (1) photons with energy lower than the band gap are not absorbed by the semiconductor, and (2) photons with energies above the band gap generate carriers that almost immediately thermalize to the conduction or valence band edge, thereby losing the energy in excess of the band gap. Tandem solar cells address these limitations by utilizing two or more junctions to absorb a greater portion of the solar spectrum while lowering the total thermalized energy. In an example two-junction tandem device, the shortest wavelength (highest energy) photons are absorbed in the high band-gap top junction and thermalize only to the top-junction band gap, whereas the longer wavelength (lower energy) photons are absorbed in the lower band-gap bottom junction and thermalize down to the bottom-junction band gap.

Many approaches have been developed to couple different wavelengths of light into solar cells with different band gaps. Vertical stacking of junctions is the most widely used approach. The resulting tandem solar cells are often classified by the number of terminals (external electrical contacts) for the smallest repeating unit of the device. Figure 1 shows the possible arrangements for different cell types and terminal

[1]National Renewable Energy Laboratory, Golden, CO 80401, USA

[2]Renewable and Sustainable Energy Institute, University of Colorado, Boulder, CO 80309, USA

[3]Department of Physics, University of Colorado, Boulder, CO 80309, USA

[4]Present address: School of Chemistry and Materials Science, Rochester Institute of Technology, 84 Lomb Memorial Drive, Rochester, NY 14623, USA

*Correspondence: kirstin.alberi@nrel.gov

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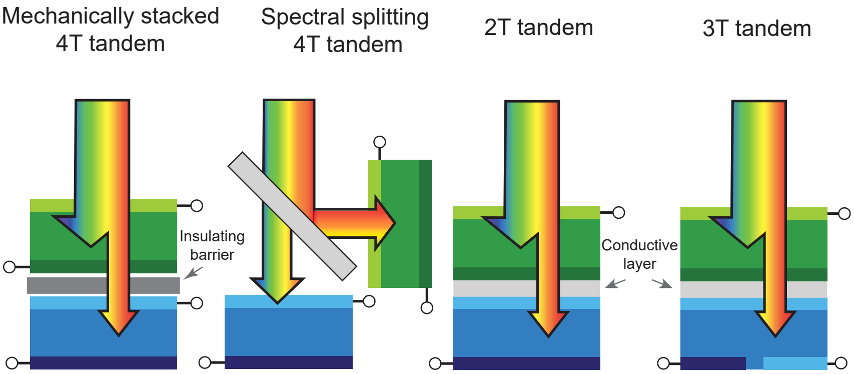


Figure 1. Schematic of simple configurations for tandem solar cells: 4T stacked, 4T with spectral splitting, 2T, and 3T

configurations (modified from Yu et al.[12]). In the remainder of this section, we will provide an overview of different terminal configurations of tandem devices, focusing on the cell-level design. In the following section, interconnection of multiple cells will be addressed. We also note that optically directing different portions of the solar spectrum onto physically separated cells (also known as spectral splitting) is another approach that can be taken (see Figure 1). We do not focus on the distinct technological challenges of that approach here.

2T tandem solar cells

Two terminal (2T) tandem devices consist of multiple semiconductor junctions that are both optically and electrically connected in series. They are typically fabricated by directly depositing or growing one solar cell junction on top of the other and including a tunnel junction (TJ) or recombination layer in between to electrically couple the junctions in series.[9–11,13–17] 2T configurations can also be achieved by separately fabricating the top and bottom junctions and then connecting them electrically via wafer bonding,[18] metallic bonding of grids or metal particles,[19] or using a transparent conductive adhesive material.[20] The resulting device is sometimes referred to as ''monolithic'' structure, but we avoid this term due to its multiple uses, for example, in also describing interconnect approaches of thin-film modules. The key aspects are that the interconnect layer provides electrical connection with low resistance, high optical transmission (which may require layers such as conductive anti-reflection coatings if the refractive index changes), and strong mechanical properties that do not degrade under thermal cycling or other stresses likely to be encountered.

For a series-connected 2T tandem cell, in the absence of luminescent coupling, the overall current will be determined by the junction with lowest generated photocurrent (the current-limiting cell). When the junction with the excess photocurrent is the top junction and has good radiative efficiency, it will share the radiatively emitted part of that excess with the bottom junction through luminescent coupling. When the junction with the excess photocurrent is the bottom junction, the excess photocurrent will be lost to radiative and non-radiative recombination. There may be more minor secondary benefits, such as photon recycling and fill factor enhancement. The ideal distribution of photocurrents is a complicated optimization problem that considers the power produced in each junction at each operating voltage, but the maximum efficiency is generally reached when the individual cells produce the same current (i.e., current-matched conditions) so that very little excess photocurrent is lost (although there are conditions under which this is not strictly the case).[21] Ideally, band gaps are chosen so that the individual junctions are optically thick while evenly dividing up the incident photon flux, thus generating the same photocurrents. The appropriate choice of band gaps has been modeled by many authors, taking into account the incident spectrum (e.g., AM1.5 global, AM1.5 direct, or AM0), the concentration level, and the number of junctions. If materials are not available at those band gaps, current matching can sometimes be achieved by thinning one or more of the individual junctions in order to reduce light absorption in one cell and increase light absorption in another cell.[22] Although 2T configurations can often simplify tandem device design and fabrication, these current-matching constraints can limit their performance. Changes in the solar spectrum throughout the day as well as non-ideal band-gap combinations can lead to efficiency losses of a few percent if care is not taken to mitigate these issues.

4T tandem solar cells

Four terminal (4T) tandems are coupled optically in series but isolated electrically (vertically) at the cell level. Junctions are typically fabricated separately and then joined using an insulating, optically transparent layer. Because of the ability to fabricate junctions separately, 4Ts are generally the most adaptable with respect to junction material, processing, and geometry combinations. For example, III–V/Si 4T devices have very high demonstrated efficiencies at the cell level[8] and are compatible with bifacial designs.[23] Another advantage of the 4T configuration is that they are not subject to current-matching constraints because the junctions can be operated independently at their maximum power points if appropriate power electronics are used. 4T tandems can also benefit the most from photon recycling when high radiative efficiency junctions are used, since the intermediate layer usually has a lower refractive index.[24]

A drawback of 4T tandems is scaling to larger areas and modules requires connecting cells of each junction type laterally in series. These lateral transport layers can introduce substantial optical and resistive losses at the module scale.[25] The intermediate bonding layer must also be able to withstand high voltages arising from differences in the operating voltages of the top and bottom strings.[26] Given the flexibility of 4T tandems to different material combinations, processing methods, junction band gaps, and junction designs, 4T tandems present many pathways for commercialization initially. These qualities provide advantages not only at the design phase but also may improve tolerance to non-uniformities, differential degradation rates of the junction material, and other factors affecting commercial potential.

3T tandem solar cells

Three terminal (3T) tandems are less common than 2T or 4T configurations but have received recent attention because they offer several potential benefits. Primarily, they do not need to be current matched, and some configurations do not require TJs. They also do not need to be electrically insulated between or require lateral charge transport between the cells. These factors make them considerably more flexible with respect to junction material choices and cell designs. A comprehensive overview of 3T tandem configurations can be found in Warren et al.[27]

Fabrication of 3T devices is similar to 2Ts in that the vertical interconnect between top and bottom junctions must be conductive. For 3Ts that use Si bottom cells, an interdigitated back contact (IBC) approach provides the third terminal.[28] IBC configurations are also possible for thin-film bottom cells, although more work is needed to

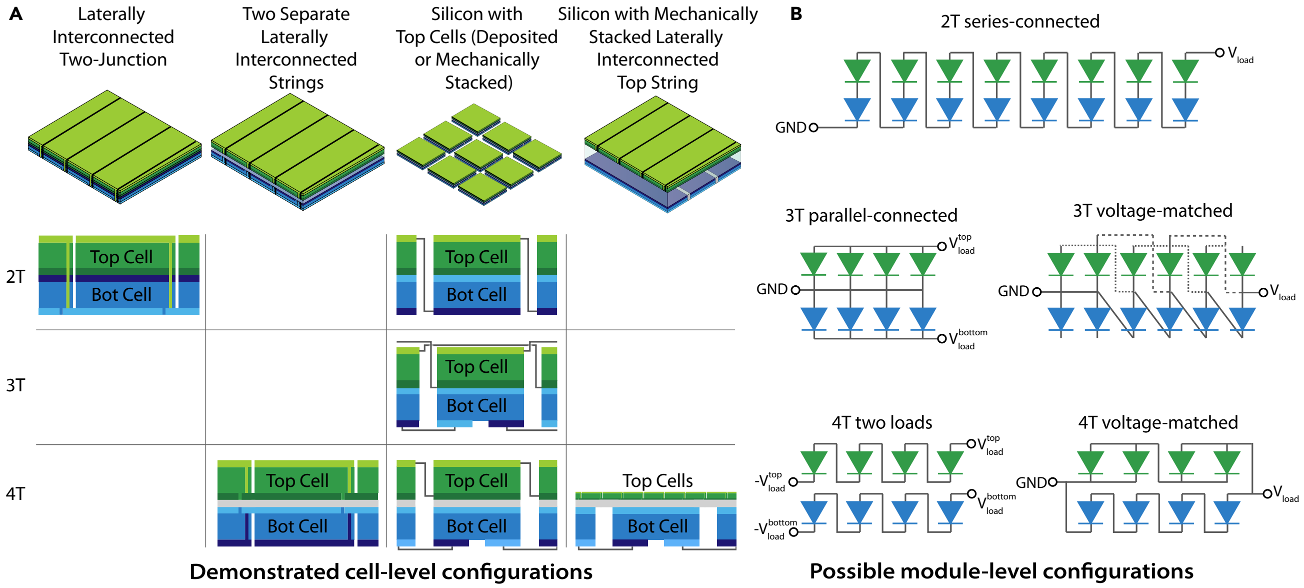


Figure 2. Illustration of possible tandem configurations

(A) Most common geometries for combinations of thin-film and Si wafer tandems for 2T, 3T, and 4T configurations.

(B) Diode schematics of 2T, 3T, and 4T tandem strings.

improve the viability of this approach.[29] A middle contact can be used instead, but it will reduce the active area of the devices by either doubling the number of top grids or requiring removal of some of the bottom cell material to make room for rear middle grids. Despite these challenges, high-efficiency and tunnel-junction-free designs with middle contacts are possible.[30]

Terminal configurations for different cell designs

Implementing 2T, 3T, and 4T designs also depends to some extent on the types of junctions that are integrated. For example, thin-film cells can be interconnected in series via scribed interconnects, whereas wafer-based modules rely on tabbing and stringing together individual cells. Figure 2A displays a number of potential module-level configurations based on common fabrication methods. Notably, mechanically stacked 4T configurations are accessible for thin-film/thin-film and thin-film/Si combinations, but 2T and 3T may not be practical for some combinations.

Tandem module configurations

Single-junction modules have two electrical terminals. Whether tandem modules continue to follow the 2T convention or deviate depends on several benefits and drawbacks.

As depicted in Figure 2B, 2T tandems are the simplest to string because they can be connected just as single-junction cells are, with minimal changes in wiring layout or power electronics. Stringing is more complex for 4T tandems, where two general approaches are possible. The first is to string the top and bottom cells in series independently. This configuration requires the module to be operated with two loads, which is not common for PV installations. This approach also requires robust electrical insulation between the top and bottom strings, which may operate at very different voltages. Alternatively, this complexity can be alleviated with the implementation of voltage-matched designs. The number of subcells for the top and bottom strings is chosen such that the strings all output the same voltage. The strings

Table 1. Table of common tandem subcell materials

				Form factor	Typical
Cell material	Approximate Eg	Top cell	Bottom cell	Wafer or film	Film configuration
Si	1.12		x	wafer	–
CIGS (and related)	range, typically 1.15		x	film	substrate
Perovskite narrow	range, 1.2–1.4		x	film	superstrate
InSb	1.23		x	wafer	–
Organics	range	x	x	film	super/substrate
GaAs	1.42	x	x	wafer/Film	substrate
Cd(Se,Te)	range, 1.4–1.5	x		film	superstrate
Perovskite wide	range, 1.6–1.9	x		film	superstrate
$CuGaSe_2$	1.68	x		film	substrate
Amorphous Si (a-Si)	1.7	x		film	superstrate
GaInP	1.8–1.9	x		film	substrate

are then combined in parallel to create a 2T module.[26] Power electronics can then be configured to eliminate losses associated with temperature and spectral variations and imperfect subcell matching.[31]

3T tandems require the most complex stringing. Voltage-matched configurations are possible here too, maintaining some of their cell-level benefits of reduced sensitivity to spectral fluctuations, imperfect subcell matching, etc. Many other options for stringing 3T tandems also exist, and the best configuration will depend on the type of cell (series or reversed connections) and voltages generated by each subcell. Strings of 3T tandems will almost always have end losses of at least one tandem cell, unless complementary cell pairs are used, which requires multiple different cell types to be fabricated and integrated.[32] More information on how to string 3T tandems and calculate expected end losses is discussed by McMahon et al.[33]

MATERIALS FOR SUBCELLS

Given the multitude of solar cell absorber materials in development today, there are a number of possible combinations to create tandem devices. Absorber materials can be divided into two groups: those that would be best as top cells and those that would be best as bottom cells. Here, we use a band gap of 1.3–1.4 eV as the dividing line between the two and list a wide variety of possible materials in Table 1. The performance status of each cell type can be found in the latest version of the bi-annual publication, "Solar cell efficiency tables."[34] The goal of this section is to discuss which material combinations are the most advantageous in light of a set of basic selection criteria.

Requirements for tandem junctions are similar to those for single-junction solar cells, with some additions. The first is that the performances of the top and bottom junctions must have similar efficiencies when operated independently as single-junction devices, in criteria laid out by Peters et al. as the "marriage of equals."[35] If that is not the case, the tandem will not be sufficiently more efficient than the best performing single junction alone, and likely not worth the additional manufacturing cost. A common example is a tandem consisting of an amorphous silicon (a-Si) top cell on a crystalline Si (c-Si) bottom cell. The bottom Si cell has a higher efficiency in the spectral range where the a-Si cell absorbs light, resulting in a tandem that can have a lower efficiency than a single-junction Si cell.[12,36] The second component of the "marriage of equals" criteria is the requirement that the manufacturing per unit area and installation costs of each of the single-junction devices should be similar. Again, if either the top or bottom cell is much cheaper to manufacture as a single junction, it has the potential to outperform on a levelized cost of electricity (LCOE) basis.[37]

The third basic requirement is that top cells should be as transparent as possible to below band-gap photons, as sub-band-gap absorption can significantly cut into the performance of the bottom cell. Finally, the combination of top and bottom cell band gaps influences the total efficiency of the tandem. This is particularly true for 2T tandem designs that are subject to current-matching constraints.

Considering these requirements, several materials could make good top cells for a tandem. III–V absorbers (e.g., GaAs and GaInP) have the highest power conversion efficiency (PCE) of single-junction devices and are components of high-efficiency multijunction solar cells. Their main drawback is the high cost of fabrication. Perovskites are also promising for top cells due to the tunability of their band gaps, high operating voltage, and low-cost/low-temperature processing. Improving the stability and module lifetimes will be important aspects of future efforts to develop these materials for commercial tandem products. Rounding out this category, CdTe and II–VI materials can be considered for top cells.[38] CdTe is the second-most deployed technology in the world, with demonstrated stability and bankability. Although CdTe modules are currently alloyed with Se, which reduces the band gap from 1.5 to ~1.4 eV, the tandem potential for CdTe/Si modules can be increased through alloying CdTe with other elements to obtain wider band-gap cells, an under-explored area for additional research. More about these aspects will be discussed in section "a roadmap for future development."

An obvious bottom cell material is Si. Si is the most deployed technology worldwide, with many different cell technologies that are available at industrial scale.[39] The single-junction theoretical efficiency limit for Si is around 29.5%.[40] However, the upper end of practical commercial module efficiencies in the near term is expected to be around 26%–27%.[41] Si cells are available in several different designs that are amenable to tandems.[39] A common one is the PERC cell, which contains a passivated rear contact. TOPCon (oxide-passivated front and rear side contacts) and SHJ (amorphous Si-passivated front and rear contacts) progressively improve on this design. Finally, IBC Si cells, with both sets of contacts located on the rear surface, allow for additional design flexibility in interfacing with the top junction. CIGS and related chalcogenide thin-film materials are also suitable bottom cells. They have shown good stability and relatively high technology maturity, and their direct band gaps are tunable down to 1 eV. One challenge is the need for more cost-effective mass-production processes. Narrow band-gap perovskite, III–V, and organic PV (OPV) materials are also currently being considered for bottom cells. Advantages of thin-film bottom cells are the ability to fabricate lightweight and flexible tandem modules without the need for intentionally textured surfaces.

As noted above in section "tandem module configurations," the form factor of the absorber (thin film vs. wafer) also influences which ones can readily be combined into modules. Table 1 shows the most common form factor of each technology. Thin-film absorber technologies can be further classified by whether they are commonly fabricated in a superstrate (transparent glass substrate is on the top of the cell) or substrate (substrate is underneath the cell) design. Each technology typically has been developed for one configuration, as shown in Table 1, but extra research and development can enable most thin-film technologies to be fabricated in both configurations. Combining superstrate top cells with compatible substrate bottom cells may have some benefits. For example, well-encapsulated 4T tandems can be fabricated without the need for additional protective top and bottom glass or polymer layers, reducing the embodied carbon and energy associated with these layers.[42] Individual subcells can also be processed independently of each other to prevent subcell damage, such as when high-temperature depositions are required. Additional processing considerations are described in section "scaling to modules and commercial production."

As PV technology evolves, new materials suitable for tandems are always possible. Improvements to those listed in Table 1 could also make them better contenders than they are now. For example, the significant improvement in perovskite cell efficiencies in the past several years now makes them much more promising top cells than they were in 2016.[12] The tunability of the band gaps of many PV material systems could also make them suitable for either the top or bottom cell. Perovskite and organic cells can fit into both categories and can even be fabricated as all-perovskite or all-organic tandems. Research breakthroughs could make wide-band-gap chalcogenides practical for top cells as well. We anticipate that as tandem demonstrations increase, more consideration will be given to fabricating materials specifically for tandem applications.

Depending on the combination of junction materials, switching the processing order may be required. Perovskites are often deposited in the n-i-p configuration (referring to the deposition order of layers, typically for a superstrate architecture, such that an n-type electron transport layer is deposited first, followed by the intrinsic perovskite absorber, and lastly, a p-type hole transport material), but when used as a top cell in a 2T configuration, deposition in the inverted p-i-n order may be preferred. Deposition of one cell directly on the other may require the first cell to be able to withstand subsequent processing temperatures, pressures, and chemicals required to deposit the second cell. Several of these challenges will be covered in section "scaling to modules and commercial production."

We highlight several review articles that cover specific tandem junction combinations. Many propose Si as the bottom junction in tandems.[12,36,43,44] Others discuss the challenges, advances, and needed future development for all-perovskite tandems.[45,46] Zhang et al. estimate that the best partners are 1.70–1.85 eV perovskite top cells with 1.1 eV bottom cells and has tables of tandem data for perovskite on multiple bottom cell materials.[47] Tong et al. make the case for wide-band-gap perovskites as top cells.[30,47] Weiss reviews three alternatives to perovskite/Si tandems: perovskite/CIGS, CdTe/CIGS, and CdTe/Si. The analysis explores the efficiency, stability, manufacturability, and band-gap tunability of the constituent junctions.[48] All-organic tandems are reviewed in a book chapter by Meng et al.,[49] and low-cost tandem options are explored by Todorov et al.[50] A new periodic publication called "Device Performance of Emerging Photovoltaic Materials" will monitor tandem device performance going forward.[51]

FUNDAMENTAL TANDEM EFFICIENCY LIMITS

Solar cell efficiency limits are typically evaluated under the detailed balance framework, wherein equilibrium is established between photon absorption and emission based on the band gap of each junction absorber. This approach was first established for single-junction solar cells and has since been extended to treat tandems and multijunctions.[2,52–55] Figure 3A presents tandem efficiency limits derived from this approach assuming a 4T configuration.

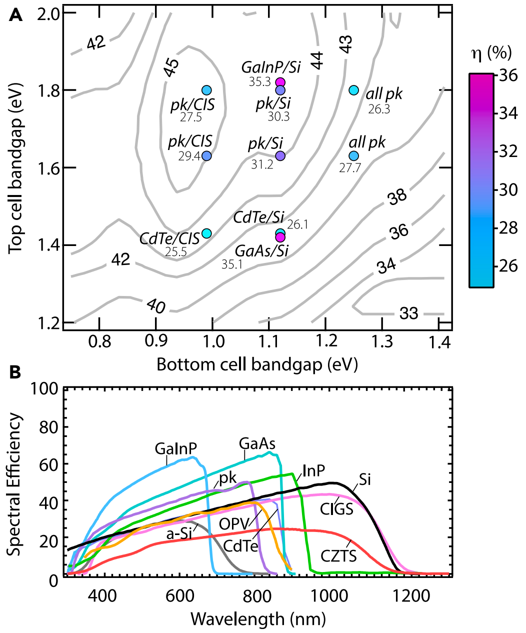


Figure 3. Calculated tandem efficiencies

(A) Tandem efficiency contours calculated with the detailed balance method. Efficiencies of specific tandem combinations calculated with the spectral efficiency method are overlaid. Calculated spectral efficiency values are noted next to each data point as well as indicated by the color scale at the right.

(B) Spectral efficiency curves for selected single-junction PV technologies.

Because the detailed balance framework only accounts for radiative recombination, it is the most simplified method for calculating tandem efficiencies and should thus be viewed as the upper efficiency limit. In some instances, this approach has been modified to take into account more realistic device parameters, such as the dark current, J0, based on reasonable W_{OC} estimates,[56] or designs that offer flexibility in the spectrum transmitted through the device by adjusting the layer thicknesses.[22] Alternatively, the spectral efficiency (SE) model accounts for spectrally resolved cell performance to create a more accurate efficiency estimate of a tandem comprised realistic junctions.[12,57,58] The input parameters are the current-voltage (JV) characteristics and the external quantum efficiency (EQE) spectrum. Using data that incorporates additional loss mechanisms (either through experimental measurement of actual cells or modeling JV and EQE data with non-radiative recombination and optical and resistive losses) provides a way to compare tandems fabricated from specific junction technologies that would otherwise not be readily evident from only considering the band-gap energies using the detailed balance model.

To demonstrate the utility and insights derived from both efficiency evaluation approaches, 4T efficiencies of specific tandem combinations are calculated by the SE method and compared with the detailed balance limits (gray contours) in Figure 3A. Detailed balance dark currents and, thus, efficiencies for each junction were calculated according to the formulation of Steiner et al.[59] The two junctions are optically thick, with the bottom filtered by the top. The junctions are under the AM1.5 Global (ASTM G173) spectrum and operate at 25°C. SE performance was calculated from experimental cells measured independently. Representative SE curves for some PV technologies are displayed in Figure 3B for Yu et al.[12] Perfect optical coupling between the junction pairs was assumed, making this an ideal efficiency limit.

Several points can be deduced from this comparison. First, accounting for realistic losses in the junctions lowers the efficiencies estimated by the SE method considerably compared with the detailed balance approach. For example, the SE tandem efficiency limit of a realistic 4T GaInP/Si tandem is 35%, which is ~10% lower than the detailed balance calculation of 45%, whereas the efficiency difference for a perovskite/CIS ($Eg_{,PVK}$ = 1.8 eV) tandem is ~17%. The SE estimate is much closer to the experimental record for a 4T GaInP/Si tandem (32.8%) than the detailed balance prediction. Second, the SE method quickly shows that the details of the junction technologies matter. For instance, replacing the perovskite (Eg = 1.8 eV) top junction of a Si/perovskite tandem with a GaInP (Eg = 1.82 eV) top junction could increase the tandem efficiency by ~5% without substantially changing the top-junction band gap. The difference is entirely due to the additional efficiency losses in high band-gap perovskite cells, which can be improved through continued research and development. In combination, the detailed balance and SE methods can be used to quantify the potential efficiency gains made in a tandem structure by improving the efficiency of a specific junction.

We note that these efficiency projections are based on a 4T configuration and do not account for additional losses associated with 2T and 3T configurations. Many reviews have been published about specific tandem configurations and combinations with additional details.[60,61]

ENERGY-HARVESTING EFFICIENCY

Because different tandem cell configurations can have different sensitivities to spectral changes and other operating conditions (like cell temperature), tandem PV systems are expected to produce different total energies throughout the year at different outdoor locations. To understand the impact these sensitivities have on energy production, it is useful to compute the total amount of energy produced by a PV device over a period of time in a specific location, also known as the energy-harvesting yield (EHY). To compare EHY between locations, the energy-harvesting efficiency (EHE) can be calculated as the energy produced over a period of time, divided by the incident solar energy during the same time period. EHE is also sometimes referred to as ''specific yield'' in the literature, and methods for calculating it can be found in several comprehensive review papers.[61–63]

Calculations of EHE are performed for two principal reasons. One is to estimate how much energy an actual PV system will produce at a particular site, and the other is to optimize system design. System performance depends upon myriad factors that affect both single-junction and tandem solar cells, i.e., solar irradiance, ambient temperature, wind, and heat-dissipation properties of the module. Because this sort of energy-production estimate is important (i.e., for PV system design, project financing, etc.), EHE calculations and the associated solar-resource assessment have been performed and refined for many decades, but most studies have focused on single-junction modules. There are existing models, ranging from commercial products (e.g., PVsyst) to open-source software platforms (e.g., pvlib) that can be used to design and model the performance of single-junction PV systems.

Tandem cell EHE calculations are complicated by the fact that each junction has a different band gap and absorbs light from a different portion of the spectrum. Consequently, the design and performance of tandem cells are affected by the spectral content of the incident light, and this, along with other environmental conditions, constantly changes. To properly understand how a tandem cell will perform at a particular site, it is therefore important to properly assess the spectral variability at that site. This is often done with a set of hourly spectra over the course of an entire year, but this large set can be a reduced to a smaller set of spectra by grouping together similar spectra.[64] The AM1.5G standard spectrum is a good starting point for design for most locations, but there may be some additional benefit to creating site-specific reference spectra.

To facilitate progress, we recommend the tandems community work together to achieve a cohesive evaluation of tandem PV systems by:

1. Reaching consensus on what resource data to use for site characterization. Ideally, the spectral data from different methods (satellite-based estimates, ground-based estimates, and direct measurements) could all be brought into agreement.
2. Selecting a consensus method for reducing large spectral sets to smaller representative sets to facilitate site comparison, cell design, and EHE calculations. There are many different methods currently being developed for this purpose. However, there is inherently no unique correct method, and it may be the case that different methods will be developed for different purposes.
3. Develop a consensus understanding of the performance benefit for redesigning tandem cells for specific sites and the related performance penalty for using a single design at different sites. Points (1) and (2) feed into doing this properly.
4. Establish a better community-wide understanding of the merits of adding additional junctions and the use of 2T, 3T, and 4T cell architectures. These design choices are guided by EHE calculations, and comparison is hindered by differing assumptions and methods among the proponents of different designs.

Addressing these recommendations will better position the community to understand possible energy mismatches between 2T, 3T, and 4T tandem configurations. Based on previous work on high-efficiency III–V multijunction devices, energy losses in 2T configurations may be low for perfect current matching. However, a more quantitative picture of the extent of those losses and trade-offs in design and performance will help to guide tandem development. We emphasize that this is still an important and open area of research that we expect to be resolved with future improvements to the models as well as clarity in tandem design.

CELL AND MODULE DEMONSTRATIONS

Figure 4 presents the evolution in 2T, 3T, and 4T hybrid tandem combinations that have been demonstrated at the cell level to date. Perovskite/Si tandems now hold the highest record efficiencies, having recently exceeded those of III–V/Si configurations.[10,11] This progress has been made on the basis of improving single-junction perovskite efficiencies and tailoring their band gaps. Tandem combinations with perovskites, especially those with Si or CIS bottom cells, also have the potential for high efficiency based on the detailed balance limit (see Figure 3A). Interestingly, the highest efficiency 2T perovskite/Si devices have now exceeded the projected spectral efficiencies based on individually measured subcells, which are 30.3% and 31.2% for a perovskite with band-gap energies of 1.8 and 1.63 eV, respectively. These calculations were done with different perovskite formulations than the record 2T devices, but show the experimental progress that has been made in the field. So far, vertically integrated 2T perovskite/Si tandems have slightly outperformed 4T architectures under standardized laboratory test conditions. This result points to an insensitivity to processing constraints when vertically integrating perovskites on Si solar cells.

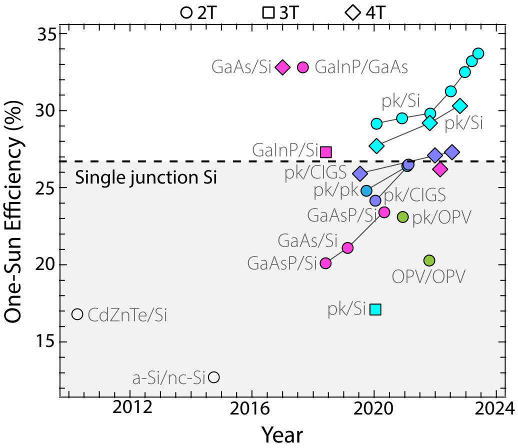


Figure 4. Measured tandem efficiencies over time

Data taken from Chin et al.,[10] Mariotti et al.,[11] Lepkowski et al.,[13] Al-Ashouri et al.,[15] Green et al.,[34] Carmody et al.,[65] Matsui et al.,[66] Lin et al.,[67] and Duong et al.[68]

By contrast, the best 4T III–V/Si tandems are substantially more efficient than 2T devices owing to the challenges in epitaxial growth and the sensitivity of III–V cells to defects.

Few experimental demonstrations have been published for tandems containing CdTe and its higher band-gap alloys. The device reported from 2010 involved direct growth of a CdTe junction on top of a Si cell. An architecture that would be more amenable to current manufacturing methods while minimizing losses due to co-processing involves mechanical stacking of separately fabricated CdTe top junctions on Si or CIS bottom junctions. Efficient demonstrations of both are needed to evaluate the potential of these combinations.

At the module level, III–V multijunction modules have been primarily been developed and demonstrated for space applications. Three-junction GaInP/GaAs/Ge solar cells have been the standard for space power since about 2000, but innovations such as the inverted metamorphic multijunction (IMM) design have allowed flexible cells and significant improvements in specific power. Record module efficiencies are in the range of 30%–40%, depending on the exact configuration.[69] Hybrid tandem modules (for example, perovskite/Si tandems) have more recently gone under development in industry, but few results have been reported in the literature.[70] Publication of module-level performance, even if it is low to start, is critical for identifying failure modes and research needs necessary for accelerating tandem development toward commercialization.

MEASUREMENT

Tandem solar cells present additional challenges for accurate measurement of their performance characteristics compared with single-junction devices.[71] Optical and/or electrical coupling between the junctions exists to some extent in all tandem architectures (i.e., 2T, 3T, or 4T), so the measurement of tandems should be considered holistically.[72] For comparison of performance between technologies (single cell and tandem), the efficiency is reported under standard test conditions (STCs).[73] The simulated spectrum for performance measurements should be adjusted to achieve the same photocurrents as under the actual AM1.5G solar spectrum within each junction simultaneously. In 3T and 4T architectures, two measurement loads should be controlled simultaneously to account for coupling.[72,74] If these aspects are not carefully considered and addressed, the measured performance of a tandem solar cell will be inaccurate, and over the long term, systematic and widespread errors could hinder tandem technology development.[71]

To address the issue of spectrum, protocols[75–77] have been established to perform a spectral mismatch correction[78] for each junction by determining the quantum efficiency of each junction while considering coupling artifacts.[79,80] The simulator spectrum is then adjusted by means of filters[81] or multiple light sources[82] to achieve the proper irradiance on each junction.

Emerging solar cell materials, such as perovskites, OPVs, quantum dot technologies, and other thin films, often deliver dynamic responses under traditional I–V measurement conditions, such as hysteresis affected by scan direction and rate and device state changes due to light soaking. Short-term performance changes require stabilized measurements using maximum power point tracking[83] or asymptotic techniques.[84] Longer-term degradation of these materials is also a subject of considerable study.

Accredited solar cell calibration labs are continuously improving tandem measurement methods as the development of these devices is becoming more widespread. The development of new standards and increased education about proper measurement methods will also help the tandems field advance.

VALUE PROPOSITION AND ASSOCIATED METRICS

Given the characteristics discussed above, tandems have the potential to benefit a number of use cases. The ability to reach >30% efficiencies will allow more power to be generated per unit area and may also make PV practical for powering space-constrained applications. Both aspects can accelerate the expansion of PV installations, especially in densely populated areas where clean power generation is most needed. The ability to integrate a variety of different PV absorber materials also provides flexibility in designing the form factor, module-level specifications, or other attributes as desired for specific applications. Finally, the use of a smaller number of higher efficiency modules to meet the power generation requirements of applications or installations may require less material for cells, racking, and other BOS components. In some instances, it may help to alleviate pressure on supply chains.

Several metrics are important to consider when designing tandems with these value propositions in mind. The first is the LCOE (the cost of the electricity produced over the lifetime of the system). LCOE is useful as it is articulated as price per kWh of electricity produced ($/kWh), which is directly relatable to the financial performance of energy generation systems. Lower LCOE typically correlates with improved competitiveness and can be realized by increasing the PV module efficiency and PV system EHY as well as decreasing the manufacturing cost. It is a useful metric at the research level for identifying opportunities for cost reduction, but it often falls short when evaluating the true cost of a PV technology or system.

Considering that PV is intended to deliver abundant and sustainable clean energy, the energy and resources that go into manufacturing the modules and system components should continue to be reduced. EPBT is an important metric for evaluating the environmental footprint of a PV system. EPBT utilizes the embodied energy calculated from the life cycle analysis (LCA) to determine how long it takes to produce enough electricity to offset the cumulative primary energy required for manufacturing.[85,86] EPBT is typically calculated for a complete system, as any given

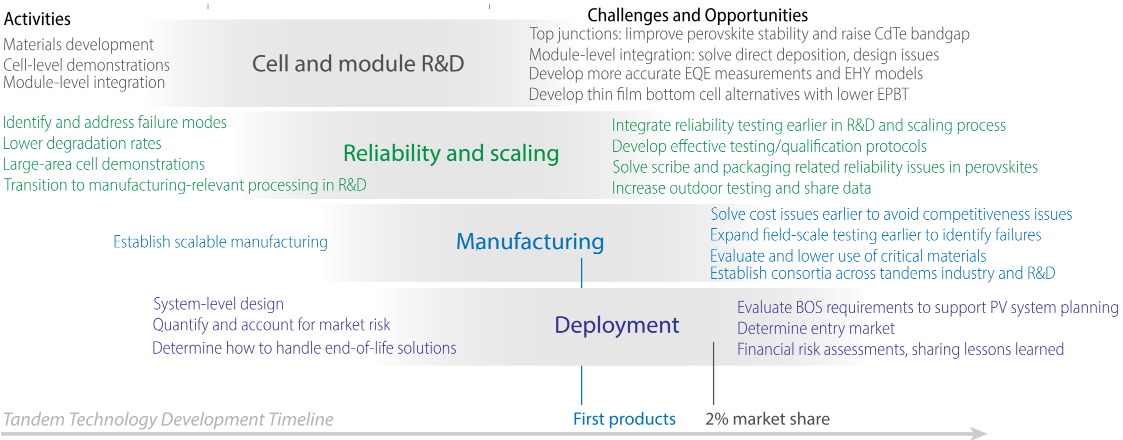


Figure 5. Generalized timeline and activities required to commercialize tandem solar cells

Activities fall into four categories: cell and module research and development, reliability and scaling, manufacturing, and deployment. The tandem PV field is currently positioned at the intersection of cell and module R&D, and reliability and scaling. To meet the present International Technology Roadmap for Photovoltaic (ITRPV)-estimated timeline for perovskite/Si tandems to reach 2% market share, the "2% market share" milestone would be reached in 2030.

component, such as a module, does not operate on its own. EPBT calculations are dependent on the manufacturing grid efficiency. Therefore, the same module produced on a renewable grid will have a longer EPBT than one produced on a coal-powered grid.[42] Lowering the energy required to produce PV modules and system components will translate to lower manufacturing costs and lower embodied carbon.

The PV module degradation rate connects the objectives of the LCOE and EPBT metrics. Lowering the degradation rate is important for ensuring that the PV modules will continue to generate as much energy as possible over the course of their lifetimes. Longer lifetimes in turn reduce the necessary manufacturing capacity, material and energy consumption, and disposal required to power the world over the next 50–100 years. As tandem modules are developed, degradation rates must be improved alongside efficiencies. This requires understanding the origins of degradation, keeping in mind that new mechanisms may arise when integrating two well-established PV technologies. Emerging PV technologies typically have higher degradation rates that will require additional attention to address.

A ROADMAP FOR FUTURE DEVELOPMENT

Despite the head start of single-junction PV technologies and the low technology readiness of tandem devices and modules today, we believe there is a path to widespread deployment of tandems if technical and cost challenges can be addressed on a timeline that keeps pace with the build-out of new PV manufacturing facilities needed to meet our energy demand. Figure 5 depicts a high-level roadmap of activities that must be carried out to ready tandems for commercialization. Importantly, they must be carried out in parallel by researchers and manufacturers with expertise across multiple PV technologies, who must work together to learn from past challenges and develop new solutions. This section breaks down the critical areas for consideration to guide those interactions and efforts, as well as outlines a high-level pathway to long-term market relevance.

Cell-level challenges and opportunities

The performance of single tandem devices (cells) has rapidly increased in a very short time span. Efficiencies of III–V/Si and perovskite/Si single-cell demonstration devices are now very close to the values predicted by SE analysis of record single-junction devices, indicating that much of the future device-level improvement will come from increasing the efficiency and performance of the individual junctions. The development of perovskite top cells has been a major focus area for tandems research in recent years. In turn, the efficiency of perovskite-based tandems has climbed rapidly. Because of these trends, we focus disproportionately here on perovskite top cell improvements, but we also note the potential for advances in other absorber materials as well.

Perovskite junction development

Although the ideal perovskite band gap for pairing with a Si or CIGS bottom junction lies in the range of 1.7–1.8 eV, many initial demonstrations were carried out using top junctions with lower band gaps around 1.55–1.63 eV.[87] Raising the perovskite top-junction band gap will be critical for realizing the full potential of the tandem architectures, but this task comes with significant challenges.[88] A primary route involves increasing the Br/I halide ratio in mixed-halide materials, which is presently limited by greater V_{OC} losses and reduced stability. Suppressing phase segregation, reducing non-radiative recombination at traps in the bulk and at grain boundaries, and tailoring interface properties are important areas for future focus. A recent example of progress is the use of tailored gas-quenching methods during the processing of Br-rich wide-band-gap perovskite cells to produce >20% efficient 1.75 eV band-gap cells with larger grains, reduced defect densities, and greater stability.[89] A second, longer-term route to increasing the band gap is to develop new all-inorganic perovskite materials with lower driving forces for phase segregation.[88] These research activities will also benefit the development of all-perovskite tandems.

An additional technical challenge for perovskite top-junction development is the ability to deposit it on textured or roughened surfaces to create 2T or 3T devices. In the case of a Si bottom junction, pyramidal texturing will remain an important factor for enhancing long-wavelength absorption. However, solution processing of perovskites on pyramid textures has proven tricky, as incomplete coverage of the pyramid tips can lead to shunting. One promising avenue forward is the use of a combination of conformal vapor deposition and solution processing compatible with large areas.[87] Another is to modify the Si texturing process to produce pyramids with height variations that are less than a micron (often referred to as nanotexturing).[90] CIGS surfaces can also exhibit roughness that is problematic for conformal coverage of perovskite device layers. The strategies for improving 2T perovskite/CIGS tandems are similar to those for perovskite/Si tandems. One way includes planarizing the top of the CIGS devices by creating an extra thick transparent conducting oxide (TCO) layer and then chemical-mechanical polishing it before depositing the perovskite top cell.[91] Another strategy is to employ bi-layer hole transport layers with one conformal film to reduce shunting and a subsequent layer that passivates the interface and provides a better contact to the perovskite junction. One study used atomic layer deposited NiO_x as a conformal layer plus a spin-coated poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine] (PTAA) film.[92] Another explored sputtered NiO_x:Cu plus a self-assembled monolayer (SAM, MeO-2PACz).[93]

CdTe and CIGS junction development

There are also opportunities to improve CdTe and CIGS thin-film junctions for tandems. Both technologies have been commercially realized as single-junction modules, with established manufacturing bases and good stability. CdTe, in particular, is already cost-effective to manufacture and has a functioning transparent back contact.[48] One challenge for utilizing CdTe as a top junction is increasing its band gap beyond 1.5 eV to harness additional output from the bottom junction.[48] Doing so will likely require alloying (either with Zn or Mg), which has the potential to produce 15%–16% efficient cells but has so far received little research attention.[94] Combating Mg and Zn diffusion into adjacent layers, improving passivation treatments, and selecting appropriate contact layers are all tasks that must be carried out to improve the efficiency and stability of higher band-gap CdTe-based top junctions.[94] A linked challenge is to reduce sub-band-gap absorption in CdTe top junctions, which will likewise limit photon transmission to the underlying bottom junction.[95,96] The absorption tail has been associated with the presence of point defects associated with As doping, which may also be responsible for up to 100 mV of voltage loss in CdTe devices.[97,98] Improving As (or other group V) activation in polycrystalline CdTe represents one route to lowering the required concentration of As dopants and the related sub-band-gap absorption.[99] A third issue that must be addressed in a CdTe top junction is reducing back surface recombination, which currently limits V_{OC}. This will enable thinning of the absorber to ≤ 1 μm. Together, these improvements to the single-junction photovoltage and efficiency will also make CdTe more attractive as a tandem junction by increasing its SE. Regarding CIGS for bottom junctions, many of the improvement strategies already being explored for single-junction devices (i.e., enhanced light trapping, defect passivation, electron and hole-selective contacts, and manufacturing cost reductions) will also translate to improved tandem performance and cost metrics.[100]

OPV junction development

Finally, additional development could also make OPV attractive for top or bottom cells. Already, OPV/OPV and OPV/perovskite tandems have been demonstrated with efficiencies over 22% and 23%, respectively,[101,102] which take advantage of common solution processing conditions and associated low-cost manufacturing potential. However, OPV could be paired with other PV technologies as either the top or bottom cell. Very little work has been performed to lower the band gap of OPV devices below 1.2 eV specifically for use as bottom cells, but the non-fullerene acceptor materials found in the highest efficiency single junction (1J) OPVs and in near-infrared (NIR) organic photodetectors are a promising starting point toward this goal.[103] These materials have exceptional spectral efficiencies, stabilities, and absorption deep into the IR. Pairing an OPV bottom cell with a non-OPV top cell would also prevent high energy photons from reaching the OPV bottom cell, thereby aiding long-term stability. Further material developments are needed to improve the efficiency and stability of wide-band-gap OPV for top cell integration. Given the readily tunable spectral properties of OPV through synthetic chemistry, and their insulation from critical material scarcity or supply chain disruptions, the technology has potential to supplement tandem PV in unique ways.

Scaling to modules and commercial production

In contrast to the prolific activity in cell-level demonstrations, the performances of very few tandem modules have been publicly reported to date. Given the complexity of the integration process, research and development efforts aimed at the module level have the potential for the greatest impact in advancing tandems toward commercialized products. Only three single-junction PV technologies have so far successfully been scaled to GW production: Si, CdTe, and CIGS. These success stories can provide insight into the important aspects of scaling that should not be overlooked as we now chart a pathway forward for tandems. Challenges generally fall into the categories of cell-to-module performance gaps, module-level integration, and designing effective and scalable manufacturing processes. As we discuss

Table 2. This table shows the efficiency gaps in record cell and module demonstrations for different single-junction technologies to highlight the challenge of physically scaling

Technology	Record 1J cell efficiency	Record module efficiency	Delta
Si	26.7%	24.7%	2.0%
CdTe	21% (22.3%[a])	19.5%	1.5% (2.8%[a])
CIGS	23.6%	18.6% (20.3%[b])	4.75% (3.3%[b])
GaAs	29.1%	25.1%[b]	4.0%[b]
Perovskite	23.7% (26.0%[a])	18.6%[b]	5.1%[b] (7.4%[a,b])
OPV	19.2%	13.1%	6.1%

[a] For each technology, the record cell efficiency from Table 1 is provided; however, there is a "notable exception" in the solar cell efficiency tables.[34]

[b] Module areas that are <900 cm^2, as they are much smaller than commercial module values. Note that the areas of the devices (cells and modules) reported here vary over a large range across technologies.

below, the simple act of integrating two different PV technologies into a tandem module instantly links these challenges, resulting in the need to navigate more than one simultaneously.

Some efficiency loss when scaling from cells to modules is expected. Table 2 presents the differences between record cell efficiencies and record module efficiencies for single-junction PV technologies. A minimum of about two percent difference is expected due to geometric fill factor losses (e.g., from gaps between cells) when scaling from small area cells ($\sim$1 cm^2) to a full-size module. Singulated (i.e., wafer-based) technologies like Si can be binned by cell efficiency before integrating them into a module, thereby minimizing the cell-to-module difference. However, additional losses introduced by junction processing incompatibilities, optical and resistive losses, and module construction have the potential to further reduce tandem module performance compared with record cells and can be influenced to some degree by the subcell interconnection scheme. Each of the interconnection configurations (2T, 3T, or 4T) have benefits and drawbacks in light of these challenges. We emphasize that there is no one-size-fits-all solution, and the configuration will need to be selected based on the specific PV technologies being integrated, their processing and packaging constraints, the application (i.e., utility-scale ground-mount, residential roof-mount, flexible form factors, etc.), and even the environment where they will be deployed (i.e., hot/humid, dry/cool, etc.).

The scaling challenges are most different for singulated (wafer-based) and thin-film technologies, based on the processes used for module fabrication and the cell interconnections, as discussed above in section "tandem module configurations." We will discuss these two approaches separately below and highlight implications for 2T, 3T, and 4T configurations.

Module-level integration of singulated devices

Silicon is a natural candidate for a tandem bottom junction, in part because the wafer acts as a suitable substrate. Singulated tandem configurations designed for vertical current flow through the junctions (2T or 3T if utilizing IBC Si bottom junctions) are conceptually straightforward to construct: one device is simply deposited on or bonded to another, and then electrical contacts are added. 4T configurations based on singulated junction are also possible and can take advantage of mechanical stacking (particularly in the case of III–V/Si combinations).[8] A main challenge is ensuring the addition of the top junction does not impact the bottom Si junction performance beyond optical absorption of short wavelength light. In the case of direct deposition, considerations include processing temperatures, reactive chemistries, and ambients (e.g., $CdCl_2$, Se, and O), Fe contamination, and solution processing with harmful solvents. Developing processes that protect the Si, such as utilizing appropriate barrier layers and chemistries, are critical for vertical integration.

A second development question for 2T tandems is the choice of the interconnection layer. This interconnection needs to have good vertical conductivity, low contact resistance, high transparency, and create a robust mechanical connection between the two subcells. For perovskite/Si tandems, this is often a TCO deposited between the two subcells that serves as a recombination layer,[10,11] but TJ-based interconnection layers have been used and have advantages in minimizing shunting.[104] Many different strategies have been used in all-perovskite tandems, including thin metal layers and, more recently, ambipolar two-dimensional semiconductors. Rational design choice of interconnection layers that are scalable and can optimize light management and energetic alignment between cells is an important consideration in the integration of tandem cells and modules.[105]

A third challenge for wafer-based tandems is developing appropriate processes and methods to integrate the discrete units. Si modules typically utilize metal fingers and soldered metal ribbons to electrically connect individual junctions. This may be a problem if high temperatures (180°C–350°C) solders are used to string together 2T perovskite/Si tandem units, as high temperatures have the potential to damage perovskite junctions under prolonged exposure.[106] Lower temperature solders must be used. Potential solutions include the use of indium-based alloys and SmartWire interconnection designs, consisting of copper wire coated with bismuth-based low-temperature solders.[107] Another alternative is to use electrically conductive adhesives loaded with silver. However, intermediate processing temperatures and off-gassing involved in forming interconnects with these adhesives may enhance perovskite degradation. A recent review on 2T perovskite/Si module design and fabrication calls for additional research on the consequences of conventional Si tabbing and stringing methods on perovskite/Si tandems and the development of new architectures and processing methods that can accommodate the processing constraints of perovskite junctions.[106] Given the relative scarcity of In and Bi and the growing demand for Ag as contacts for Si solar cells, the search for new contact and interconnection materials and designs is also important to support the scaling and commercialization of tandems.[107]

Module-level integration of thin-film devices

Single-junction thin-film technologies utilize scribing during the deposition process to isolate and laterally connect subcells on large-area substrates. This approach can also be applied to directly deposited 2T thin-film configurations or be used to create strings of top or bottom subcells that are later mechanically stacked with a second junction to form 4T tandem modules. Scaling thin-film tandems to modules will face a number of potential challenges. Both 2T and 4T configurations are sensitive to non-uniformity in terms of pinholes, film thickness, composition, and deposition temperature, which can lead to variations both in optical and electrical properties. Compositional uniformity is especially a concern for increasingly complex alloys, such as CIGS and perovskites. Homogeneity can be impacted by different vapor pressures for certain components (e.g., Se) and solvent drying conditions, leading to microscale variations. Ultimately, heterogeneity introduces bandtail absorption and lowers long-term stability. Manufacturers of CdTe and CIGS single-junction panels have largely addressed these challenges in closing the cell-to-module gap.

Lateral scribing also presents a challenge. Again, CdTe and CIGS manufacturers have worked out this process, but it requires further improvements for perovskite-based modules (single junction as well as 2T and 4T thin-film tandems).

Optical and resistive losses in the transparent conductive oxide layer are a large contributor to the cell-to-module gap in efficiency in CIGS and perovskite thin-film modules.[108,109] They will also contribute to module-level efficiency reductions for tandem architectures, but the impact will be multiplied by the presence of multiple transparent front and back contacts throughout the stack. For example, one transparent contact is needed for 2T configurations, while two transparent contacts are needed for 3T configurations, and three transparent contacts are needed for 4T configurations. Lab-scale demonstrations often consist of small subcells to minimize these resistive losses and/or utilize additional metal grids and frames. With only a single transparent conducting contact, polycrystalline thin-film cells are typically about 5 mm wide. Resistive losses from a second transparent contact, without a grid, would likely reduce the cell width further, which would lead to a greater percentage of dead space to active area in a module. Several options are being explored for pairing metal grids with transparent conducting oxides. They include screen printing, ink jet printing, nanoimprint lithography, and cracked film lithography.[110–112] Although screen printing is widely used with Si PV, none of these approaches have been demonstrated with thin-film PV at the GW scale. Advances for bifacial thin-film PV are also expected to benefit tandems manufacturing.

Optical coupling of the top and bottom junctions through an additional insulating layer also presents a loss pathway for 4T configurations. Ideally, this interlayer is completely transparent to long-wavelength light over the lifetime of the module, undergoes minimal off-gassing during processing, acts as a suitable encapsulant to protect against moisture ingress (critical for limiting the degradation of perovskite top junctions), and prevents electrical breakdown if the top and bottom subcell strings are operated at different voltages. This combination of properties limits overall materials selection. Further research is needed to identify promising materials classes and evaluate them with each of these criteria in mind as appropriate for the needs of specific PV pairings.

Combining architectures

Singulated and thin-film technologies can also be integrated together via mechanical stacking. This approach has the distinct advantage of using established and mainstream manufacturing methods for each junction while building on the large Si manufacturing base. Again, the challenges lie in managing the optical and resistive losses and improving thin-film lateral cell integration at the module level, which is still in the early stages for perovskite junctions.

Perovskite-based module considerations

The perovskite cell-to-module gap is amplified by the lack of focus on transitioning from small area cell fabrication with non-scalable techniques like spin-casting to large-area cell fabrication with scalable techniques. A transition to scalable perovskite processes further requires ink reformulation for high performance with a wide process window[113] and compatibility with gas or vacuum quenching approaches. Further efforts on ink formulation should be taken to improve green process solvents with the target of large-scale manufacturing.[114] Implementing lateral cell interconnection schemes with P1, P2, and P3 scribe lines also leads to trade-offs between dead areas and resistive losses due to low conductivity in transparent conductors as well as the bulk absorbers compared with Si. These trade-offs must be re-assessed when optimizing tandem module performance compared with single-junction modules, especially if any of the contact layers must be changed to improve optical coupling between layers. Although lateral interconnection presents challenges in scaling, we note that large-area thin-film modules come off production lines such that there tends to be only a small difference between record thin-film modules and commercial offerings. Given the potential benefits of laterally integrating thin-film cells in tandem modules, a greater focus on solving these integration challenges up front have the potential to more rapidly advance tandem scaling in the long term.

Modules containing perovskite junctions will require advanced encapsulation strategies, as they present a unique challenge given the moisture sensitivity of the perovskite subcell. The degradation of ethylene-vinal acetate (EVA) into acetic acid as a by-product due to hydrolysis of vinyl-acetate monomers has been well documented.[115] Additionally, thermal fluctuations expected during PV operation can compromise the mechanical properties of the EVA encapsulation.[115] To this end, there has been recent interest in developing low-cost, ultrathin hermetic sealings for perovskite cells that can conformally cover the perovskite cell to impede moisture and oxygen ingress.[116–118] This is particularly important for the Sn-based lower bandgap perovskite chemistries, which are known to be very sensitive to both. A 1-µm thick silicon oxide (SiO_X) barrier was recently reported to protect SnPb cells during ambient exposure in the absence of a conventional encapsulation.[116] The barrier also improved tolerance to ultraviolet radiation. These lightweight electrically insulating barriers can be deposited directly on top of a finished tandem module at high processing speeds ($\sim$10 nm.min^{-1}), employ low-cost oxides, and can reinforce conventional encapsulation via an integrated design.[116] A more recent report combined the SiO_X barriers with indium tin oxide (ITO) as the back metal contact demonstrating remarkable stability promise, thanks to the added barrier advantage associated with ITO.[119] Given the higher environmental sensitivity and unconventional nature of the polar perovskite semiconductors, it is important to put them through rigorous reliability and qualification testing (see section "reliability challenges").

Manufacturing considerations

The contrast in the commercialization trajectories between Si and polycrystalline thin-film technologies CdTe and CIGS also provides some insight into the equipment challenges that must be overcome to establish a GW-scale tandem technology. Silicon PV benefited from massive investments (>$50B) by the semiconductor community in developing shared, non-lithography processes and equipment toolsets[120] resulting in an industry that largely depends on standardized processes, toolsets, and device architectures. Standardization, together with intellectual property (IP) leakage, has allowed experience gained by one company to be quickly shared across the industry such that there is limited differentiation across Si PV manufacturers. Furthermore, the various manufacturing stages from polysilicon to wafers to cells are all considered commodities that can and are transferred between manufacturers. This compatibility helps with economies of scale. By contrast, many of the toolsets and processes to generate CIGS and CdTe have been carefully guarded as IP. Companies have pursued a wide range of absorber deposition techniques, including physical vapor deposition, sputtering, electrodeposition, vapor transport deposition, close-space sublimation, and spray deposition. Such isolated and independent approaches have slowed the thin-film PV industry's relative growth as each new player continually develops its own unique fabrication process and associated deposition equipment to ensure large-area uniformity. As a result, larger individual research and development (R&D) budgets have been required per company to stay competitive with the Si PV industry.

The widely available and commodity nature of Si PV makes it the most strongly favored junction in an emerging terrestrial, GW-scale tandem PV technology, especially as Si modules reach their practical efficiency limits. The availability of Si cells also aids the academic community in making quicker progress. Mechanical stacking of junctions fabricated by separate companies is another potential way to fabricate tandems from two thin-film technologies without the need for one entity to maintain deep knowledge and fabrication lines for two separate technologies.

In addition to the impact that shared information has on accelerating manufacturing scale-up, developing scalable and cost-effective manufacturing processes early on in the commercialization phase is also critical. The CIGS industry has had to learn this lesson, and it can serve as a cautionary tale for tandems as well. In the CIGS process, heating glass to almost 600°C, as required for some deposition methods, is energy intensive, and the long cooling times slow down production lines. Furthermore, translating small-scale co-evaporation of four elements to square meter areas was a significant engineering challenge. Monitoring tools to track the quality of processes have become important for helping control thin-film uniformity, but they were unfortunately not perfected for use on pilot production lines early in CIGS manufacturing history. Moving forward, tandem processing and manufacturing must be designed at the outset with these lessons in mind. New CIGS processes would be useful for decreasing energy cost and cost associated with capital expenditures for equipment at new factories. We have also reached a critical juncture in translating perovskite cell fabrication to the manufacturing setting. Solution processing does present an opportunity to limit the equipment development pains in scale-up experienced by CIGS and CdTe, as many scalable deposition processes (e.g., slot-die, gravure, ink-jet, spray) are available as turn-key tools. This would reduce the required knowledge to scale-up and put more focus on aspects like device architecture, material compatibility's, and ink development which can more readily be aided by academia. Regardless of the specific device fabrication methods that are selected, we recommend that development of tandems at the bench scale utilize methods and even tools that are designed from the outset to be scalable to GW production. This will reduce the time and effort of translating a lab-level breakthrough to new products.

Reliability challenges

Reliability and qualification testing

Reducing the degradation rates of PV systems (and thus increasing operational lifetime) has a quantifiable value both in terms of reduced maintenance costs and resource expenditure necessary for end-of-life recycling.[121] PV modules based on conventional technologies, such as c-Si and CdTe, are typically expected to have lifetimes of 25+ years, with some manufacturers now offering warranties up to 40 years.[122] The physical mechanisms that lead to performance loss in these technologies are generally well understood and mitigated through appropriate testing, design, and qualification. Internationally recognized qualification standards such as International Electrotechnical Committee 61215-2 (2021) and 61730 outline the minimum operational and safety requirements for commercial PV products.[123,124] These tests were designed specifically to activate the degradation modes that can lead to large performance drops or failure in the early life of the module in the environments in which they are deployed. They do so by accelerating those degradation modes in a time frame that can be reasonably tested in the laboratory before large-scale deployment. New products and technologies must go through rigorous qualification testing before being deployed on a massive scale or risk premature failure in the field. Likewise, testing protocols must be updated for new technologies.

In recent years it has become more difficult to identify and mitigate new degradation mechanisms in PV modules as the sometimes decades-long learning cycle for new degradation phenomena is outpaced by the rate of technological innovation.[125] Many of the newly discovered degradation mechanisms arise because the combinations of incompatible materials introduce new degradation pathways into modules. The consequences of failing to catch and address them can be severe. One well-known example is the failure of polyamide-based co-extruded backsheet known as "AAA." This backsheet met all the testing requirements as outlined by various IEC and ASTM standards and was sold at a more attractive price point than other products on the market. Eventually, up to 15 GW of modules with this backsheet were deployed, and >90% of modules failed within 4–7 years.[126] A chemical incompatibility with some EVA encapsulants was later identified as a significant driver for the failure of this backsheet.[127] This public failure highlights the importance of fully understanding the reliability implications of new materials and designs and developing the correct testing protocols to catch them earlier in the technology development process. Another more traditional example is the potential-induced degradation (PID) phenomenon. PID comes in many forms with slightly different mechanisms, but the degradation is generally attributed to ion migration induced by electric fields between the cell and the grounded module frame. Mitigation strategies for PID have included selecting better encapsulants with high bulk resistivity that can prevent, or at least reduce, the migration of ions to the cell and thus limit the degradation.[128]

Issues related to tandems and perovskites

The long-standing confidence and understanding of the reliability and durability of established technologies makes them attractive for tandem applications. However, the stability and durability of newer technologies, such as organic- or perovskite-based devices, are much less understood. Combining multiple PV technologies into one device and the device design itself can also pose new reliability challenges. Readying tandem technologies for commercialization will require identification and advanced understanding of these new degradation mechanisms, the development of testing protocols to properly screen for them on the desired timelines for deployment, and comprehensively applying those qualification testing protocols to all new products.

Perovskite solar cells are especially exciting due to the tunability of the band gap and the very low formation energies that are required. However, perovskites have long suffered from degradation issues. Perovskites are well-known to have a low tolerance to moisture exposure, which can cause irreversible degradation. The mechanisms have been summarized elsewhere.[129] Oxidation and photoxidation related degradation issues are also well documented in the literature. Oxygen can affect charge transport layers (such as PTAA or spiro-OMeTAD)[130] as well as the bulk perovskite layer.[131] Some of these issues can be engineered around through appropriate packaging. For example, moisture ingress can be mitigated through the use of a double-glass package and desiccated polyisobutene (PIB) edge-seal, which has been demonstrated to prevent moisture ingress for up to 20 years or more.[132] In this case, the IEC 61215-2 module qualification test (MQT) 13 test will really test the effectiveness of the packaging, rather than degradation of the perovskite cells. Other stressors affecting the durability of perovskites include light and elevated temperature, which leads to mechanisms such as ion migration,[133] halide segregation,[134,135] and compositional degradation.[136]

Light and elevated temperatures (>50°C) are normal operating conditions for PV modules, and thus unavoidable, so the longer-term degradation kinetics under these conditions need to be fully defined and understood. Testing for and identifying these issues in perovskite-based junctions is not guaranteed by the present IEC qualification standards, and updated protocols must be developed. The acceleration factors of these new protocols must also be considered, as lower factors will require longer testing periods for fully working out issues. The Perovskite Accelerator for Commercializing Technologies (PACT) has endeavored to validate the relevance of the IEC 61215 stress tests and also identify gaps and develop appropriate additional tests that may be necessary for qualifying perovskite-based PV technologies.[137]

Partial shading of PV cells brought about by fixed obstructions (chimneys, trees, etc.) can force cells in a string into reverse bias, which then causes extreme localized heating known as hotspots.[138,139] Modern commercial single-junction silicon-based PV modules use bypass diodes (typically 1 diode for every 25-cell string) to mitigate potential damage from partial-shading stress. The breakdown voltage of cells is reduced such that a shaded cell may pass the reverse-bias current without excessive voltages and heating. For thin-film technologies such as CIGS or CdTe, partial shading has been demonstrated to cause permanent damage through shunt formation.[140] Damage from partial shading in these thin films could also be mitigated by reducing the breakdown voltages in the cells. The partial-shading durability of perovskite solar cells has been shown to be quite poor, with catastrophic and irreversible damage even under very low reverse-bias voltages manifested as hotspot formation, shunting, and phase segregation.[141–143] This low durability means that reducing the breakdown voltages of the cells is not a sufficient strategy for mitigating damage. It has, however, been demonstrated that in a 2T perovskite/silicon tandem configuration, the perovskite is protected from its poor reverse-bias durability because the majority of the reverse-bias voltage is dropped across the silicon cell.[144]

Additional degradation modes may be introduced in tandem device architectures, especially given the number of new interfaces and interaction between junctions. Mechanical and chemical incompatibilities between layers have introduced reliability issues in single-junction PV technologies in the past and could arise again in tandems, where junctions are interfaced directly or through an interlayer.

Configuration is also likely to influence the potential degradation modes and mechanisms in tandem devices. For 4T devices, shorts between the subcells can be an issue. Preventing shorts will require appropriate design and material selection of the interlayer. A material with a high voltage breakdown (V_{bd}) characteristic will be necessary to ensure isolation. Additionally, the material will require mechanical robustness such that displacement of the two subcells leading to shorting is avoided. The mechanisms of PID could also be influenced by the configurations. Perovskite solar cells have demonstrated mobility of ions under voltage bias,[145] it is not clear whether these ions could migrate to, and negatively impact, the Si bottom cell. In an appropriately packaged 4T device, this could be mitigated with the inclusion of a high bulk resistivity interlayer material. In a 2T configuration, this is not an option.

Outdoor testing is a critical component of the reliability learning cycle. There are a growing number of studies looking at long-term outdoor performance of perovskite-based devices. Out of the limited number of field demonstrations, many early deployments of scribed single-junction perovskite modules saw module failure within 12 months of operation.[146] Smaller scale devices, both single-junction perovskite cells without scribes and individual 2T perovskite/Si tandem solar cells, have demonstrated a year of outdoor performance.[147],[148] These different module configurations have different potential degradation pathways, so it is important that each module type be tested independently. Since the existing qualification standards, IEC 61215 and 63209, are not designed for long-term reliability there remains a challenge in guaranteeing the longer-term operational lifetime for tandem PV modules. Even for commercial silicon PV modules, the 25-year service lifes are only backup up by legally binding warranties, and not based on scientific evidence. Appropriately accelerating 25 years of service life into a reasonable testing timeframe continues to be a challenge for the PV industry as a whole.

Although multiple companies are actively pursuing tandem module concepts, there is limited publicly available data on the performance of full-size modules. Very little has been reported on the progress of any tandem product toward qualification according to IEC 61215. A handful of publications have reported on the testing of tandem devices using specific IEC 61215 procedures, but most have not yet met the minimum electrical degradation requirements as outlined by the IEC 61215 standard. A summary of the publications was published by Duan et al.[149] Outdoor testing will be critical to validate the long-term efficiency advantages of tandem devices and design testing protocols to qualify commercial products. Sharing this data with the PV community will also help to speed up the reliability learning cycle and aid the deployment of tandems with predictably longer lifetimes. Given the importance and timescales associated with solving reliability issues in PV modules, it is imperative that efforts to uncover and address these issues be significantly ramped up now and carried out in parallel with cell and module R&D, not after. This approach will provide more time to solve issues prior to commercialization and will also inform the design of tandems as they are developed. The tandems industry must also commit to going through extensive qualification testing for new products to avoid mass early failures in the field that can set back these technologies.

Economics, environmental, and social impact

Section 7 introduced LCOE and how it will continue to be used as an important metric in evaluating the market potential of tandems, in the same way that it has influenced the deployment of single-junction PV technologies. Traditionally, technoeconomic analysis (TEA) has been the main evaluation method for quantifying the economic viability of PV technologies as well as providing valuable information to direct near and long-term research efforts on where to cut costs. Capital expenditure (capex) and operations expenditure (opex) are included in these calculations and are important considerations for manufacturers and owners of tandems modules and systems. The LCOE values that come out of this analysis are highly dependent on module efficiency[150] and bottom-up cost model generation.[151] When calculating LCOE values, the system design and performance capabilities can be critical considerations that can change the economics. Aspects or capabilities that add manufacturing cost can be justified when they result in an lower LCOE.[152] Examples include change that lengthens lifetimes, lowers temperature coefficients, and designs that require less maintenance or result in cheaper installation costs. The main benefit of tandems is that their increased efficiency, EHY, and lower footprints will lead to lower BOS costs per watt per area, racking, cheaper installation, and reduced embodied carbon. Better utilization of incident sunlight may also lead to less overall heating of the module and associated efficiency losses.[153]

Several studies have evaluated the module cost ($\$/m^2$) of different tandem configurations. This work is important, although it is premature, as tandem design and manufacturing methods are still evolving. In particular, several aspects of perovskites show promise for reduced capex (i.e., relatively low precursor costs, less energy-intensive fabrication methods, and potential for high-throughput manufacturing). It will be important to consider these factors while designing tandem modules, but these technologies are at a relatively early stage, and some details are not yet worked out. As they do become more established, the module cost will be more robustly understood. An interesting outcome of the analysis of Peters et al. is that the monetary incentives for PV module manufacturers will differ from PV system installers to utilize tandem modules due to the large fraction of non-module-related costs utility-scale installations.[34] This makes accurate EHY calculations and BOS cost analysis critical for determining the LCOE benefits of tandems. These analyses will need to be continuously updated as tandem module designs, efficiencies, manufacturing methods, and associated costs evolve.

One open question for tandems built on Si bottom junctions is whether traditionally lower performance/lower cost Si cells, such as those utilizing PERC designs, provide an LCOE benefit over higher performance/higher cost cells, such those utilizing SHJ and IBC designs. TEA suggests that perovskite/PERC tandems have the potential for a lower LCOE than perovskite/SHJ tandems or their single-junction perovskite and Si module counterparts for residential installations in the near term (with lower perovskite top-junction efficiencies) and utility-scale installations in the long term (with improved perovskite top-junction efficiencies).[150] If the cost and performance trends hold, it could influence the future direction of tandem design and manufacturing. Future development of tandems utilizing Si bottom junction should focus in part on the experimental evaluation of devices utilizing low-cost Si cell designs, and TEA should continue to be performed in parallel to confirm or adjust these conclusions. Of course, if the cost of high-performance Si cells drops substantially, it may drive the construction with those devices instead.[154]

We also note that the cost of power electronics (inverters and converters) will play a significant role in determining which tandem interconnection configurations (2T, 3T, or 4T) will be adopted and deployed. Series-connected 2T configurations will likely be able to use similar electronics to single-junction installations, effectively neutralizing these costs in the evaluation of single-junction vs. tandem technologies. However, 4T and voltage-matched 2T and 3T configurations will require additional power electronic components to operate optimally.[31,33] Evolving trends in the power electronic components that are employed in single-junction systems, reductions in their costs, as well as innovative stringing and system designs will further modify this equation. Further in-depth evaluation of the power electronics needs for tandem PV systems and their implications on installation costs is needed to help the PV community better evaluate the subcell interconnection trade-offs and preferred tandem configurations.

Beyond economics, as the magnitude of PV deployment goals becomes clear, developers, investors, and consumers are starting to demand that PV module production meet criteria of environmental and societal benefit beyond the economic measure of LCOE. This has been referred to as the triple-bottom line.[155] Some of these new metrics can be difficult to quantify and will depend on non-technology factors beyond the module itself, such as labor force, local water usage, etc. However, there is already precedent for utilizing non-technology-specific metrics in LCOE calculations, such as irradiance, racking options, location, etc. It will be critical to transparently present the assumptions used and to ensure that the same assumptions are applied equally when comparing competing technology options.

The environmental footprint of a PV system can be evaluated through LCA, which is performed in either cradle-to-gate or cradle-to-grave cycles. At minimum, LCA can quantify the embodied carbon and embodied energy in a PV installation. Recent analysis demonstrated that if reducing the carbon footprint is a critical consideration, the PV module manufacturing location and technology choice are important.[42] CdTe was found to have about half the embodied carbon of wafer Si manufactured in the same location. This trend will be generally true for any thin-film technology, where the embodied energy and carbon are determined most by the module's glass and Al frame.[42] Just as efficiency and cost/W benefits follow a "marriage of equals" principle, the resulting embodied energy and carbon of a tandem module can be evaluated in a similar way.

The early development stage of tandems provides an opportunity to consider the circular economy and specifically end of life. Intentional design decisions made now could better enable the ability to recycle modules, resulting in high-value closed-loop recycling reducing life cycle waste upward of 80%[156] and enable manufacturing efficiencies reducing waste upward of 20%.[157]

Early stage development of tandems further provides an opportunity to integrate design and testing to address stakeholder end-of-life environmental concerns. Preliminary work has found potential risks from lead, cadmium, or selenium from single-junction CdTe or perovskite modules during disposal were below U.S. regulatory thresholds at the estimated worst-case risk.[158,159] Similar work has shown that fire and potential impacts to soil and groundwater are below risk-based screening levels and maximum contaminate levels.[160] Given the energy benefits these thin-film PV technologies promise to deliver, there is an argument to be made about responsibly packaging and disposing of modules but not letting concerns preclude deployment of these technologies.[161] Nevertheless, future efforts to solve toxicity issues and assuage concerns regarding tandem modules end of life will provide significant benefit.

Although TEA and LCA provide an understanding of the impacts on greenhouse gas emissions and techno-economics, neither is individually adequate to quantify sustainability or account for aspects of social justice. Robust models or even fully agreed-upon measures to encompass these concepts do not yet exist. The United Nations Environment Programme has put together a framework to outline guidelines[162]; however, significant additional work remains. Miehe et al. state "Although sustainability represents a key factor of future production, it is not conclusively defined in order to be technically applicable."[163] If sustainability is to truly be a factor considered in the scale-up and deployment of PV technologies, quantitative metrics must be put in place to guide future R&D.

Commercializing tandems

The path to reach 2% share of tandems in the PV market depends on physical factors related to the research and scaling of module designs as well as economic factors. The economic concerns broadly fall under the categories of bankability and marketing, also presented in the broad activity of deployment in Figure 5. The bankability of a tandems project describes the financial risk associated with manufacturing and distributing tandem modules for industry participants. These risks include the location or country of production, technology level risks, and market risks.[164] Although these aspects typically come into play near the later part of the PV technology development cycle, it may be beneficial to consider them earlier in the case of tandems, where design decisions could be made to ease market entry.

Location risks vary depending on the stability of the local government, consistency in industry support, and reliability of infrastructure.[164] Together, these factors determine the security of conducting business in a locale. The Renewable Energy Country Attractiveness Index (RECAI) has tracked these risks more generally for renewable energy technologies since 2003.[165]

Technology risk for tandems depends on how similar module designs are to the existing market. For Si bottom cells, these introduced risks are low because the processes for production and testing are well established.[166,167] Depending on the tandem design, new commercial technologies may have additional risks associated with field testing, sensitivity to soiling (i.e., for higher efficiency devices), and long-term system stability.[168] Tandems benefit from similarities to existing PV technology, however, each new design element introduces new technology risks.[169]

Market risks are determined by the costs, size, and consistency of the supply chain for a given technology. Market risks are closely tied to country and technology risks. The policies of a country's government and raw materials required by a specific module design dictate the supply chain for that module. In tandems, the market risk is dictated by the availability of constituent elements and precursors. The path those components take to reach the manufacturing line varies from design to design, and any government tariffs and incentives along the way affect the market risk.[164]

Although country, technology, and market risks categorize the main financial considerations for increasing the market share of a new technology, some factors lie outside these descriptors. Namely, the size and reputation of the manufacturing and distribution companies of the new technologies will define who bears the risk. Large corporations operating internationally with diverse products have the funds to support new markets themselves, financed through separate operations. Medium-sized, PV-specific companies vary in approach, investing in research and development over time and introducing a new module design with ongoing considerations for market risks. Small or start-up companies require financial backing, insurance, and often re-insurance to reduce the risk to potential customers and provide assurance that the company can support its products or offer financial reimbursement for the stated product lifetime or warranty.[164,170]

Increasingly, the full life cycle of new technologies must be assessed before they are commercialized. This assessment is particularly necessary for technology in the energy sector.[171] If the technology can inequitably produce any adverse effects, i.e., chemical leaching during use or even during recycling or disposal, a plan should be implemented to reduce unjust impacts. LCA should be considered in coordination with bankability to ensure longevity of a new technology in a market.[172]

Because of the uncertainty in multiple factors of bankability, including energy production for a given location, system cost, and lifetime, bankability often takes many years to establish. The timeline can also vary depending on the application or market. Tandems may therefore need to enter commercialization through niche markets and smaller scale installations (i.e., demonstration projects and residential rooftops) before being bankable in larger, utility-scale systems.

Development considerations in a snapshot

Figure 6 assembles the factors discussed above into a comprehensive guide for tandem development. It is primarily broken out by subcell interconnection architectures

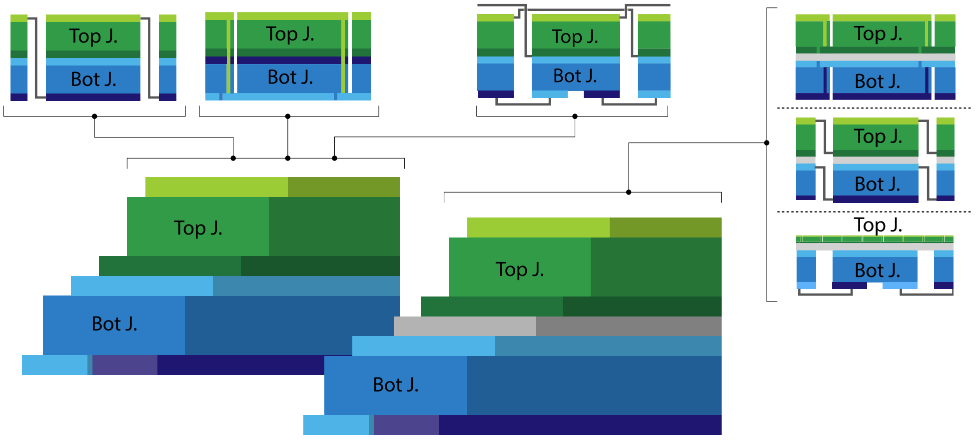
	Directly Deposited			Mechanically Stacked	
	2T on Si	2T Thin Film	3T on Si	3T on Si or other	4T/voltage-matched 2T
Configuration					
Advantages	•Streamlined integration through deposition of one cell on top of the other •Low optical, resistive losses between junctions •Standard 2T module configuration serves as a drop-in substitute in PV systems		•High energy harvesting yield if strings are designed correctly •Opportunities to probe juntion performance (for R&D)		•Highest potential energy harvesting yield •Design and processing flexibility •No tunnel junction (TJ) (or equiv.) required
			•Lower optical losses in directly deposited tandems	•Design and processing flexibility	
Potential challenges to address	•Current matching requirements can lower the energy harvesting yield •TJ (or equiv.) required •Potential for processing incompatibilities •Need for low temperature tabbing methods for perovskite top cells		•Greater processing complexity •Loss of contribution from cells on ends of strings •Processing incompatibilities •Additional sub-string/wiring		•Greater optical and resistive losses •Higher costs (more layers, electronics) •Potential for breakdown if true 4T •Additional sub-string/ wiring •Scribing of laterally interconnected perovskite cells
	•Challenge of depositing top cell on textured Si		•Directly deposited configurations: challenge of depositing top cell on textured Si •Potential for higher cost when using IBC Si cels (near-term)		
Additional considerations	•Cost of changing top cell processing as the Si wafer size/configuration changes •Manufacturing business model: does processing of both cells need to be performed by the same company?		•Cost of changing top cell processing as the Si wafer size/configuration changes •Manufacturing business model: need to evaluate trade-offs in manufacturing complexity and improved energy harvesting yield		•Manufacturing business model: do mechanically stacked modules enable early entry into markets?
	Top cell development Identify reliability challenges and reduce degradation rates Suitability of low-cost Si bottom cells Transition to scalable and cost-effective manufacturing processes Design for lower material use, lower energy payback time, and circularity				

Figure 6. Considerations for selecting and developing the most popular tandem configurations explored to date

because they each have distinct advantages and development challenges. However, many of the topics we have outlined cross-cut all three and should be viewed as important aspects that demand attention. These considerations lay the foundation upon which future research and development efforts should be built.

SUMMARY OF DEVELOPMENT NEEDS

The ITRPV's predicted timeframe for commercializing tandem solar cells is fast approaching, and there are still many stage gates to meet. Below, we highlight several aspects that must be addressed concurrently. Rapid progress will require collaboration between research scientists, engineers, and industry and must also be supported with sufficient resources.

Near-term needs

(1) Commercialization of tandem solar cells in the near term is likely to leverage mature PV technologies (i.e., Si and CIGS) to enable large-scale deployment. Therefore, research should focus on development of the top cell as well as methods, designs, and materials for integration at the module level.[87,173,174]

(2) Tandem module architectures and fabrication methods should also be developed at the outset with scaling and manufacturing in mind.

(3) New module-level components, such as interlayers, encapsulants, and contacts, must be developed to suit the needs of new tandem architectures and their junction technologies, particularly those containing perovskite junctions.

(4) Lowering degradation rates of novel materials and module designs is critical for deployment. Identifying and understanding the origins of degradation, especially those that arise from new modes not observed in single-junction technologies, is the first step. We must then develop appropriate lab and field-scale tests and standards to detect them before modules are deployed. Included in this category is the development of robust module packaging, which is necessary for moisture-sensitive PV technologies like perovskites.[175,176]

(5) Accurate measurement of cell and module performance is the foundation upon which tandem PV systems will be designed. The quantum efficiency and JV measurement techniques must continue to be improved for both, and the tandems community must adopt them to correctly rate commercial products as well as report new breakthroughs at the cell development level.[71,177]

(6) New EHE models must also be developed to evaluate tandem interconnection configurations at the research level and support PV system planning at the deployment level.[166,178]

(7) BOS requirements, including the power electronics needed for common interconnection configurations, must be thoroughly evaluated to improve TEA of tandem technologies and assist PV system design and planning activities.

(8) Anticipating that tandem PV systems will eventually be deployed on the TW scale, we should evaluate the use of critical materials, such as Ag, In, Bi, Cd, and Te, and search for ways to minimize or eliminate their use.[42,179]

(9) Like previously commercialized PV technologies, some early tandem modules are likely to fail. A key activity to assist in working through the failure mechanisms in nascent module technologies without damaging their reputation early on will be to create test facilities where they can "safely fail." Facilities like the U.S. Department of Energy-supported PACT program provide this service for small batches of modules, but expanding to field-scale testing facilities is necessary to support the development of new products by industry.

(10) Consortia have been instrumental in helping the PV industry as a whole address cross-cutting technology challenges. For example, the U.S. Manufacturing of Advanced Perovskites (US-MAP), Manufacturing of Advanced Cadmium Telluride (US-MAC), and Cadmium Telluride Accelerator Consortium (CTAC) bring together researchers and industry to discuss common issues and share lessons learned. A consortium aimed specifically

at tandem solar cell development with broad participation across industry, national labs, and academic research teams will help to make tandems the same progress as other PV technologies.

Medium- and long-term needs

(1) Bankability must be evaluated to determine the most economically sustainable path to increase the PV market share of tandems. This financial risk assessment depends on the size of companies introducing tandems, their location, and the differences between the tandem designs chosen and present commercially available PV technologies.[164,168,170]

(2) Alternative PV technologies for the bottom junctions should also be explored and developed over the long term to meet the needs of different applications. These could include perovskite and OPV thin-film technologies, or other emerging materials.

OUR OUTLOOK

Given the maturity of established single-junction solar cell technologies as well as recent breakthroughs in high band-gap PV technologies that will support tandem devices, there is growing momentum for tandem PV development. To reach even modest shares of the PV market in the next decade, each of the development aspects indicated in the roadmap presented in Figure 5 must be addressed in parallel. We have outlined some of the challenges and areas where future development should take place. We also note that no one group or company will be able to accomplish all of these advances alone. Collaboration, shared lessons learned, and investment (especially in cross-cutting research) will be required. Fostering the nascent tandem PV industry in such a way is the only path forward to realizing the enormous potential for these technologies and contributing to the TW-scale clean energy-production goals of the PV field as a whole.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

Some of the authors of this paper are inventors on patents related to tandem PVs, including US 9,287,431, US 10,087,535 B2, US 11,462,688, US 11,367,802 B2, US 11,120,990 B2, US 10,991,847 B2, US 11,508,864, and US 11,658,258.

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