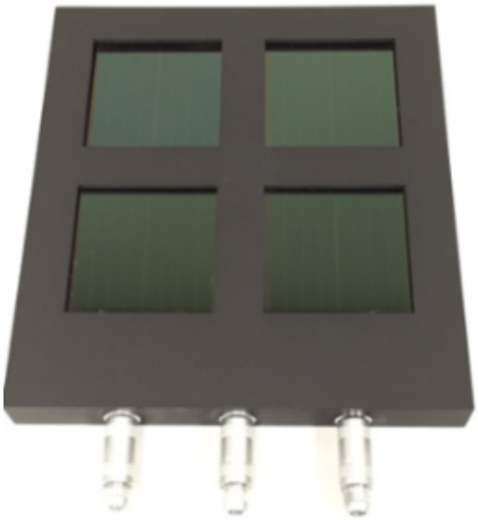
Hybrid tandem solar cells

A route towards high efficiency solar cells



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The front cover shows an image of the first perovskite /c-Si hybrid tandem mini-module consisting of 4 c-Si cells located under 4 perovskite mini-modules, each approximately 4 cm x 4 cm. The hybrid tandem mini-module was prepared by Solliance partners imec, Holst Centre, ECN in collaboration with Heraeus.

Preface roadmap hybrid tandem solar cells

The point of all this was, and remains, accelerating the advent of sustainable energy, so that we can imagine far into the future and life is still good.

E. Musk, 2016

Preface roadmap hybrid tandem solar cells

Aanleiding

Het energie-innovatiebeleid in Nederland is sinds 2012 gericht op specifieke speerpunt-technologieën. Zonne-energie (PV) is daar één van. Hierbinnen richt het ondersteuningsbeleid zich op de gebieden wafer-gebaseerde silicium PV-technologieën en dunne-film PV-technologieën. Recent is daar het gebied het gebied 'hybride tandem PV-technologieën' bijgekomen. Deze hybride tandems zijn, simpel gezegd, een stapeling (vandaar tandem) van bijvoorbeeld een kristallijn-silicium cel en een speciaal daartoe ontwikkelde dunne-film cel (vandaar: hybride). Met zo'n combinatie kan een hoger rendement worden bereikt dan met kristallijn silicium of een dunne film alleen en wordt het mogelijk om de barrière van ≈26% te breken.

Hoewel tandem-PV niets nieuws is, is de belangstelling ervoor de afgelopen drie jaar explosief toegenomen. Dat is vooral het gevolg van de spectaculaire ontwikkelingen op het gebied van perovskieten, een (in de gebruikte vorm) nieuwe familie van dunne-filmmaterialen die in een paar jaar tijd een celrendement van meer dan 20% heeft laten zien. Perovskieten kunnen in potentie zowel voor 'autonome' dunne-filmcellen worden gebruikt als voor dunne-film topcellen in een tandemstructuur met een kristallijn-silicium bodem cel. Door de snelheid van de ontwikkelingen en de vele vragen die er zijn met betrekking tot de technologische en economische haalbaarheid van hybride tandems is er behoefte aan een analyse van de huidige situatie en een roadmap van de te verwachten ontwikkelingen tot 2020 en daarna. Dit ondanks de vele onzekerheden die er zijn.

Dit document heeft als doelstelling de wetenschappelijke en technische inzichten en ontwikkelingen tot nu toe in relatie tot hybride tandems in kaart te brengen en tevens het opstellen van een technologie-roadmap voor de komende 5 jaar.

Motivation

Since 2012, the energy innovation policy in the Netherlands has been aimed at specific focus areas - solar energy (PV) is one of them. Within this area, the support policy covers wafer-based silicon PV technologies and thin-film PV technologies. Recently, ‘hybrid tandem PV technologies' were added. These hybrid tandems are, simply put, a stack (hence ‘tandem’) of, for example, a crystalline silicon cell and a specially developed thin-film cell (hence ‘hybrid’). With such a stack of solar cells, higher efficiencies can be achieved than for crystalline silicon or thin film cells only and it becomes possible to break the barrier of ≈26%.

Although tandem solar cells are not new, interest has increased very rapidly in the last three years. This is mainly due to the dramatic advances in the area of perovskites, a new class of thin-film PV materials that has yielded cells with over 20% efficiency in just a few years of research. Perovskites can potentially be used both for 'autonomous' thin-film cells as well as for thin-film top cells in a tandem structure with a crystalline silicon bottom cell. Because of the rapid developments and the many questions that are related to the technological and economic feasibility of hybrid tandems, there is a need for an analysis of the current situation and a roadmap of the expected trends for 2020 and beyond. This despite the many uncertainties that currently exist.

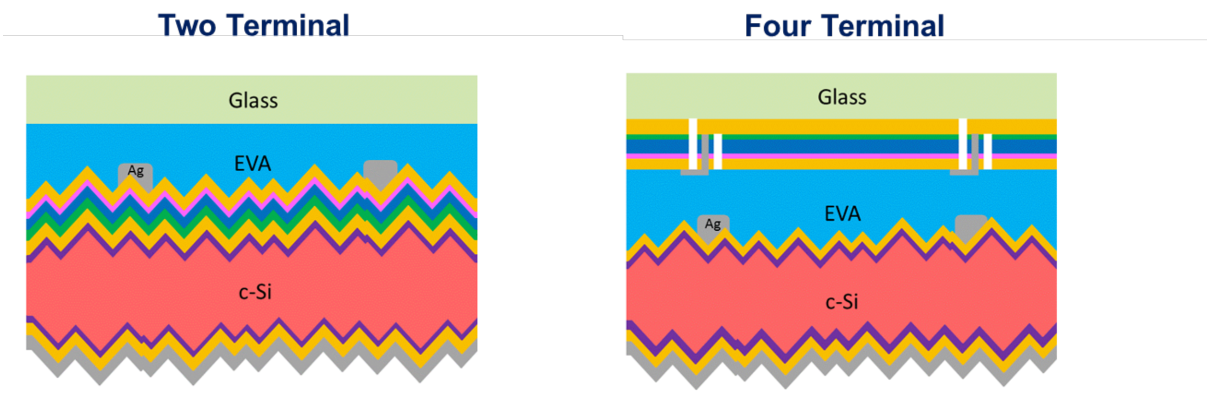
This document aims to give an overview of the scientific progress and technical developments achieved so far in relation to hybrid tandems and to provide a technology roadmap for the next five years.

Nederlandse samenvatting

Managementsamenvatting

Tandemzonnecellen bestaan uit twee of meer gestapelde (sub)cellen. De subcellen absorberen ieder afzonderlijke delen van het zonnespectrum. Hierdoor is het mogelijk om iedere (sub)cel in de tandemzonnecel te optimaliseren voor een specifiek deel van het zonnespectrum. Door het combineren van deze geoptimaliseerde subcellen in kan een zeer efficiënte tandemzonnecel verkregen worden. De efficiëntie van een tandem zonnecel kan een factor 1,3 hoger zijn dan een zonnecel gebaseerd op een enkele junctie of enkele subcel. Dit betekent dat een kristallijn-silicium (c-Si) zonnecel van 24 % gebruikt kan worden om een ~ 30% hybride tandemzonnecel te realiseren door de cel te combineren een optimale topcel.

Tandemzonnecellen zijn niet nieuw, ze zijn er al tientallen jaren. Voorbeelden zijn III-V 'multi-juncties' toegepast in concentrator-zonnecellen (CPV). Er bestaan nu III-V multi-junctie zonnecellen met een recordrendement van 46% onder geconcentreerd zonlicht. De bandkloof of 'bandgap' van III-V materialen kan worden afgestemd over een breed energiegebied. Hierdoor is het mogelijk om complementaire licht-absorberende halfgeleidermaterialen in een tandemzonnecel te combineren. Voor een aantal andere materialen die toegepast worden in zonnecellen, is het aanpassen van de bandkloof niet mogelijk (bijv. c-Si), of het leidt tot slecht presterende tandems (bijv. CIGS). Voor deze materialen kunnen hybride tandems een uitkomst bieden: de tekortkomingen worden opgelost door andersoortige materialen te combineren. Daarmee komen we tot de kerm van deze roadmap: *hybride tandems toegepast als vlakke-plaatmodules, voor het omzetten van direct en diffuus zonlicht in elektrische energie.*



Figuur MS 1 Schematische weergave van een twee- ('two terminal, 2T') en viervoudig bedrade (4T) tandemstructuur met een dunne-film cel (boven) en een c-Si cel (onder).

De subcellen van een tandem kunnen op verschillende manieren bedraad worden: de twee meest gebruikte methoden zijn:

- een in serie verbonden tandemcel, ook wel twee-terminal (2T) tandem genoemd, en
- een vier-terminal (4T) tandemcel, waarbij iedere afzonderlijke subcel individueel gecontacteerd is.

Figuur MS 1 geeft een voorbeeld van beide tandemstructuren. Er is een belangrijk verschil tussen 2T- en 4T-tandemzonnecellen: de subcellen in een 2T-tandem zijn in serie aangesloten; hierdoor wordt de stroom van de tandem begrensd door de subcel die de laagste stroom genereert. Het is daarom belangrijk om in beide sub-cellen evenveel stroom op te wekken. Dit wordt 'current matching genoemd'. Als het lukt om de stroom van beide subcellen te 'matchen', dan kan een 2T-tandem theoretisch een vergelijkbare efficiëntie behalen als een 4T-tandem. Echter, als er geen 'current matching' is, dan kan het verschil in efficiëntie tussen 2T- en 4T-tandems groot worden. Een nadeel van een 4T-tandemontwerp is dat er meer licht in het nabije-infrarode deel van het zonnespectrum verloren gaat als gevolg van (parasitaire) absorptie in de transparante elektroden. Het is ook mogelijk om meer dan twee absorptielagen in een multi-junctiezonnecel toe te passen. In dit document verwijst de term 'tandem' meestal naar een multi-junctie met twee absorptielagen, maar is daar niet aan voorbehouden.

Als lokale instralingsdata en temperatuurgegevens beschikbaar zijn, is het mogelijk om het verschil in jaarlijkse energieopbrengst voor de twee verschillende tandemarchitecturen in te schatten. De jaarlijkse energieopbrengst van 2T-tandems is gevoeliger voor spectrale variaties. Tabel MS 1 geeft een overzicht van de belangrijkste verschillen tussen 2T en 4T hybride tandems.

	Two terminal	Four terminal
Current matching	**Ja**	**Nee**
Efficiëntie	**(Theoretisch) vergelijkbaar binnen 1-1.5% relatief, wanneer er een goede combinatie van halgeleider materialen gekozen is en er geen lichtabsorptie plaatsvindt in de overige lagen van de hybride tandem cel**	
Jaaropbrengst	**Gevoelig voor 'spectrale mismatch'**	**Ongevoelig voor 'spectrale mismatch'**
Optische verliezen	**Minimaal aantal lagen**	**Extra transparante elektrodes zijn nodig**
Grensvlak	**Een elektrisch geleidende laag vormt de grenslaag tussen beide subcellen.**	**Optisch transparante, elektrisch isolerende laag**
Integratie	**De tweede subcel wordt direct op de eerste subcel aangebracht. Een alternatief is 'wafer bonding'.**	**Eerst worden beide subcellen gemaakt. Vervolgens worden werkende subcellen samengevoegd in een tandem.**
Vermogens-management	**Wellicht kan gebruik gemaakt worden van huidige omvormers, mogelijk met kleine aanpassingen**	**Nieuwe omvormers moeten waarschijnlijk gemaakt worden.**

Tabel MS 1 Overzicht van de typische kenmerken van twee-terminal en vier-terminal hybride tandems.

Verschillende PV-technologieën kunnen worden gecombineerd in hybride tandems. Tabel MS 2 geeft een overzicht van de belangrijkste aspecten van een aantal geselecteerde PV-combinaties. De efficiëntiewinst is een belangrijke factor voor hybride tandemzonnecellen. Deze winst moet voldoende zijn om de extra kosten van een extra subcel te kunnen financieren. Let wel, deze extra kosten moeten beschouwd worden op hybride-tandemmodule- of op systeemniveau. Om de efficiëntie van tandemzonnecellen te maximaliseren, moet de bandkloof van de subcellen bij voorkeur dichtbij de (theoretische) ideale bandkloofcombinatie zijn.

Combinatie (hoog Eg/laag Eg)	Efficiën-tie toe-name	Jaarlijkse degradatie-snelheid	Kosten	Opmerking
a-Si:H / c-Si	--	-	+	(Te) lage efficiëntietoename
GaInP / c-Si	+	?	--	Hoge kosten, opschaling vereist, photon recycling is belangrijk
CGS / c-Si	--	-	?	Geen hoge Eg, semi-transparante, efficiënte cel
CdTe/ c-Si	?	+	?	Geen hoge Eg, semi-transparente, efficiënte cel
Perovskite / c-Si	+	?	+	levensduur, opschaling, laag TRL
Perovskite / CIGS	+	?	+	levensduur, opschaling, laag TRL

Tabel MS 2 Samenvatting van de belangrijkste aspecten voor hybride tandems op basis van verschillende PV-technologiecombinaties. "CGS" staat voor koper-gallium-sulfide of selenide, materialen die gelijkenis vertonen met CIGS, maar in vergelijking daarmee een hogere bandkloof bezitten. "Eg" staat voor bandkloof. De symbolen hebben de volgende betekenis: "--" - belangrijke hindernis voor commerciële toepassing; "-" - vereist significante verbetering voordat commerciële toepassing mogelijk wordt; "?" - dit aspect is onzeker / onbekend, verder onderzoek is nodig om voor deze parameter te bewijzen dat het de markt invoering van deze technologie niet belet; "+" - aspect is bewezen bij een laag TRL (Technology Readiness Level), extra werk kan nodig zijn, bijvoorbeeld voor opschaling, of om de prestaties te optimaliseren, etc.

Gedetailleerde kostenberekeningen voor hybride tandem PV-systemen vereisen een groot aantal betrouwbare invoergegevens die momenteel niet beschikbaar zijn. Uit de eerste techno-economische analyses blijkt dat kosteneffectieve hybride tandemzonnecellen gebaseerd moeten zijn op twee subcellen met een ideale combinatie van bandkloven, vergelijkbare prestaties van de subcellen met betrekking tot de Shockley-Queisser limiet, vergelijkbare levensduren; vergelijkbare kosten (in termen van EUR/Wp) voor beide subcellen. Tenslotte is het belangrijk overbodige lagen (glasplaten, EVA, belemmeringen etc.) zoveel mogelijk te beperken bij het combineren van twee zonneceltechnologieën in hybride tandems.

Naar verwachting nemen de komende 5 jaar de efficiënties op celniveau verder toe. Men kan efficiëntietoenames verwachten (in vergelijking met de best presterende subcel van de tandem) van 5-6%. De toename van de efficiëntie wordt o.a. mogelijk gemaakt door betere transparante geleiders (TCO's) en/of recombinatielagen, geoptimaliseerde contactlagen en absorptielagen met een ideale combinatie van bandkloven. De onderste cel, waarschijnlijk op basis van c-Si, CIGS of III-V dient ook geoptimaliseerd te worden om goed te functioneren in een hybride tandemzonnecel en de kosten te minimaliseren.

Ook op moduleniveau verwacht men in de komende vijf jaar een soortgelijke efficiëntiewinst te kunnen laten zien door gebruik te maken van deze hybride tandemtechnologie. Dit vereist onderzoek naar het integreren van subcellen in hybride tandemmodules. Voor dit type werk is en een opgeschaalde, reproduceerbare pilot-lijn nodig voor de subcellen van de hybride tandemmodules en de integratie van deze subcellen op moduleniveau.

De volgende stap is dan systeemintegratie in verschillende PV-toepassingen en veldtesten van de eerste hybride tandem PV-systemen. Systeemintegratie kan nieuwe systeemcomponenten zoals (micro) omvormers / power optimizers en junction boxes nodig maken.

Deze ontwikkelingen bieden goede vooruitzichten voor materiaalleveranciers en fabrikanten van apparatuur, maar ook voor bedrijven die actief zijn op het gebied van verkoop van apparatuur voor karakteriseren en installatie.

Naast de ontwikkeling van de technologie, is wetenschappelijk onderzoek nodig om beter te begrijpen hoe de kloof tussen de Shockley-Queisser limiet en de praktisch bereikte efficiënties verder gedicht kan worden. Begrip kan verkregen worden door optische en elektrische modellen te ontwikkelen voor (hybride tandem) zonnecellen. Ook is het nodig om nieuwe materialen te ontwikkelen voor efficiënte en stabiele lichtabsorberende lagen. Dat geldt ook voor de omliggende lagen zoals (ladings-) transportlagen, recombinatielagen en transparante electroden. Sinds kort is het ook mogelijk om de eigenschappen van nieuwe materialen vrij nauwkeurig te voorspellen, zoals energieniveaus, optische eigenschappen en (chemische) stabiliteit. Dit type onderzoek kan leiden tot goedkope, efficiënte, stabiele zonnecellen gebaseerd op veelvoorkomende, niet-toxische materialen.[1]

Hybride tandem PV-modules maken het mogelijk om de efficiëntie van PV-systemen aanzienlijk te verhogen. Het is waarschijnlijk dat dit zal resulteren in een kostenbesparing voor PV-systemen. Meerdere PV-technologiecombinaties kunnen gemaakt worden. Dit rapport geeft een overzicht van de mogelijkheden van de technologie en een routekaart voor de meest besproken technologiecombinaties.

Kleine en middelgrote bedrijven zijn bereid om hun rol te spelen in het innovatieproces, echter, als gevolg van de krappe marges in de PV-industrie, is de tijdshorizon voor innovatie typisch in de orde van een jaar. Voor deze bedrijven kan de overheid een belangrijke rol spelen door innovaties te ondersteunen met subsidie-instrumenten. Grote bedrijven zien de PV-markt als een aantrekkelijke groeimarkt. Deze bedrijven hebben meestal korte- (maand - jaar) en middellangetermijn (één - vijf jaren) onderzoeksprogramma's. Onderwerpen voor het middellange- en langetermijnonderzoek moeten generiek zijn: wanneer de technologie alleen geschikt is voor een specifiek deel van de PV-markt, is er een risico dat de investeringen in onderzoek niet terug verdiend worden. Het is duidelijk dat er ook hier een belangrijke rol weggelegd is voor de overheid om de ontwikkeling van deze technologie mogelijk te maken.

De sterke positie van de Nederlandse academische groepen die werken aan zonne-energie, in combinatie met instituten zoals ECN, TNO, en hun dochterorganisaties: Solliance en SEAC, geven Nederland een goede positie om een belangrijke rol in de ontwikkeling van hybride tandems te spelen. Zowel KMO's als grote bedrijven zien een rol voor zichzelf in de ontwikkeling indien ondersteund door de overheid om deze duurzame-energietechnologie te ontwikkelen.

Executive Summary

Tandem solar cells consist of two or more (sub-)cells stacked together. The different sub-cells absorb complimentary parts of the solar spectrum and as such, each (sub-)cell in the tandem solar cell can be optimized to a specific part of the solar spectrum. By combining sub-cells efficient in complementary parts of the solar spectrum, the tandem solar cell can outperform single junction solar cells by approximately a factor of 1.3 to 1.4. For example, a 24% c-Si solar cell can be turned into a ~ 30^+ % hybrid tandem solar cell when combined with an optimum top cell.

Tandem devices are not new, they have been around for decades. Examples include III/V multi-junctions applied in concentrator solar cells. III-V concentrator multi-junction solar cells have been reported with record efficiencies of up to 46 % under concentrated sunlight. The band gap of III-V materials can be tuned over a wide range, making it possible to stack similar absorber materials on top of each other with complimentary absorption spectra. For some materials applied in solar cells, tuning of the band gap may not be possible (e.g. c-Si), or results in poor performing tandems (e.g. CIGS). Here *hybrid* tandems enable the efficiency to be boosted beyond the limits of the single junction technology. Hybrid tandems are based on a combination of different semiconductor 'families' and are often prepared using different process methods. The scope of this roadmap is: *hybrid tandems applied as flat plate modules, converting direct and diffuse sunlight into electrical energy*.

The sub-cells of a tandem can be wired in several ways: the two most commonly used methods are: a series connected tandem cell, also called 'two terminal' (2T) and a four terminal (4T) device stack whereby each sub-cell is contacted separately. Figure ES 1 shows an example of the two configurations. This is an importance difference between 2T and 4T tandem solar cells: as the sub-cells in 2T are connected in series, the current from the tandem is limited by the sub-cell which has the lowest response. It is therefore important to match the currents from both sub-cells. If current matching is obtained, 2T tandems can theoretically reach (nearly) as high efficiencies as unconstrained or 4T tandems. However, if current matching is not obtained the difference in efficiencies between 2T and 4T tandems can be great. A disadvantage of a 4T design is that more light in the near-infrared part of the solar spectrum is lost due to (parasitic) absorption in the additional electrodes.

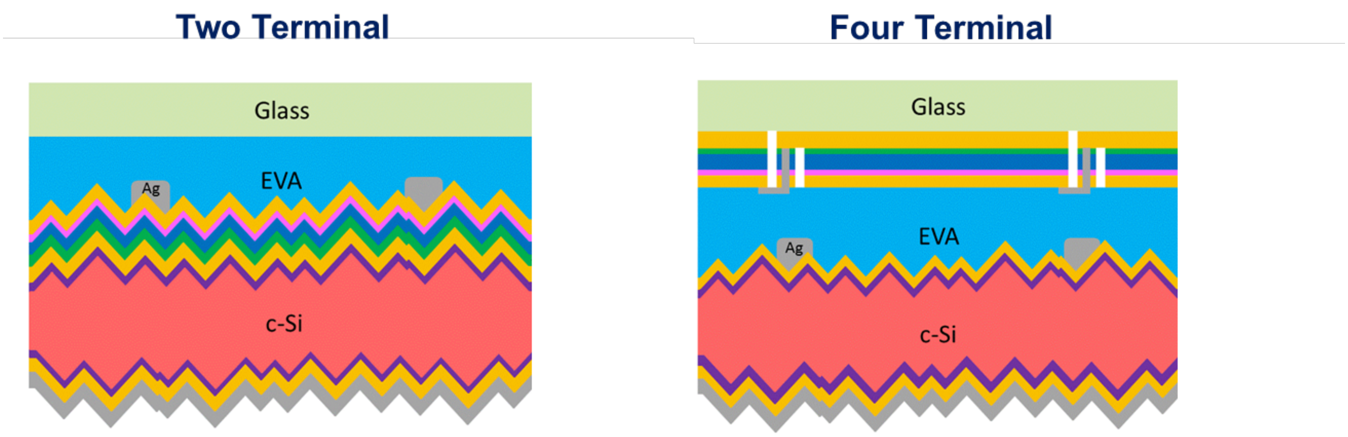


Figure ES 1 Schematic representation of a two terminal and four terminal tandem device structure based on a thin film top cell and a c-Si bottom cell.

If local irradiance and temperature data are available, it is possible to estimate the difference in the yearly energy yield of the two different tandem architectures. The yearly energy yield of 2T device is more sensitive to spectral variations. Table ES 1 gives an overview of the main differences between 2T and 4T hybrid tandems.

	Two terminal	Four terminal
Current matching	**Y**	**N**
Efficiency	**(Theoretically) equal within 1-1.5% rel., if band gaps are optimized and assuming no optical loss in non-absorber layers of the multi-junction**	
Annual Yield	**Sensitive to spectral mismatch**	**Forgiving w.r.t. non-optimal Eg combination and spectral mismatch**
Optical losses	**Minimal number of layers**	**Additional transparent electrode(s)**
Interface	**Contact layer processed directly on sub-cell / (textured) wafer**	**Optical spacer / insulator**
Integration	**Process directly on sub-cell / wafer bonding**	**Combine two sub-modules**
Power management	**Connect to 'standard' inverters**	**May require novel inverters / optimizers**

Table ES 1 Overview of typical characteristics of two terminal and four terminal hybrid tandems.

Various PV technologies can be combined in hybrid tandems. Table ES 2 summarizes the main aspects of the selected PV combinations considered for hybrid tandems. The efficiency gain is an important factor for hybrid tandem solar cells. This gain should be sufficient to bare the extra cost of an additional sub-cell. Note that the additional cost should be considered on module or on system level. To maximize the gain in tandem efficiency, the band gaps of the sub-cells should be preferably close to the (theoretical) ideal pair of band gaps.

Combination (hi Eg/low Eg)	Eff. Gain	Annual degrade. rate	Cost	Remark
a-Si:H / c-Si	--	-	+	(Too) limited eff. gain potential
GaInP / c-Si	+	?	--	High cost, up scaling required, importance of photon recycling
CGS / c-Si	--	-	?	No high Eg, semi-transparent (ST), efficient cell
CdTe/ c-Si	?	+	?	No high Eg, ST, efficient cell
Perovskite / c-Si	+	?	+	Lifetime, up scaling, low TRL
Perovskite / CIGS	+	?	+	Lifetime, up scaling, low TRL

Table ES 2 Summary of key aspects for hybrid tandems based on various PV technology combinations. CGS abbreviates for copper-gallium-sulfur or selenium, group of materials with similarities with CIGs, but with a higher band gap (Eg). Symbols indicate "--" major hurdle for commercial application; "-" needs significant improvement for commercial application; "?" this aspect is uncertain/unknown, further work is needed to prove this parameter does not prevent market uptake of the technology; "+" aspect is proven at a low TRL (Technology Readiness level) additional work may be needed for up scaling, or to optimize performance, etc.

Detailed cost of ownership calculations on hybrid tandem PV systems require a large set of reliable input data which is currently not available. The first techno-economic studies show that hybrid tandem solar cells should be based on two sub-cells with a close to ideal band gap combination, similar performance of the sub-cells with respect to the Shockley-Queisser limit, similar lifetimes, and similar cost (in terms of EUR/Wp) for both sub-cells, and in particular, low cost related to each sub-cell (e.g. the c-Si cell or the thin film layer stack) compared to common module and system costs. Finally, it is important to minimize redundant layers (glass plates, EVA, barriers etc.) when combining two PV technologies in hybrid tandems.

It is expected that in the next 5 years the efficiency at the cell level will further increase and one may expect efficiency gains (compared to the best performing stand-alone system) of 5-6 %. The increase in efficiency will be enabled by improved TCO's, optimized contact layers and absorber layers with optimized band gaps (top cell). The bottom cell, most likely based on c-Si, CIGS, or III-V, requires optimization to be able to function well in hybrid tandem devices.

Also on module level one expects to see similar efficiency gains for hybrid tandem modules in the next five years. It will require a significant research effort to integrate the sub-cells on module level, since an up scaled, reproducible pilot line for the sub-cells of the hybrid tandem modules is required to develop the integration of these sub-cells on module level.

The next step is then system integration in various PV applications and to field test the first hybrid tandem PV systems. System integration may require novel system components like (micro)inverters/optimizers and junction boxes.

These developments offer good prospects for material providers and equipment manufacturers, as well as for companies selling characterization equipment and installation services.

Besides technology development, academic research is needed to better understand how to reduce the gap between the Shockley–Queisser limit and the practically attained efficiencies and how to realize more efficient hybrid tandem devices. The challenges here are to identify new chemical routes for efficient and stable absorber and envelope layers. The envelope layers are contact layers typically located on either side of the absorber layer. Once the absorber layer is optimized and bulk recombination is minimized, these contact areas often have a decisive role in the device performance. High-level multidisciplinary material research will elucidate the correlations between (local) material properties and device performance. These correlations will enable accurate device simulations to optimize complete device stacks.

Hybrid tandem PV modules offer a clear route to increase the efficiency of PV systems significantly, likely resulting in a cost reduction for PV systems. Several PV technology combinations can be made. This report provides an overview of, and a roadmap for, the most discussed technology combinations for hybrid tandem PV systems.

To further develop this technology, small and medium sized companies are willing to play their role in the innovation process, however, due to the very tight margins in the PV industry, the horizon for innovation is typically one or a few years only. For these companies, the government needs to play an important role to facilitate the development of this technology to such an extent that the companies can participate and take over. Large companies see the PV market as an attractive growth market. Furthermore, they typically have short- (month - year) or even medium- (one to five years) and long-term (more than five years) research programs. Topics for these medium- and long-term research activities need to be generic, for when the technology is suitable for only one specific market segment within the solar industry there is a risk the investment in research will not pay off. So also the large companies will not develop such a technology by themselves. Clearly, there is an important role for the government to enable the development of this technology.

The strong position of the Dutch academic groups working on solar energy combined with institutes like ECN, TNO, and their ‘daughter organizations’, Solliance and SEAC, gives the Netherlands a good position to play an important role in the development of hybrid tandems. Both SMEs and large companies see a role for themselves, if supported by government, in the development of this sustainable energy technology.

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1. Introduction

Selected PV facts:

Worldwide newly installed PV capacity was about 50 gigawatt-peak (GWp) in 2015.

In the first quarter of 2016, Europe passed the 100 GWp mark of installed PV capacity.

4% of the electricity demand in the EU-28 was covered by solar electricity in 2015; in frontrunner countries like Spain and Germany, the share of solar was 8%.

It is estimated that about 600-700 GWp of total solar installed power is possible by 2020.

Solar is thriving. Perhaps the main reason for the success of solar energy is the impressive price reduction of crystalline silicon (c-Si) PV modules, which comprise by far the largest share of the world market, resulting in a strong growth in installed PV power over the last four decades, see Figure 1.[2]

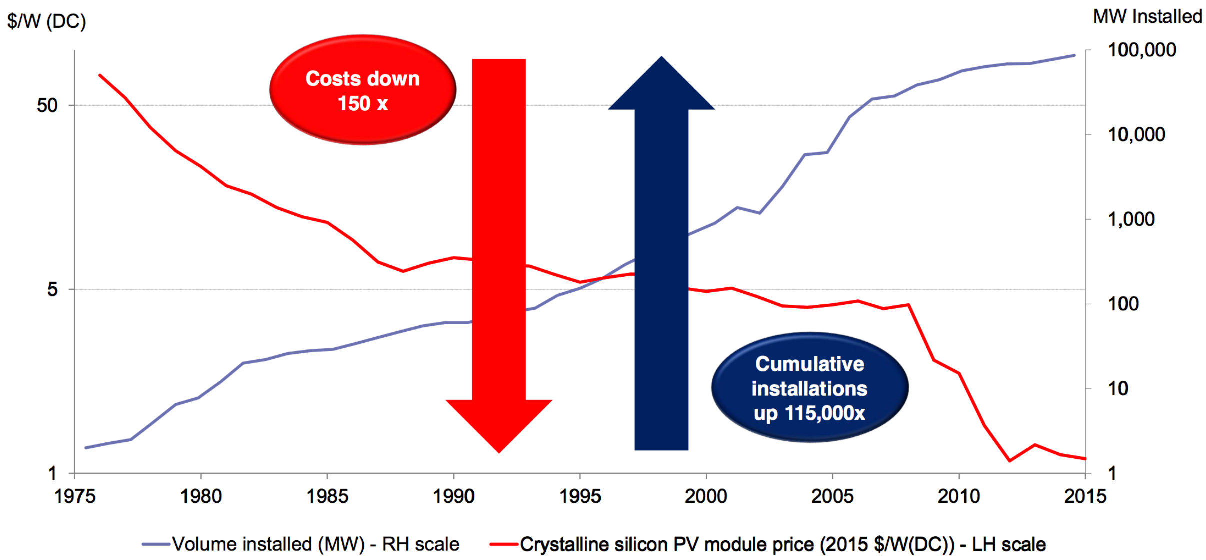


Figure 1 **The cost of solar power has fallen to 1/150th of its level in the 1970s, while the total amount of installed solar has soared 115,000-fold. Data from reference [2].**

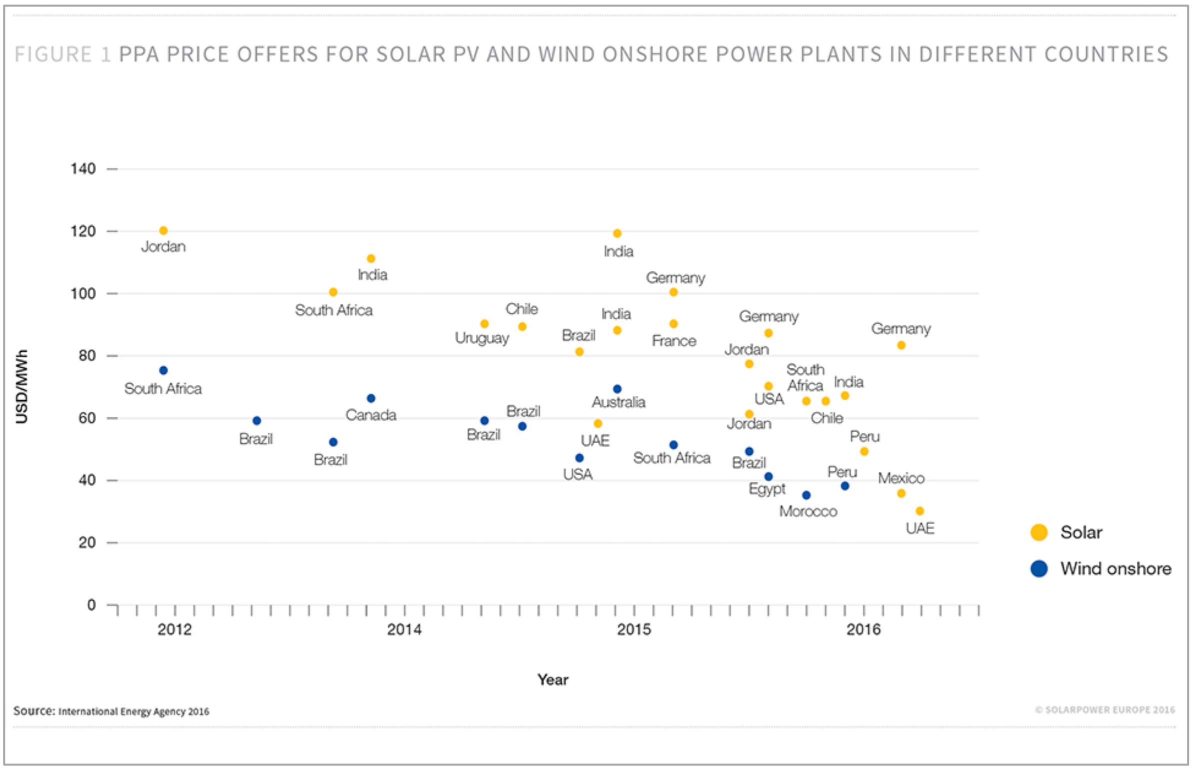


Figure 2 **Power Purchasing Agreement (PPA) price offers for large PV plants (and onshore wind farms), illustrating rapid decrease of generation costs, see text[3].**

The combination of low module cost, low balance-of-system cost, low cost of capital and long PV system lifetimes lowers the cost of solar electricity generation to such an extent that it becomes competitive with conventional electricity in an increasing number of countries and markets. This is demonstrated in its most extreme form by the rapid decrease of Power Purchasing Agreement (PPA) price offers: long-term contracts for supply of solar electricity at a fixed price. Values around or even below 0.03 US$/kWh for large PV plants in sunny regions to be built in a few years from now have been reported see Figure 2[3]. A similar trend is observed for rooftop PV systems and large PV plants in regions with moderate insolation like the Netherlands. Note that generation costs vary with system size and type, model of financing, and other parameters.

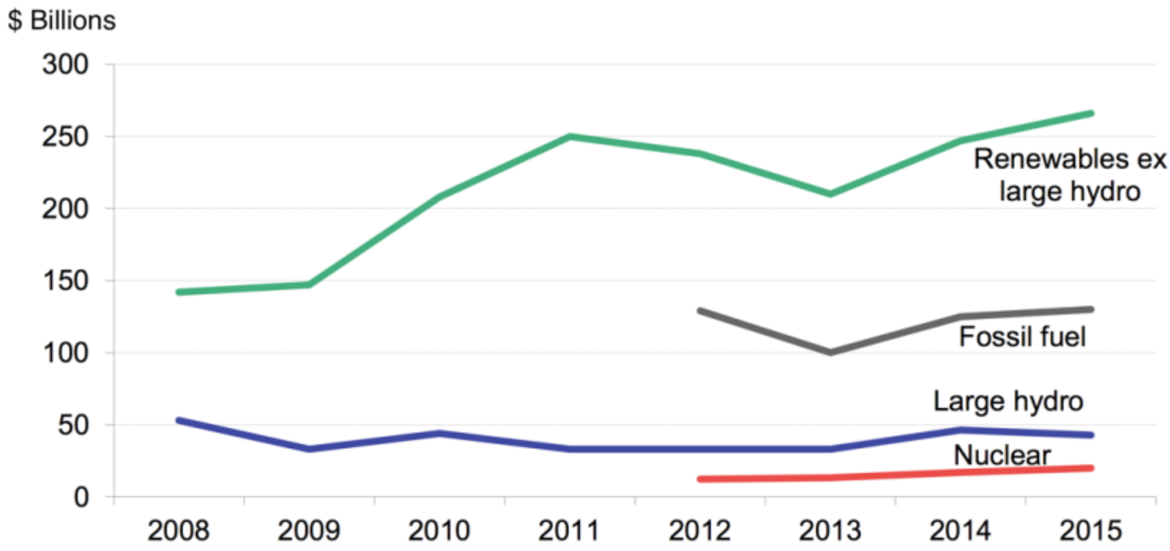


Figure 3 **Renewable power investment versus fossil-fuel power investment, 2008-2015 in $BN. Within the group "renewables ex large hydro", wind and solar dominate the investments 110 and 161 $BN respectively in 2015. Data from references 1 and 3.**

Because of these price developments and the need to mitigate climate change, already today, renewable energy sources (including solar) are no longer niche markets. On the contrary, renewables account for the largest share of power investments in recent years, solar being the largest contributor with 160 $BN in 2015, see Figure 3. Indeed, solar is thriving.

As will be described in more detail in Chapter 6, increasing the efficiency at module level is crucial to realize the full potential of low-cost PV. Several approaches exist which can increase the efficiency of solar cells (see Chapter 2), and a combination of approaches can result in a doubling in PV efficiency at system level in the long term. Of these, hybrid tandems solar cells are often considered as the most straightforward and promising approach to increase the efficiency of PV systems and reduce the cost of solar electricity. Furthermore, it is expected that this technology will reach the market in the next decade.

Scope

This document describes a new development in the field of photovoltaic devices: hybrid tandem solar cells. In tandem solar cells, different parts of the solar spectrum are absorbed and converted to electrical power in different sub-cells within the device. As each (sub-)cell in the tandem solar cell can be optimized to a specific part of the solar spectrum, these cells can be very efficient over a wide spectral range. By combining cells which are efficient in complementary parts of the solar spectrum, the tandem solar cell can outperform single junction solar cells.

Tandem devices are not new, they have been around for decades. Examples include III-V multi-junction cells[1] applied in concentrator PV. III-V concentrator solar cells have been reported with record efficiencies of up to 46%.[5] Thin film silicon solar cells based on a combination of amorphous and microcrystalline silicon are another example of tandem solar cells. These cells are typically applied in flat plate tandem modules and absorb the sunlight directly without a concentrator. In both examples the cells within the multi-junctions are based on the same semiconductor 'family' and often prepared using similar process methods.

Tandems based on different material families and often produced using different processing methods for each material family, have recently attracted a lot of attention in the PV community. These, so-called 'hybrid tandems solar cells' have the potential to increase the efficiency of commercially successful PV technologies such as c-Si and CIGS. Examples of hybrid tandem solar cells include combinations of perovskite with CIGS and III-V with c-Si, the reported efficiency of the latter combination reached 29.8% in 2016.[6] See also Table 1 for examples of tandems and hybrid tandems and .

Tandem Solar Cells		Hybrid Tandem Solar Cells	
based on **similar**	Examples	based on **different**	examples
semiconductor materials	III-V / III-V	semiconductor materials	III-V / c-Si
fabrication processes	a-Si:H/μc-Si:H	fabrication processes	a-Si:H/a-Si:H/OPV
PV technologies	OPV/OPV	PV technologies	PSC/ c-Si

Table 1 Description of tandem solar cells and hybrid tandem solar cells.

The scope of this roadmap is hybrid tandems applied as flat plate modules, converting direct and diffuse sunlight into electrical energy. While this roadmap documents provides extensive documentation on background and state-of-the-art of tandem PV and hybrid tandem technologies, and general recommendations for research, it is recommended that updates of this roadmap in the near future should describe recommended technology development and milestones in more detail.

[1] Note, 'tandem' and 'multi-junction' may be interchanged in this context.

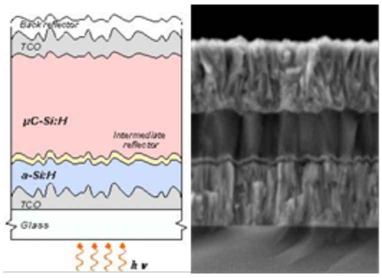


Figure 4 Schematic and SEM cross-section of a tandem solar cell. The image shows an example of a tandem solar cell based on an amorphous silicon top cell and a micro-crystalline silicon bottom cell (source PV-lab EPFL).[47]

After the introduction, which includes also the scope of this roadmap (Chapter 1), this roadmap continues with Chapter 2 which gives the current status of the main PV technologies and the motivation to work on hybrid tandem solar cells. Chapter 2 also summarizes various approaches to increase the efficiency of solar cells. This chapter is followed with a more in-depth description of hybrid multi-junction solar cells in Chapter 3. This chapter also explains why the theoretical efficiency of tandem solar cells is higher compared to the efficiency limit of single junction devices. The two most applied devices structures for tandem solar cells are presented. Then, the efficiency limits of tandem solar cells are presented as well as factors which determine the annual yield of PV systems based on tandem solar cells.

Chapter 4 presents an overview of the best efficiencies obtained with (hybrid) tandem solar cells under 1 sun conditions. Chapter 5 covers the relevant aspects when combining two PV technologies with the aim to make hybrid tandem solar cells. Several PV technology combinations are discussed in more detail and summarized at the end of Chapter 5. Chapter 6 covers the limited literature available on the cost of hybrid tandems.

Chapter 7 presents projections of the development on hybrid tandem solar cells for the next 5 years. Finally, Chapter 8 presents recommendations. This includes a multi-annual development program of how to develop hybrid tandem solar cells.

2. Rationale for hybrid tandems

The main reason to develop hybrid tandems is to increase the efficiency of solar modules. There are several reasons why hybrid tandem modules can be more efficient compared to single junction modules.

The first and foremost reason is the possibility to reduce thermalization losses: more efficiently harvest the energy of high energy photons of the solar spectrum in the top cell of a tandem. The electrons generated in a high band gap top cell can be collected at a higher voltage compared to the situation where such a photon would be absorbed in a single junction solar cell material with a lower band gap.

Secondly, a tandem solar cell can absorb photons that cannot be absorbed by a single-junction cell. In other words, the absorption spectrum of a tandem solar cell can have a better overlap with the solar spectrum.

Efficiency and limited available area

An obvious reason as to why highly efficient solar modules could be chosen is when the available area for solar modules is limited, yet a certain energy demand should be matched. In such cases, the customer may be willing to pay a premium for high efficiency modules and so a higher price in terms of EUR/Wp.

Efficiency as a lever to reduce cost of solar electricity

Increasing the efficiency of modules is typically achieved by increasing the efficiency of the solar cells constituting the PV module. Enhancing the efficiency of these solar cells, for example, by integrating advanced cell processing steps, often increases the cost of making these cells and thus increases the cost of the (more efficient) solar modules. However, a more efficient module will generate more power (Wp) under the same conditions[2]. If the ratio of the module cost (in EUR) over the module output (in Wp) is lower for the efficient modules as compared to less efficient modules, the efficient module has a lower production cost. However, even if the ratio (EUR/Wp) of the efficient and less efficient module is the same, the more efficient module is in most cases the better choice. This becomes clear by considering not only the module cost, but also the integral cost of a PV system.

The cost of a PV system consists of the module cost and the cost of the balance of system (BoS). The balance of system cost covers the cost for the inverter, the mounting system, the cabling, the installation, permits and planning (see also Chapter 6). The ratio between module cost and BoS cost depends on the specific PV system and may vary. Here we take as an example a cost breakdown of 2/5th for the module and 3/5th for the BoS, which is quite typical. The BoS cost often scales with system area and is only weakly dependent on the output power of the system. If we compare now

[2] Wp abbreviates for Watt peak. To compare the power output of different modules, standardized test conditions (STC) are defined. The unit for the maximum power output of the module under STC is Wp.

the two PV systems both with the same cost in EUR/Wp at module level, it becomes clear that at system level, the system with the more efficient modules is more cost competitive.

Often, the module cost is shared roughly equally between cell cost and module cost which includes costs like module glass, framing, EVA and backsheet foil. In this example, the cell cost is approximately 1/5th of the PV system cost. If doubling the efficiency would double the price of the cell, the system cost would increase by only 20% (assuming no additional cost at module and BoS level), while the module output power would double. This simplified example shows that the efficiency at cell level is a large lever to reduce the cost at system level in terms of EUR/Wp.

Another way to look at the importance of efficiency is to consider the historical learning curve for PV module, see Figure 5. To continue the learning curve, there are basically two options: one is to reduce the cost of PV modules in EUR/m^2 (with constant efficiency), for example, by improving module production efficiency, and the second is by increasing the output of the module in Wp/m^2. To fully exploit the cost reduction potential of the levelized cost of electricity from PV systems, it is important to work on both options, see for instance a recent study from Agora Energiewende.[7]

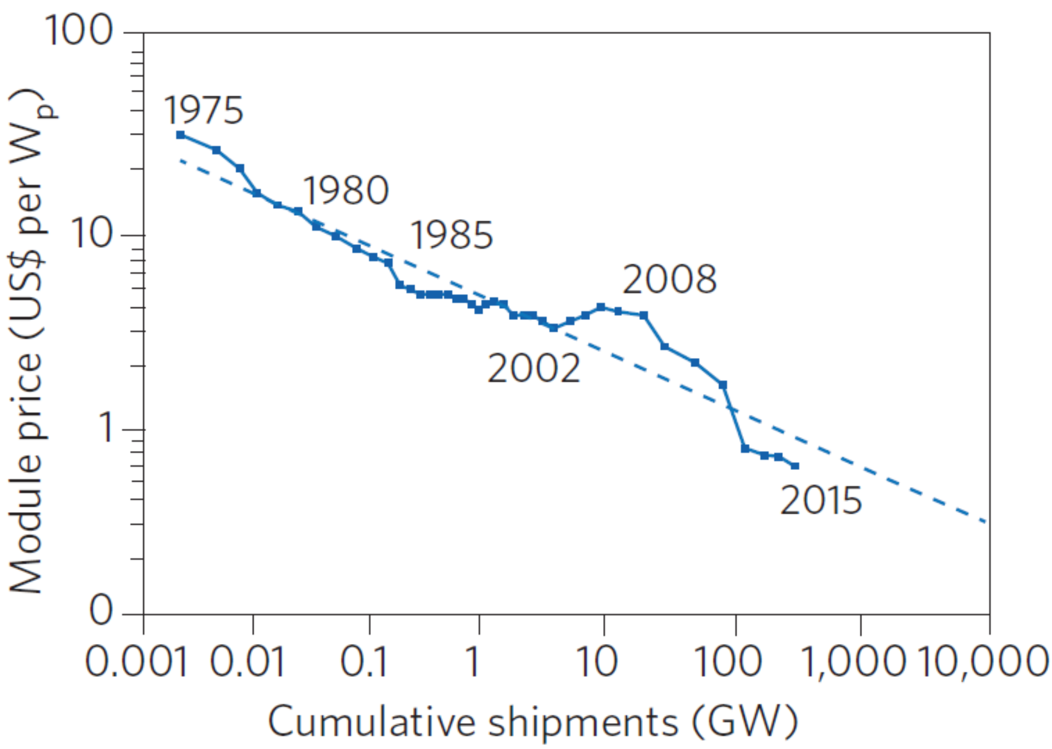


Figure 5 **Historical learning curve for PV modules. The dashed line shows the average decline in module price as a function of cumulative production, which from 1975 to 2015 has been approximately 18% for every doubling of cumulative production. Source: Sivaram 2016.**[8]

Status of PV technologies

The highest confirmed conversion efficiencies for research cells, from 1976 to the present, for a range of photovoltaic technologies is collected by NREL. The chart, as of October 2016 is depicted in Figure 6. The plot shows five semiconductor families: (1) multi-junction cells, (2) single-junction gallium arsenide cells, (3) crystalline silicon cells, (4) thin-film technologies, and (5) emerging photovoltaics.

The first group are **multi-junction devices** based on the *III-V semiconductor family*. The performance of the multi-junctions is divided into two groups: efficiencies measured under concentrated and non-concentrated light. From the graph one can see that the efficiency of III-V solar cells increases steadily with the number of junctions: 29.1 (GaAs single junction, thin film); 31.6 (dual junction); 37.9 (triple junction); 38.8 (quintuple junction). These devices come at a high cost. Applications are found when low weight and high efficiency are of main importance and cost are less of an issue.

The second group, formed of *single-junction gallium arsenide cells*, from the wider family of the so-called '*three-fives semiconductors*', result in the highest power conversion efficiencies under both one sun (AM1.5 standard test) conditions and concentrated sun conditions. GaAs, a direct semiconductor, has a band gap of 1.42 eV and adopts the zincblende crystal structure. Crystalline GaAs layers are typically produced by epitaxial growth on wafers yielding high quality crystalline films. In these films radiative decay dominates.[9]

Today the cost of making III-V cells is high compared to other commercial PV technologies like c-Si, CIGS and CdTe. There are (disruptive) innovations investigated to reduce cost, for example, by recycling the substrate (pioneered by Radboud University and now used by Alta devices), increasing the wafer size, or alternative crystal growth (aerotaxy by Sol Votaics). The recent efficiency increase achieved by Alta Devices is to a large part attributed to utilizing and optimizing photon recycling within thin film GaAs solar cells, which is also important to consider in (hybrid) tandem devices.[10]

The third group is comprised of **c-Si solar cells**. This PV technology is the most commercially successful with a dominant market share of over 75% during this century, and is currently > 90%. Various device architectures are applied. Record efficiency values are now obtained by combining c-Si/a-Si heterojunction (HIT) technology with the interdigitated back contact (IBC) cell architecture. The current record is 26.6%, held by Kaneka.[11]

Crystalline silicon has the (diamond) cubic crystal structure with a band gap of 1.12 eV. Since c-Si has an indirect band gap, a thick absorber layer is required to absorb all photons above the band gap. Long carrier diffusion lengths are therefore required to collect the generated charges and to minimize recombination losses. Commercially processed cells are based on either multi-crystalline or mono-crystalline wafers. Multi-crystalline Si wafers have a lower electronic quality due to crystal grain boundaries and intra-grain defects, as well as a higher concentration of impurities. In addition, it is more complicated to minimize reflection losses in multi-crystalline cells because of the different crystal orientations. Therefore, monocrystalline Si cells are more efficient. The Shockley-Queisser limit for c-Si is 33.3%, a practical limit, taking Auger recombination into account yields 29.4%.[12,13]

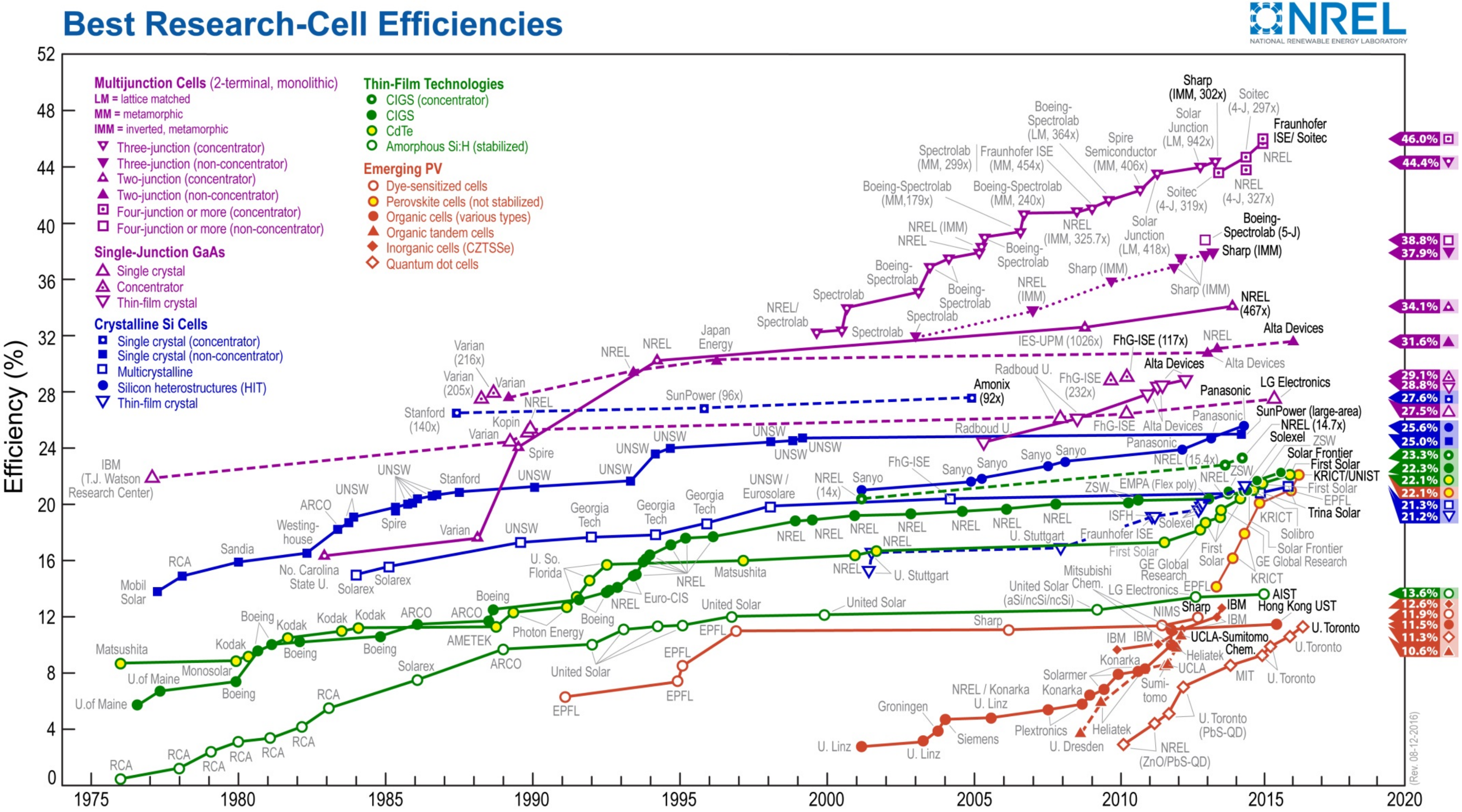


Figure 6 Solar cell efficiency chart. Cell efficiency results are provided within different families of semiconductors: (1) multijunction cells, (2) single-junction gallium arsenide cells, (3) crystalline silicon cells, (4) thin-film technologies, and (5) emerging photovoltaics. Some 26 different subcategories are indicated by distinctive colored symbols. The most recent world record for each technology is highlighted along the right edge in a flag that contains the efficiency and the symbol of the technology. The company or group that fabricated the device for each most-recent record is in bold on the plot. This plot is courtesy of the National Renewable Energy Laboratory, Golden, CO.[5]

SunPower and LG produce efficient modules based on IBC c-Si solar cells. **Fout! Verwijzingsbron niet gevonden.** compares the reported c-Si solar cell efficiency records from the NREL chart (Figure 6) with SunPower back contact (production) solar cells.[14] Clearly, SunPower is able to minimize the gap between hero lab cells and cells produced on the back contact production line for solar cells, however, SunPower expects that the practically attainable cell efficiency from the manufacturing line will be between 25 and 26%.

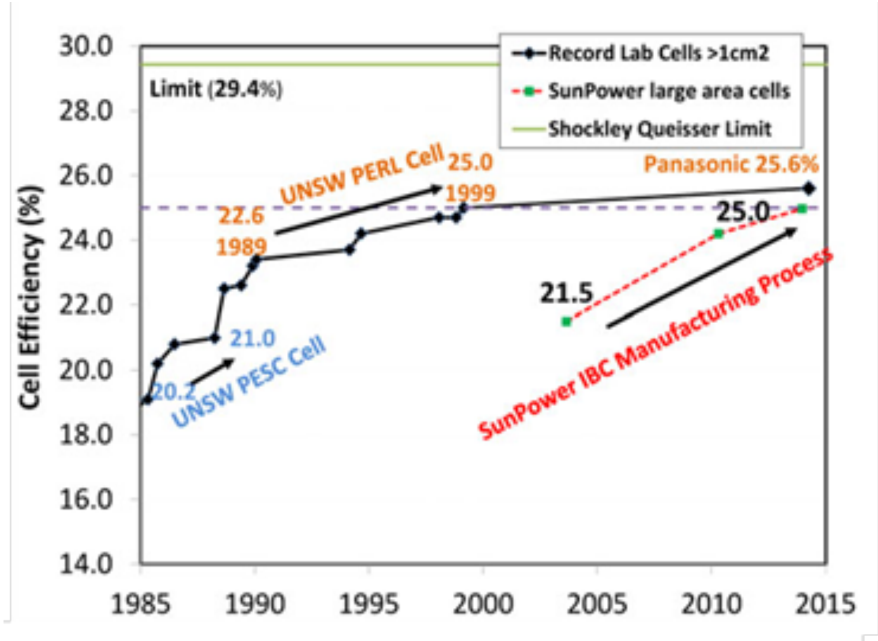


Figure 7 **Chart of silicon solar cell efficiency for lab results and SunPower back contact production solar cells. Source: Smith 2014.[14]**

Figure 8 is from the International Technology Roadmap for Photovoltaics (ITRPV).[15] The figure shows the expected development of the average stabilized efficiencies on state-of-the-art mass production lines for various types of c-Si solar cells (156 x 156 mm^2). Efficiencies are expected to increase from 18 – 23 % (2016) to 20 – 26% in 2026.

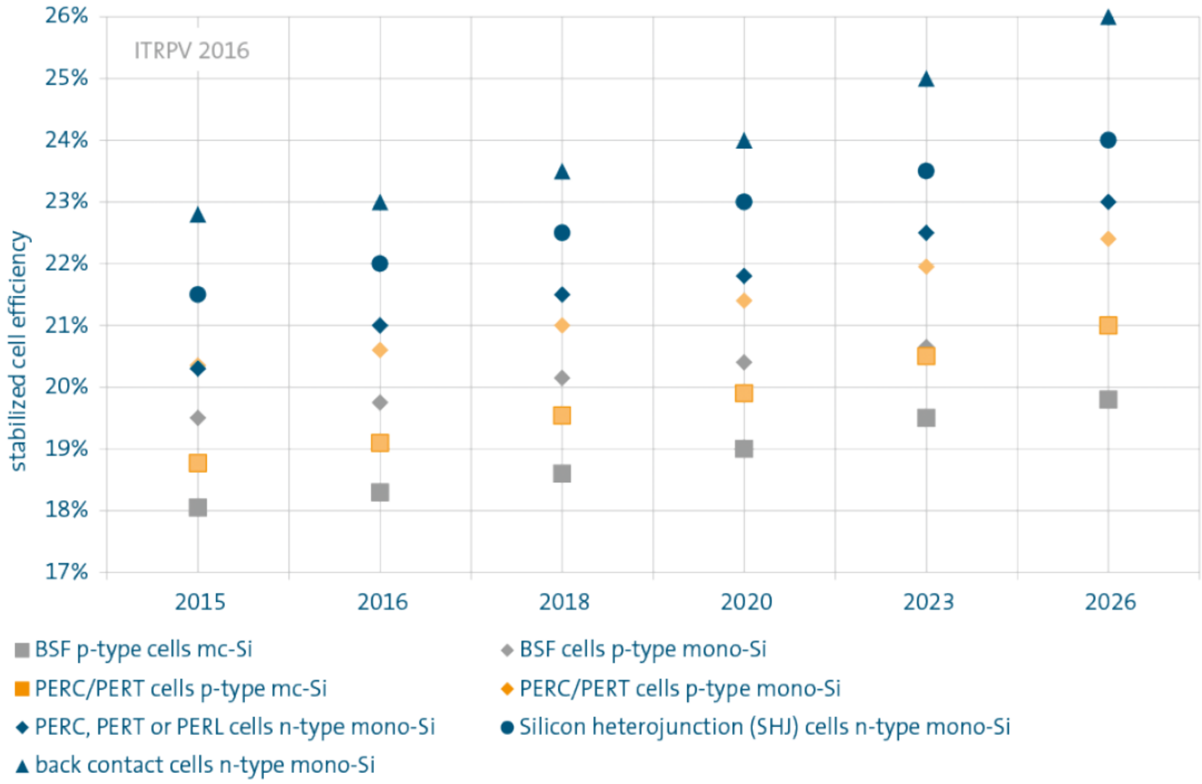


Figure 8 **Expected average stabilized efficiencies on state-of-the-art mass production lines for various types of c-Si solar cells (156 x 156 mm²). Source ITRPV roadmap.[15]**

The fourth group of the NREL chart (Figure 6) covers the **thin film PV technologies**: CdTe, CIGS and thin film Si. CdTe and CIGS have a very similar efficiency record of 22.1% and 22.3%[3], respectively.

CdTe is a direct II-VI semiconductor which, similar to GaAs, adopts the zincblende crystal structure. The band gap is 1.44 eV. Similar to CIGS (see below) the absorber layer is p-type. A pn-heterojunction is prepared by a thin CdS layer (n-type) between the transparent contact and the absorber layer. First Solar is the dominant manufacturer of CdTe solar modules. The company has a recycling scheme in place to prevent Cd compounds like CdTe and CdS entering the environment. Te, however, is a rare material and may limit the market share of CdTe solar modules in the future.

CIGS belongs to the group of the chalcopyrite solar cells based on elements from the group I-III-VI. The thin film absorber of CIGS is based on Copper Indium Selenide. To optimize the performance, the indium is partly replaced by gallium, and selenium by sulfur. By changing the composition of the absorber layer it is possible to tune the band gap of the direct semiconductor: $CuInSe_2$ (1.0 eV); $CuInS_2$ (1.5 eV); $CuGaSe_2$ (1.7 eV). The band gap of commercial CIGS is 1.1 eV. The pn-junction is formed with CdS or ZnO_xS_{1-x}. Thin film CIGS is mostly produced on glass, but commercial production also takes place on metal- and polymer foils. The annual production is currently ~1 GWp (~ 2-3% market share) and dominated by SolarFrontier.

Thin film silicon solar modules are typically prepared by plasma-enhanced chemical vapor deposition (PECVD) on rigid or flexible substrates. Thin film silicon can be doped to form a n-type or p-type

[3] ZSW announced 22.6 % in June 2016

layer, therefore it is possible to form a p-i-n structure just by changing the dopant (precursor) concentration during the PECVD deposition.

Depending on the deposition conditions, it is possible to vary the crystallinity of the absorber layer from amorphous to nanocrystalline or microcrystalline. Amorphous silicon has a band gap of 1.7 – 1.8 eV; the band gap of nanocrystalline approaches the band gap of (bulk) crystalline silicon (1.12eV). Since amorphous silicon has a relative high defect density (compared to c-Si for example) the charge diffusion/drift length limits the device thickness below the thickness required to absorb the photons above the band gap. Therefore, light management techniques are typically incorporated in the device structures. Although nanocrystalline silicon has a lower defect density, a thicker film is required to compensate for the lower absorption cross-section close to the band gap and light management remains important to optimize the carrier collection efficiency.

Band gap tuning from ~1 – 2.7 eV is possible by blending thin film Si with foreign elements like Ge, C and O. Multi-junction thin film silicon modules have been developed for example, by combining amorphous Silicon with nanocrystalline Silicon. The record efficiency of silicon single junction cells is 11.8% and 13.6% for a triple junction. In 2015 the annual production was around 0.6 GWp.

The fifth group is formed by the **emerging PV technologies**. These technologies include dye-sensitized solar cells (DSC), organic photovoltaic devices (OPV), quantum dot devices (QD) and perovskite solar cells. *Dye-sensitized solar cells* are based on dye molecules which cover a highly porous TiO_2 layer. When light is absorbed by the molecular dye, an electron is injected from the dye into TiO_2. The dye is in electrical contact with a solid or liquid electrolyte to close the electrical circuit. Best DSC cells reach about 12%. Color tuning is possible. Commercial activities exist on a relatively small scale (<<1GWp). Stable device operation is a concern.

Organic photovoltaic devices (OPV) reach similar efficiencies as DSC (12% in single junction devices). The technology is suitable for fast, roll-to-roll production of flexible solar modules. The two dominant deposition methods are thermal evaporation in vacuum chambers and solution processing such as slot-die coating and inkjet printing.

Due to the low dielectric constant of organic materials, a bound electron-hole pair is generated after light absorption. This bound e^- - h^+ pair can be separated at a donor / acceptor interface. The process is very efficient, however, the loss in potential found in many OPV devices is high compared to efficient inorganic solar cells. Commercial production of OPV, often integrated in various products, is expected in the coming years by, for example, Armor, Belectric, CSEM Brasil, Eight19, Heliatek and Mitsubishi. Best performing OPV devices make use of a multi-junction cell architecture. Device stability has improved significantly over the last years: outdoor stability has been proven for several years and indoor, accelerated lifetime tests indicate several decades.

Quantum dot (QD) solar cells are often based on PbSe or PbS. Often the QDs contain ligands to increase the solubility of the QDs in organic solvents. This enable deposition of the QDs by solution process methods like spin coating. Once the films are formed, the ligands are removed (for example through a thermal process) to improve the electrical contact between QDs. Optical properties can be tuned by changing the quantum dot dimensions. QD solar cells are at the early stages of development. Best performing devices reach 10%.

The reported efficiencies of *Perovskite Solar Cells (PSC)* have increased from below 4% in 2009, to 22 % in 2016.[5] The efficiency of perovskite hero cells of 22.1 ± 0.7% is thus on par with the hero cell efficiencies of commercial PV technologies like CIGS, CdTe (21.1 ± 0.5%) and multi-crystalline Si. It should be noted that these values should be compared with care. The hero cell device areas can vary over many orders of magnitude: for the perovskite it is 0.046 cm^2, whereas for the mc-Si cell it is 242.74 cm^2. Also, the perovskite solar cell efficiency is difficult to measure and is earmarked as 'not stabilized' in the NREL efficiency chart. This is due to the hysteresis often observed for these solar cells and, at least partially, attributed to mobile ions/vacancies. The hysteresis complicates the efficiency measurement as the current-voltage curve depends on the scan direction and scan speed. Within the perovskite community it is therefore also common to report the so-called 'stabilized efficiency'.

The most used perovskite material applied in (laboratory) solar cells is methylammonium lead tri-iodide (MAPI) with a band gap of 1.55 eV. To further explore the potential of perovskite solar cells several groups have modified the perovskite composition. For example, replacing the iodide by a smaller halogen such as bromide or chloride increases the band gap. The methylammonium cation may be replaced by another organic cation like formamidinium or inorganic elements like Cs or Rb. The Pb ion can be partially substituted by Sn to reduce the band gap to 1.2eV

The stability of PSCs is currently insufficient to withstand the typical minimum lifetime of industrial PV modules of 25 years outdoors. The most important stress factors have been identified (temperature, light, O_2, $H_2 0$, electrical stress), and mitigation measures are being developed. Also, the environmental profile of perovskite solar cells is a concern since the material typically contains Pb. More work is needed to assess the associated risks and possible counter measures, that can be arranged during the full life cycle of PSCs.

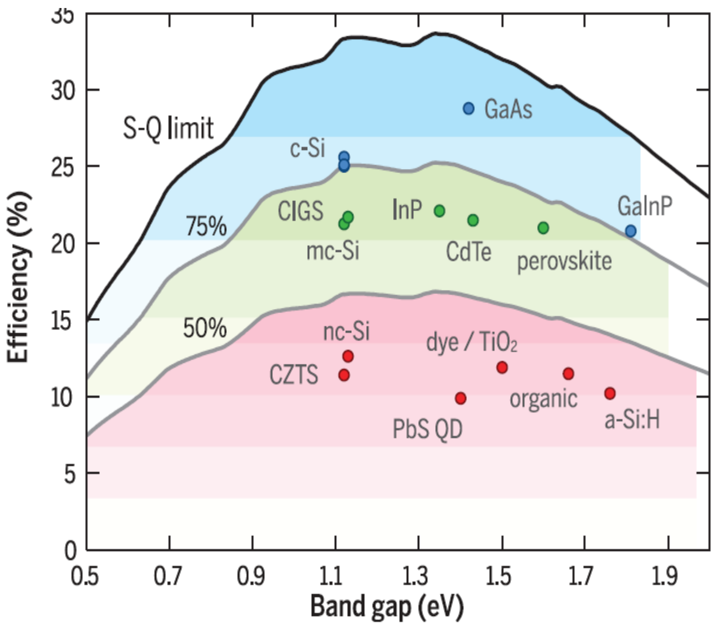


Figure 9 **Theoretical Shockley-Queisser detailed-balance efficiency limit as a function of band gap (black line) and 75% and 50% of the limit (gray lines).The record efficiencies for different materials are plotted for the corresponding band gaps. Source: Polman 2016.[13]**

Figure 9 represents the record efficiencies of the different PV technologies versus the band gap energy. Also included in the graph is the theoretical Shockley-Queisser (S-Q) detailed balance limit as a function of the band gap (bold black line). This provides an upper limit for the cell performance. Two grey lines indicate 75% and 50% of the S-Q limit.

It is interesting to note that the III-V semiconductors and (mono) c-Si can perform relatively close to the S-Q limit. The record cell efficiencies of other commercial PV technologies are in the range of 50 – 75% of the SQ limit. In this green area we find mc-Si, CIGS, InP, CdTe and perovskite solar cells. The record efficiencies of the emerging PV technologies are typically below 50% of the S-Q limit. Of the emerging PV technologies, perovskite solar cells are the only technology of which the record cell is close to 75% of the S-Q limit.

This is important, since the first techno-economic analyses show that hybrid tandem solar cells should be based on ‘marriage of equals’. So based on two sub-cells with a close to ideal band gap combination; similar performance of the sub-cells with respect to the Shockley-Queisser limit, similar lifetimes; similar cost (in terms of EUR/Wp) for both sub-cells, and in particular, low cost related to each sub-cell (e.g. the c-Si cell or the thin film layer stack) compared to common module and system costs. Finally, it is important to minimize redundant layers (glass plates, EVA, barriers etc.) when combining two PV technologies in hybrid tandems.[16]

Approaches to increase the efficiency of solar cells

From the previous section it is clear that most solar cells made today have efficiencies typically well below 25%. Figure 10**Fout! Verwijzingsbron niet gevonden.** provides a breakdown of the energetic (light blue) and entropic (dark blue) losses occurring in a GaAs solar cell with an efficiency of 28.3% [4], indicated as the green area in the graph. Only a small fraction of these losses are intrinsic losses, the dominant loss is due to thermalization of photo-generated charge carriers or lack of absorption because of a poor match of the absorption spectrum of the absorber material with the solar spectrum. By application of multi-junction structures it is possible to reduce these loss factors and increase the efficiency of solar cells significantly.

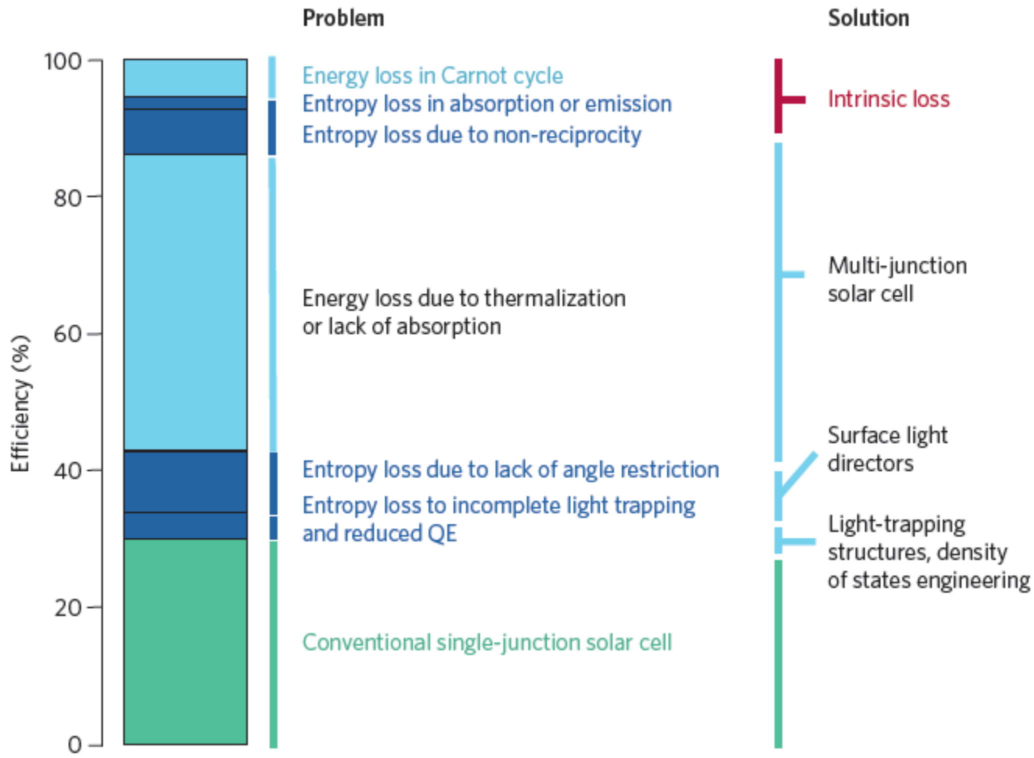


Figure 10 Thermodynamic losses in solar-energy conversion in a conventional single-junction GaAs solar cell of 28.3% [4] (indicated in green. Dark blue bars indicate entropy-related losses and light blue bars indicate energy-related losses. The main energy loss is due to thermalization and lack of absorption. The solutions for reducing the entropy- and energy-loss problems are listed in the right-hand column. Source: Atwater 2012.[17]

The Shockley-Queisser limit, or detailed balance limit, is often used to determine the efficiency limit of a solar cell with a certain band gap.[18] The Shockley-Queisser limit, as described in the original paper makes several assumptions, including:

1. The only recombination mechanism for hole-electron pairs is radiative recombination
2. Each photon incident on the surface of the absorber material with a photon energy larger than the band gap[5] will produce an electron-hole pair
3. Thermal relaxation of the electron–hole pair energy in excess of the band gap
4. Illumination with unconcentrated sunlight (AM1.5)

[4] Currently the record efficiency of GaAs single junction solar cells measured under standard test conditions with one sun intensity is 28.8%.

[5] The Shockley-Queisser limit was originally written for a single junction solar cell

These assumptions need not (all) apply, which opens the possibility to surpass this basic limit. For an extensive overview reference see reference.[19] The second assumption can be circumvented by adding different band gaps as is the case in multi-junctions. It is also possible to generate two photons from a single, high energy photon (quantum cutting). Or the inverse process: 'adding' two low energy photons to generate one high energy photon (quantum pasting).[20,21] Another way to bypass the limit is by generating more than one exciton from a single, high energy photon. This multiple exciton generation (MEG) process has been observed in PbSe quantum dots and nanorods.[22] It is also possible to prevent the thermal relaxation of the electron–hole pair by singlet fission. In this process the (high energy) singlet state is split into two triplet states which are subsequently split in mobile charge carriers.[23] Another elegant approach is the intermediate band gap solar cell. In these – mostly conceptual – solar cells, an intermediate energy level is present inside the band gap of the absorber material between the valence and conduction bands. In this way a kind of 'internal tandem cell' is created. Using the intermediate band, two photons with energy less than the band gap are capable to exciting an electron across the band gap.

Other options to reduce efficiency losses include, for example, light concentration/emission angle restriction. It is also important to note that concentrated PV only harvests the direct component of the sunlight and therefore does not necessarily translate into a higher annual yield.

With the exception of multi-junctions and concentrated PV, the above-mentioned options to go beyond the Shockley-Queisser limit are at the early stages of development, see also Figure 10.

3. Hybrid tandems

This section describes the structure of hybrid tandems. It explores the efficiency limits of hybrid tandems and also describes published results on the annual yield of hybrid tandems. At the end of the section the differences between the two main hybrid tandem device architectures (2-terminal and 4-terminal) are summarized.

Make more efficient use of the solar spectrum

Tandem solar cells contain more than one photon absorber layer. If the two or more absorber layers have different band gaps, it is possible to go beyond the Shockley-Queisser limit.[18] This can be seen from Figure 11. When a conventional, single junction solar cell is illuminated by the solar spectrum, only those photons with sufficient energy can excite an electron to the conduction band, as given by the equation: $h\nu \geq E_g$, where E_g is the band gap energy, *h* is Planck's constant and ν is the frequency of light.

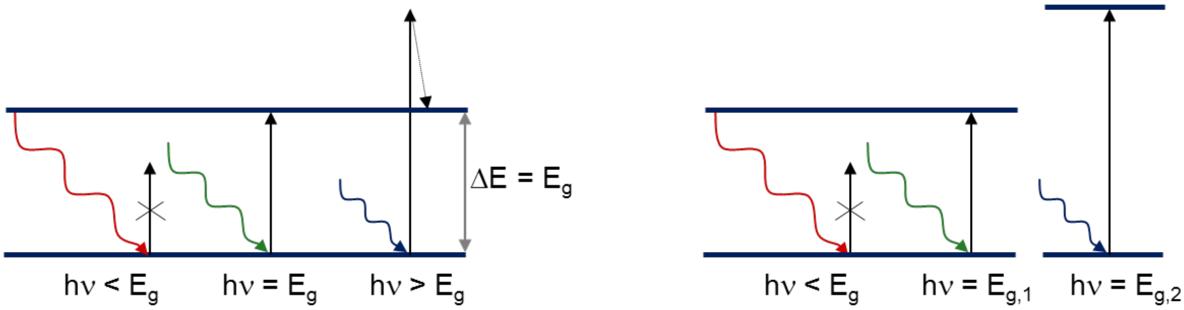


Figure 11 **Schematic representation of a single junction solar cell (left) and a tandem solar cells (right).**

The long wavelength photon indicated in red (left) in Figure 11 has insufficient energy to cross the band gap. The photon is not absorbed by the semiconductor and will not generate a charge carrier. This photon is lost and will not contribute to the efficiency of the solar cell. The photon indicated in green has just enough energy to bridge the gap. The 'blue' photon has enough energy to excite an electron to a higher, unoccupied energy level. This 'hot' electron in the higher energy level will quickly relax to the bottom of the conduction band often under the emission of phonons. This relaxation energy is therefore lost as thermal energy, thus, thermalization loss.

The schematic representation of the tandem device shows two semiconductors whereby the band gap of the second absorber layer is equal to the photon energy of the 'blue' photon. This allows for the high energy photon to be absorbed, the excited electron to be collected, a higher voltage to be produced, and thermalization losses to be avoided. The absorption by the high band gap material means that the photon does not reach the lower band gap material. This has the effect that the current generated in the low band gap material is lower than it would have been previously in the single junction cell (Figure 11, left). Ideally, the sum of the currents generated in both sub-cells on the right is equal to the current generated in the single junction cell (left). The longest wavelength photon in this example still has insufficient energy and is not absorbed by either material. This could be solved by adding a third absorber material in the multi-junction (triple-junction) with a band gap matching the energy of the low energy photon. A combination of both the prevented thermalization loss and the better overlap with the solar spectrum contributes to the higher efficiency of multi-junctions over single junctions.

Tandem device structures

A typical tandem device structure is depicted in Figure 12. The solar spectrum impinges on the top cell of the tandem. In this top cell, the high energy or 'blue' part of the solar spectrum is absorbed. Photons with energy below the band gap of the top cell are transmitted to the bottom cell where a large fraction of the 'filtered' solar spectrum is absorbed.

The inset in the graph show the AM1.5 solar spectrum. The blue filled area indicates the energy available for harvesting by a top cell with a band gap of ~ 1.7 eV; the red area indicates the remaining energy available for harvesting by the bottom cell. The top and bottom cells can be connected in series within the device. In this case the tandem has two terminals (2T). The two sub-cells can also be electrically separated from each other, this leads to a four terminal device (4T), see also Figure 14.

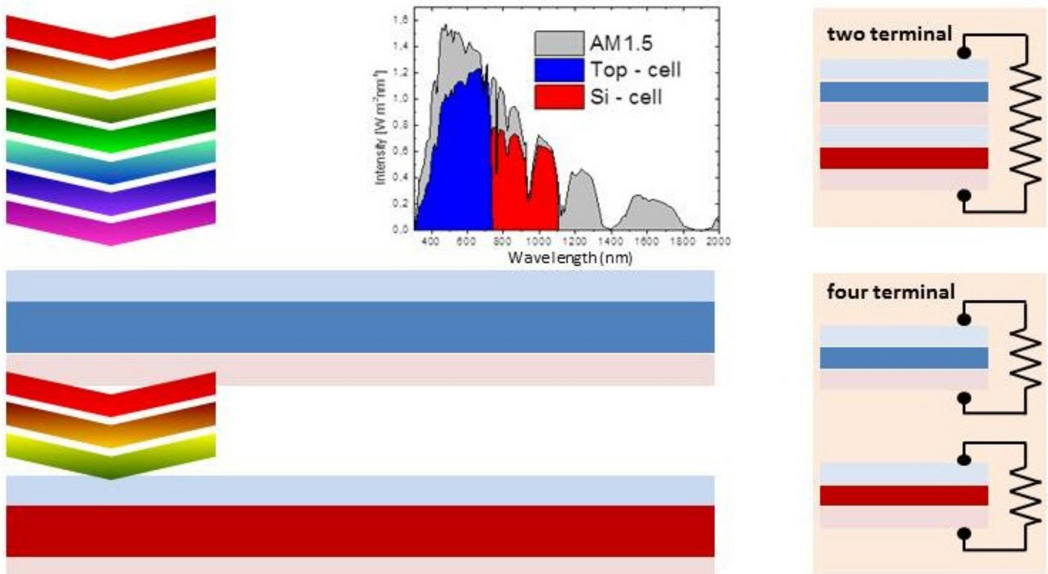
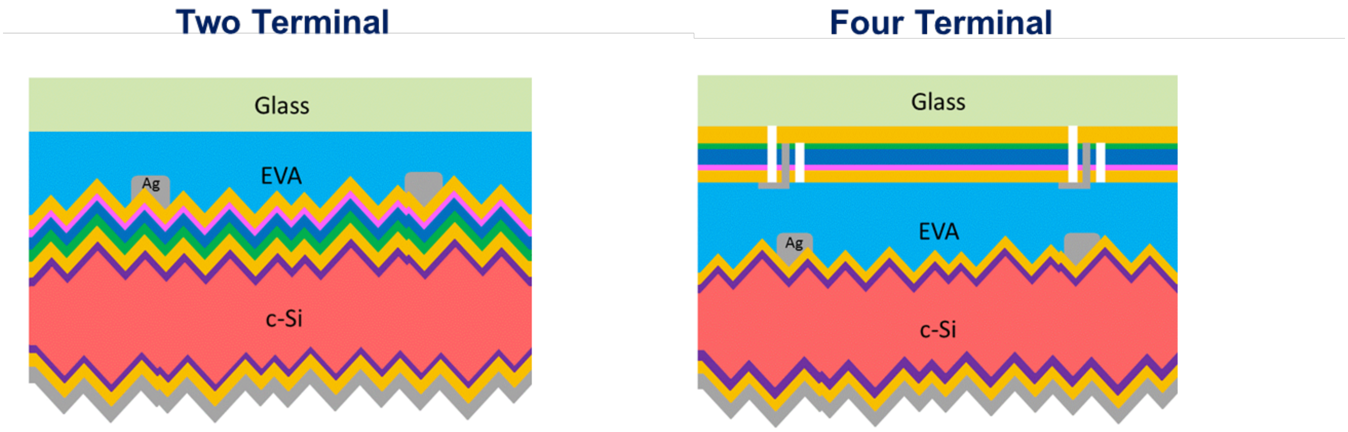


Figure 12 Representation of a tandem solar cell. The top cell absorbs the blue part of the solar spectrum, the bottom cell absorbs the red part of the spectrum. The inset gives the AM1.5 solar spectrum and the parts which can be harvested by the top cell (blue) and bottom cell (red). Connection schemes for two terminal (2T) and four terminal (4T) connections are indicated.

In case of a series connected tandem cell, the generated current in the top and bottom cell need to match as both cells are series connected. The contact between the two sub-cells is often formed by a recombination layer (the electrons extracted from one subcell have to recombine with the holes extracted from the other subcell), which can be very effective and highly transparent, so without significant resistive or voltage losses. The 'current matching' requirement has important consequences for the design of the complete stack of layers applied in the 2T tandem cell. Typically the optimization of the complete stack is done using optical modeling tools.

A 2T configuration is not the only way to realize a tandem. By inserting two extra electrodes between the top and bottom cell the degrees of freedom to design efficient tandems increases as the current matching constraint is removed, see Figure 13



. In a 4T device identical sub-cells can be wired at the module level in either current or voltage matched configurations (including multiple cell combinations, for example, two bottom cells matching the voltage of a one top cell)[24]. Often, the top and bottom cells are independently operated so that the sub-cell powers add without restriction. Modules based on 4T devices may be fabricated monolithically, like 2T cells, or they can be assembled by making the sub-cells on separate substrates, then laminating them together to form a mechanically stacked device. The disadvantage of a 4T design, however, is that more light in the near infrared portion of the solar spectrum is lost due to (parasitic) absorption in the additional electrodes.[25]

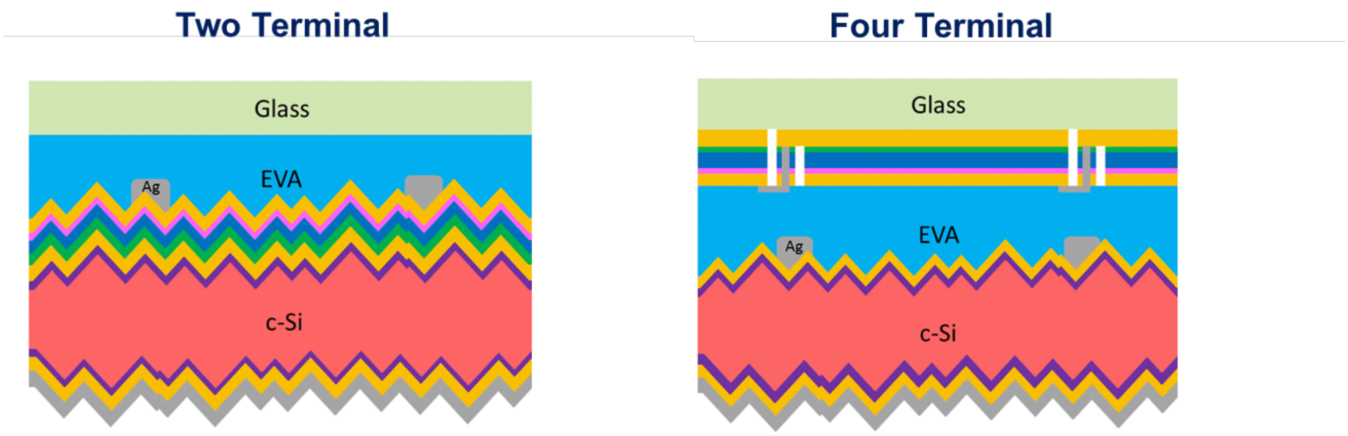


Figure 13 Schematic representation of a two terminal and four terminal tandem device structure based on a thin film top cell and a c-Si bottom cell.

Efficiency limits

The Shockley Queisser detailed balance limit can also be applied to determine the efficiency limit of tandem devices. Vos reported on these calculations in 1980, the result is given in Figure 14.[26] The optimum combination of band gaps is 1.0 and 1.9 eV resulting in a calculated efficiency limit of 42%.[6]

[6] When the AM1.5G spectrum is used, instead of a black body at 6000K, the calculated efficiencies are slightly higher: 46% for a band gap combination of 0.94 eV and 1.73 eV for in 4T configuration.[27]

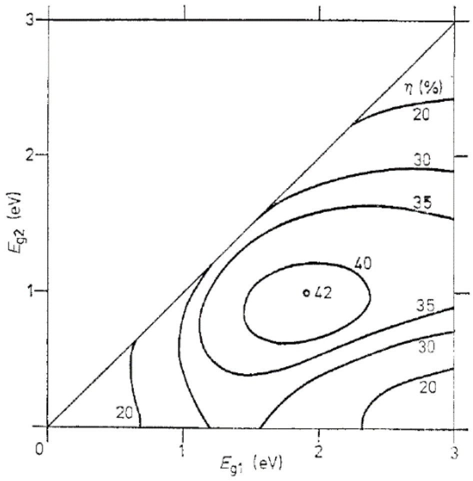


Figure 14 **Limiting efficiency η (%) of a tandem as a function of the two semiconductor band gaps $E_{g,1}$ and $E_{g,2}$.[26]**

Bremner et al. made similar calculations for multi-junctions, illuminated by the AM1.5G spectrum, instead of the emission spectrum of an ideal black body at 6000 K. The optimum band gap combinations (closed symbols) together with the limiting efficiency (open symbols) for multi-junction solar cells with 1-5 band gaps are given in Figure 15 for unconstrained (black) and constrained devices (current matched, red symbols).[27]

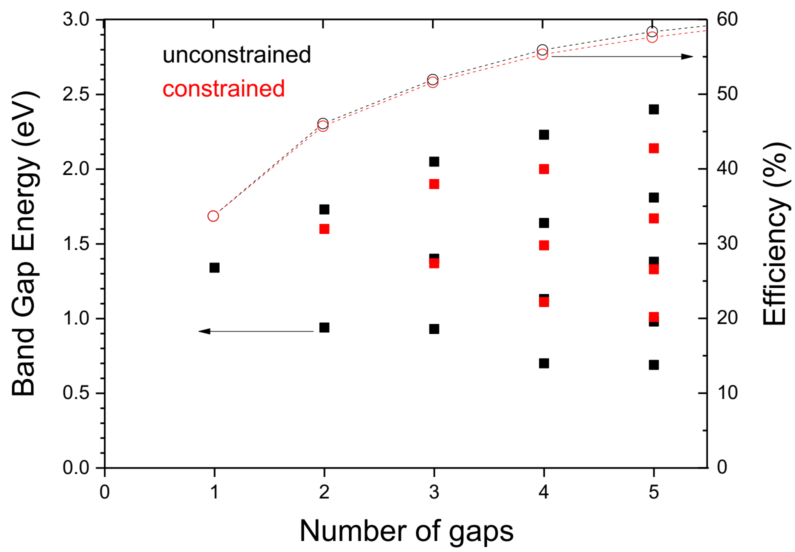


Figure 15 **Closed symbols give optimum bang gap combination for multi-junction cells with 1-5 band gaps, under one sun (AM1.5G), for unconstrained (filled black squares) and constrained or current matched multi-junctions (filled red symbols). The open symbols give the corresponding efficiency limit for unconstrained (black) and constrained multi-junctions. Data from reference [27].**

As can be seen from Figure 16, the theoretical difference in maximum attainable efficiencies between 4T and 2T tandems is small. According to Brown et al. this normalised difference is not more than 1.5% relative for a 10 sub-cell multi-junction if the cell stacks contain optimal band gap combinations, and for a tandem with 2 sub-cells is only 0.5% relative.[28]

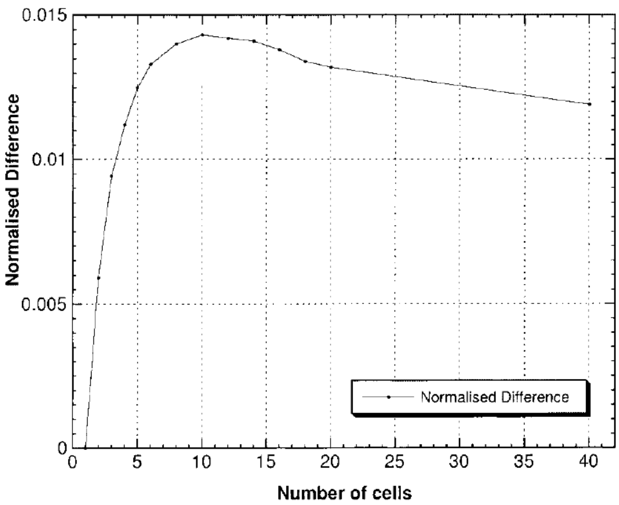


Figure 16 Normalized difference in efficiency potential of unconstrained (four terminal) and current constrained (two terminal) multi-junctions, versus the number of cells. Source: Brown 2002.[28]

Annual yield

The efficiency of a PV module or PV system is not the only parameter which determines how much electrical power a PV module ($\boldsymbol{E_{DC}^{Y}}$) or PV system will generate annually at a certain location. The efficiency of solar devices is measured under standard test conditions (STC) with a fixed irradiance spectrum and temperature. A module in the field operates under a range of conditions with varying temperature and irradiance (intensity, spectrum, angle of incidence).

The yearly or annual energy yield of a module (E_{DC}^{Y} in Wh/year) is:

$$\boldsymbol{E_{DC}^{Y}} = \int_{year} \boldsymbol{P_{DC}(t)\mathrm{d}t}$$

Equation 1

Where $P_{DC}(t)$ is the instantaneous power output of the (hybrid tandem) module. Note that P_{DC} depends on i) the module area (A_{module} in m^2), ii) module efficiency (η_{module} in %) which, as mentioned above, depends on the module temperature (T_M in K) and the irradiance spectrum incident to the module (G_M in W/m^2). Therefore:

$$\boldsymbol{P_{DC} = \eta_{module}(T_M, G_M)G_M A_M}$$

Equation 2

The yearly (annual) DC electricity yield of the module (Y_E in kWh/(year W$_p$)) is:

$$\boldsymbol{Y_E = \frac{E_{DC}^{Y}}{P_{STC}}}$$

Equation 3

Where P_{STC} is the nominal power output of the module under standard test conditions (STC) in W$_p$.[9]

In equation 3, P_{STC} is well defined; E_{DC}^{Y} is given by integrating the power from the module ($P_{DC}(t)$) during a year at a specific location. The instantaneous power generated by the module depends on the local parameters: T_M, G_M which can change widely during a year. How the module responds to these changing conditions is determined by the material properties of the cells and module and the cell and module architecture.

To further discuss the temperature and irradiance dependence, we consider a tandem cell as part of a hybrid tandem module, each sub-cell of the tandem cell has a certain temperature coefficient. The coefficient describes how the sub-cell performance deviates from the performance under standard test conditions (P_{STC}) when (only) the module temperature (T_M) deviates from 25 °C. For nearly all solar cells the temperature coefficient is negative, consequently, the performance of the sub-cell decreases with increasing temperature. Figure 17 gives an example of the influence of a temperature increase on the *I-V* curve of a typical solar cell. As can be seen from the figure, a temperature increase from STC results in small increase in short circuit current and a relatively large decrease in the open circuit voltage. As a rule of thumb, the larger the band gap, the smaller (closer to 0) the temperature coefficient.

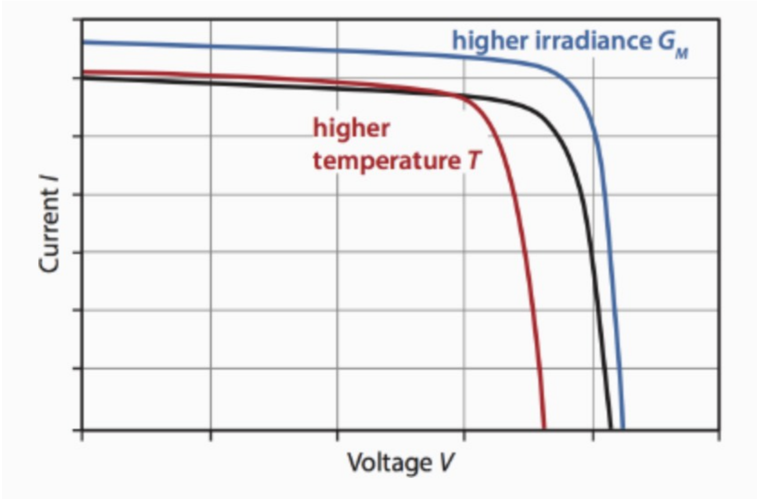


Figure 17 Effect of an increase in temperature (*T, red curve*) or irradiance (G_M, blue curve) on the I-V curve of a solar cell. The black curve represents the curve measured under standard test conditions. Source: A. Smets et al.[9]

An increase in irradiance, or more precisely light intensity, results in a concurrent increase in short-circuit current and open circuit voltage. The short circuit current depends roughly linearly on the light intensity ($I_{SC}(25°\mathrm{C}, G_M) = I_{SC}(STC)\frac{G_M}{G_{STC}}$), whereas the voltage has a logarithmic dependence ($V_{OC}(25°\mathrm{C}, G_M) = V_{OC}(STC) + \frac{nk_BT}{q}\ln\left(\frac{G_M}{G_{STC}}\right)$), where n is the diode ideality factor, k_B the Bolzmann constant, q the elementary charge and G_{STC} the irradiance corresponding to the STC.

As discussed in the section 'Tandem device structures', the top and bottom sub-cells of a tandem cell can be wired in series (constrained or two terminal configuration, 2T), or independently contacted (unconstrained or four terminal configuration, 4T), see Figure 13. When the sub-cells are contacted separately (4T configuration), the efficiency of the tandem cell is simply the sum of the efficiencies of the top and bottom cell. Note, the irradiance spectrum of the bottom cell ($G_{M,BC}$) is determined by the irradiance spectrum (G_M) and the transmission of the top cell. The power generated by the unconstrained tandem cell ($P_{tandem\ cell}$) is thus:

$$\boldsymbol{P_{tandem\ cell,4T} = \eta_{tandem\ cell}(T_M, G_M)G_M A_c = \eta_{TC}(T_M, G_M)G_M A_{TC} + \eta_{BC}(T_M, G_M)G_M A_{BC}} \qquad \textbf{Equation 4}$$

where A_{TC} and A_{BC} is the area of the top and bottom cell respectively.

The situation for a constraint or 2T tandem cell differs. The current matching constraint dictates that the current through the top (I_{TC}) and bottom cell (I_{BC}) are equal ($I_{tandem\ cell}$). To a first approximation, this means that the current of the tandem is determined by the sub-cell which generates the lowest current. Furthermore, the open circuit voltage of the tandem cell ($V_{OC,tandem\ cell}$) is the sum of the open circuit voltages of the top ($V_{OC,TC}$) and bottom cell ($V_{OC,BC}$). The fill factor of the tandem cell ($FF_{tandem\ cell}$) can be between the fill factors of the two sub-cells (FF_{TC} and FF_{BC}) and often $FF_{tandem\ cell}$ is determined by the current limiting sub-cell.

$$\boldsymbol{P_{tandem\ cell,2T}(T_M G_M) = \eta_{tandem\ cell}(T_M, G_M)G_M A_{tandem\ cell}}$$

$$\boldsymbol{= (V_{OC,TC} J_{SC,TC}\, FF_{TC})_{T_M,G_M} A_{tandem\ cell} + (V_{OC,BC} J_{SC,BC}\, FF_{BC})_{T_M,G_M} A_{tandem\ cell}}$$

$$\boldsymbol{= (J_{SC,tandem\ cell} FF_{tandem\ cell} A_{tandem\ cell})_{T_M,G_M}(V_{OC,TC} + V_{OC,BC})_{T_M,G_M}} \qquad \textbf{Equation 5}$$

Where $A_{tandem\ cell}$ corresponds to the area of the tandem cell and $J_{SC,tandem\ cell}$ is the current density of the 2T tandem which has the following constrained:

$$J_{SC,tandem\ cell} = Min(J_{SC,TC}\ ,\ J_{SC,BC}) \qquad \textbf{Equation 6}$$

Below we consider two cases where the operation conditions of a tandem deviate from the standard test conditions:

$T_M > T_{STC}$

For a 4T tandem, the generated power of the tandem cell remains the sum of the two sub-cells; temperature induced changes to the IV parameters of either sub-cell do not influence one another. For a 2T tandem, the temperature coefficients of both sub-cell are likely to be different. The reduced open circuit voltages of both sub-cells are included separately in equation 5. However, the module temperature will also affect the current generated in each sub-cell. The current increase is likely to be different for either sub-cell and the change in current of the tandem may be smaller than the change in current of one of the two sub-cells. This may result in a larger efficiency loss for a 2T tandem as compared to a 4T tandem cell because of the current constraint (equation 6). It should be noted, however, that in general, the temperature only has a weak influence on the current. Therefore, if the module temperature deviates from standard test conditions it causes only a small difference in efficiency between 4T and 2T tandem. See, for example, Figure 22.

$G_M > G_{STC}$

Increase in intensity - no change in the spectral shape of the irradiance spectrum

In a 4T tandem, the efficiency remains the sum of the two sub-cells; irradiance induced changes of the ***IV*** parameters of either sub-cell are, to a first approximation, not correlated to the ***IV*** parameters of the other sub-cell since the sub-cells are independently contacted.

When an efficient 2T tandem receives a higher light intensity, the current increases proportionally in both cells. Also, the voltages of both sub-cells will increase. The FF of the tandem may remain the same or show a small decrease. The performance of a 4T and 2T terminal tandem will respond in a very similar way to a change in light intensity.

Change in the spectral shape - no change in intensity of the irradiance spectrum

A change in the shape of the irradiance spectrum is likely to cause a change in the overlap between the absorption curves of the sub-cells and the irradiance spectrum. This will typically result in a different ratio between the current generated in the top and bottom cell. For efficient 2T tandems, this ratio is close to 1 under G_{STC} and a significant deviation results in a loss in performance as the current of the 2T tandem will be equal to the lowest photocurrent generated in either the top or bottom cell (equation 6). This constraint is absent in a 4T tandem and therefore the 4T tandem may be more efficient compared to a 2T tandem when the spectral shape of the irradiance curve deviates from the defined irradiance spectrum (G_{STC}) for standard test conditions. Deviations from the standard solar spectrum can arise for a variety of reasons, such as:

- Atmospheric conditions (i.e. the concentration of water vapor in the atmosphere),
- Optical path length of the light through the atmosphere, and
- The ratio between direct and indirect sunlight

Below the second point is further discussed.

Figure 18 illustrates how the local solar spectrum, or local irradiance spectrum, is affected by the distance the light has to travel through the earth's atmosphere. This is described by the 'air mass' (AM), expressed as the ratio of the optical path length relative to the path length vertically upwards, i.e. at the zenith.[29] With increasing air mass the intensity of the solar spectrum deceases and the maximum shifts to higher wavelength. Note, the solar irradiance curve used for standard test conditions (G_{STC}) corresponds to an air mass of 1.5 (AM1.5) and an integrated intensity of 1000 W/m^2.

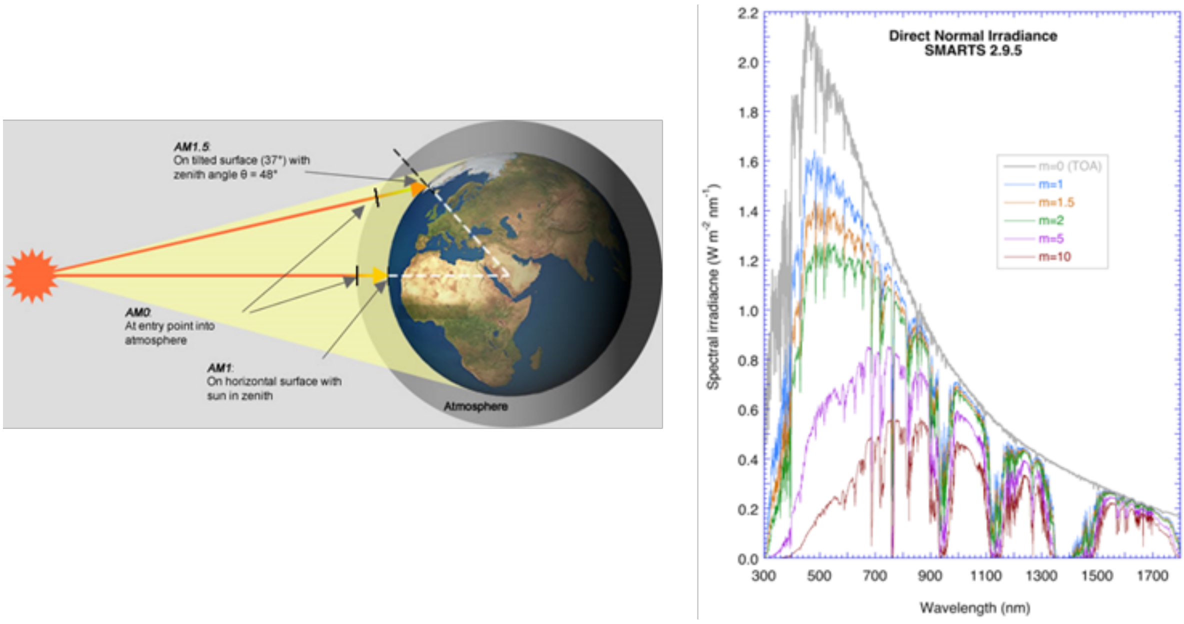


Figure 18 **The local direct 'solar spectrum' is affected by the optical path length the light has to travel before hitting a surface (left). With increasing air mass, the AM spectrum shifts to the red and the overall intensity is reduced (right).**

Fout! Verwijzingsbron niet gevonden. reveals how the (theoretical) efficiency of 2T multi-junction cells depend on the spectral shape of the irradiance curve expressed in air mass. As can be seen, the multi-junction cells are optimized for the AM1.5 spectrum. When the spectrum deviates from this air mass value, the efficiency drops quickly. For example, the efficiency of a 20 cell 2T tandem drops from 64.6% (AM1.5) to 12.6% when illuminated with an AM10 spectrum. For an unconstrained tandem, the efficiency 'only' drops from 64.9 % (AM1.5) to 52.8% (AM10).

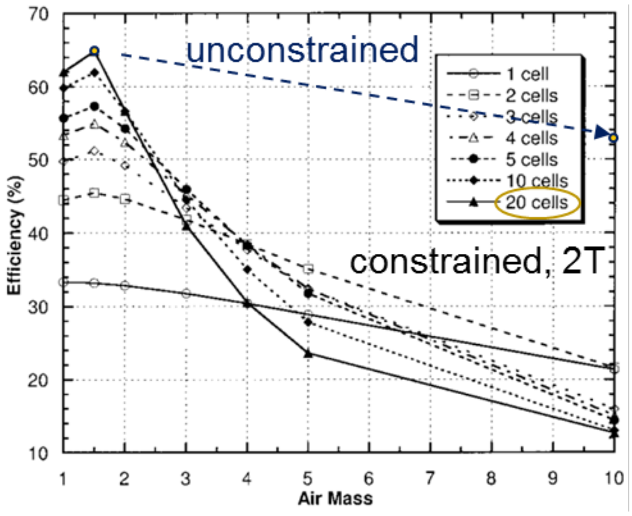


Figure 19 (Theoretical) Efficiency for the AM15G optimized cell under various global irradiance solar spectra. Source: Brown 2002.[28]

It is important to note that, as the air mass of the solar spectrum increases, the integrated energy decreases (see Figure 18). So, during the periods of the day with high air mass values there is only a limited amount of solar energy to harvest. In addition, during a day the high air mass values are only reached for a brief period during dusk and dawn. During these periods, the 4T tandem is (theoretically) more efficient compared to a 2T tandem.

Before discussing how this difference in spectral sensitivity leads to differences in yearly energy yield, it is useful to introduce the term 'average photon energy' (APE):

$$\boldsymbol{APE} = \frac{\int_{\lambda 1}^{\lambda 2} \boldsymbol{I}(\boldsymbol{\lambda}) \boldsymbol{d\lambda}}{\int_{\lambda 1}^{\lambda 2} \boldsymbol{\Phi}(\boldsymbol{\lambda}) \boldsymbol{d\lambda}} \qquad \textbf{Equation 7}$$

where $I(\lambda)$ is the wavelength resolved intensity distribution of a spectrum, and $\Phi(\lambda)$ is the wavelength resolved photon flux density.[30] The APE indicates how 'red' or 'blue' a certain spectrum is. Figure 20 gives examples of measured irradiance spectra of Singapore (a) and Denver (b).

Using the measured irradiance spectrum and the optical parameters of all layers in the tandem device, it is possible to calculate an absorption profile in the active layers of the sub-cells of a tandem. With these profiles it is possible to calculate the $\boldsymbol{IV}$ curves and determine the energy from the tandem cell. Repeating this procedure for every measured spectrum, the time-resolved power output is obtained. The annual or yearly energy yield is simply the integration of the power output over the period of one year.[30]

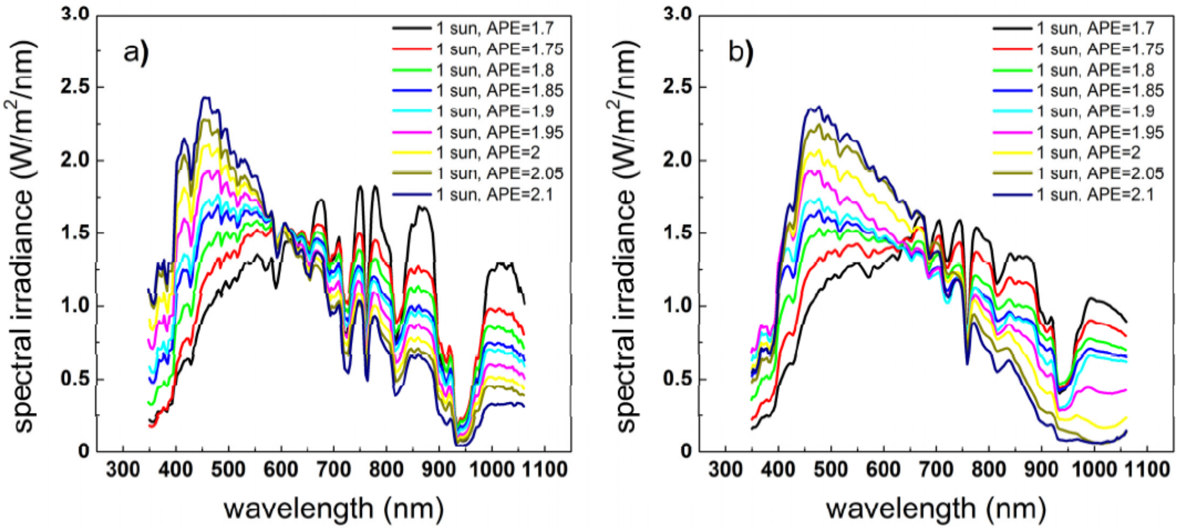


Figure 20 **Spectra with different spectral composition in (a) Singapore and in (b) Denver, characterized by different APE ranges (values in the figure indicate the left bound of an interval). These spectra are obtained from averaging real measured spectra, normalized to 1 sun. Source: Liu 2015.**[30]

Liu and coworkers determined in this way the energy yield potential of GaAs-on-Si tandem solar cells. The results are presented in Figure 21 and Table 2.[30] There is a significant difference in the efficiency of the GaAs/c-Si tandem when wired as a 2T (a) and 4T tandem (b). The yearly yield potential for 2T and 4T configurations is very different for GaAs/Si tandem solar cells. The 4T configuration has an advantage in yearly yield potential in that it is over 20 % higher than for the 2T architecture in Singapore and 17 % higher in Denver. Note, this difference is larger than what is predicted using the AM1.5G efficiency values, see Table 2.[30]

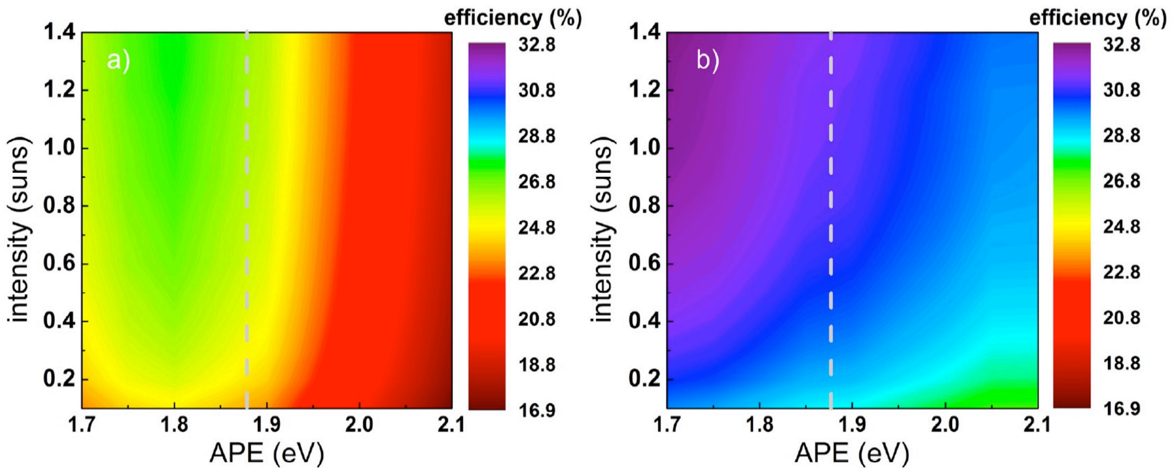


Figure 21 **Simulated tandem efficiency for (a) 2T and (b) 4T configurations under different spectral compositions and intensity levels. Efficiency can vary significantly under different illumination conditions. The variation is from 17% to 28% for 2T and 27% to 33% for 4T. APE value for AM1.5G spectrum is indicated by a dashed line. Source: Liu 2015.**[30]

Location	Configuration	Harvesting efficiency (%)	AM1.5 efficiency (%)	Yearly yield (kWh/m^2)
Singapore	2T	25.3	27.0	402
(Yearly insolation: 1588 kWh/m^2)	4T	30.3	31.1	481
Denver	2T	26.1	27.0	511
(Yearly insolation: 1958 kWh/m^2)	4T	30.5	31.1	597

Table 2 Annual energy yield calculation for 2T and 4T GaAs / c-Si hybrid tandem solar cells in Singapore and Denver. Source: Liu 2015.[30]

Mailoa and coworkers calculated the yearly or annual energy yield of CdTe/CIGS hybrid tandem cells in three different climate zones: dry, temperate/cold and humid/hot. Only the 4T device configuration was considered since current matching cannot be obtained with this combination of band gaps (1.48 eV for CdTe and 1.04 eV for CIGS).

From Figure 22 one can see that a significant increase in annual energy yield is feasible with the 4T tandem architecture (up to 38 % increase in annual energy yield). The calculations were carried out with increasing levels of complexity. The third model included the effect of temperature on efficiency. The findings show that temperature reduces the performance of the 4T tandem in a rather similar way as for the CdTe single junction device.

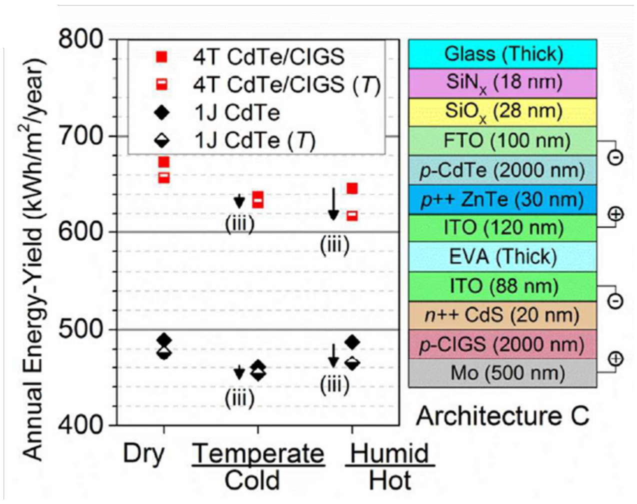


Figure 22 Results of semi-empirical annual energy-yield calculations for a 4T CdTe/CIGS tandem and cross-section of the stack. In this model the effect of cell operating temperature under illumination was included (data points denoted with T). The effect of power loss due to temperature (iii) can be calculated for 4T and 1J architectures (Tcell = 25 °C for filled points, simulated operating temperature for half-emptied points). Source: Mailoa 2016.[31]

Futscher and Ehrler of AMOLF analyzed the influence of outdoor illumination conditions, in Utrecht (NL) and in Denver (Co, USA) on the limiting efficiency of different perovskite/Si tandem solar cell configurations. Also for this combination of PV technologies, the efficiency of various perovskite/ Si tandem solar cell configurations is affected by spectral and temperature changes, see Figure 23. The authors conclude that the weather conditions at the specific site of deployment should be taken into account when designing perovskite/Si tandem solar cells.[32]

3. Hybrid tandems

As predicted, the 2T series connected tandem is most affected by spectral variations and the use of a nonideal perovskite band gap. The authors also calculate that by using a perovskite top cell with the ideal band gap for the respective tandem configuration, perovskite/Si tandem solar clls with power conversion efficiency limits above 41% are possible for all three tandem configuration even at nonideal climate conditions, see Table 3.[32] They observe a reduction for 2T energy harvest compared to 4T energy harvest, depending on how optimal the tandem bandgap combinations are, but it is not as extreme as for Liu et al. The difference is only 2.5 to 6.5 % (relative).

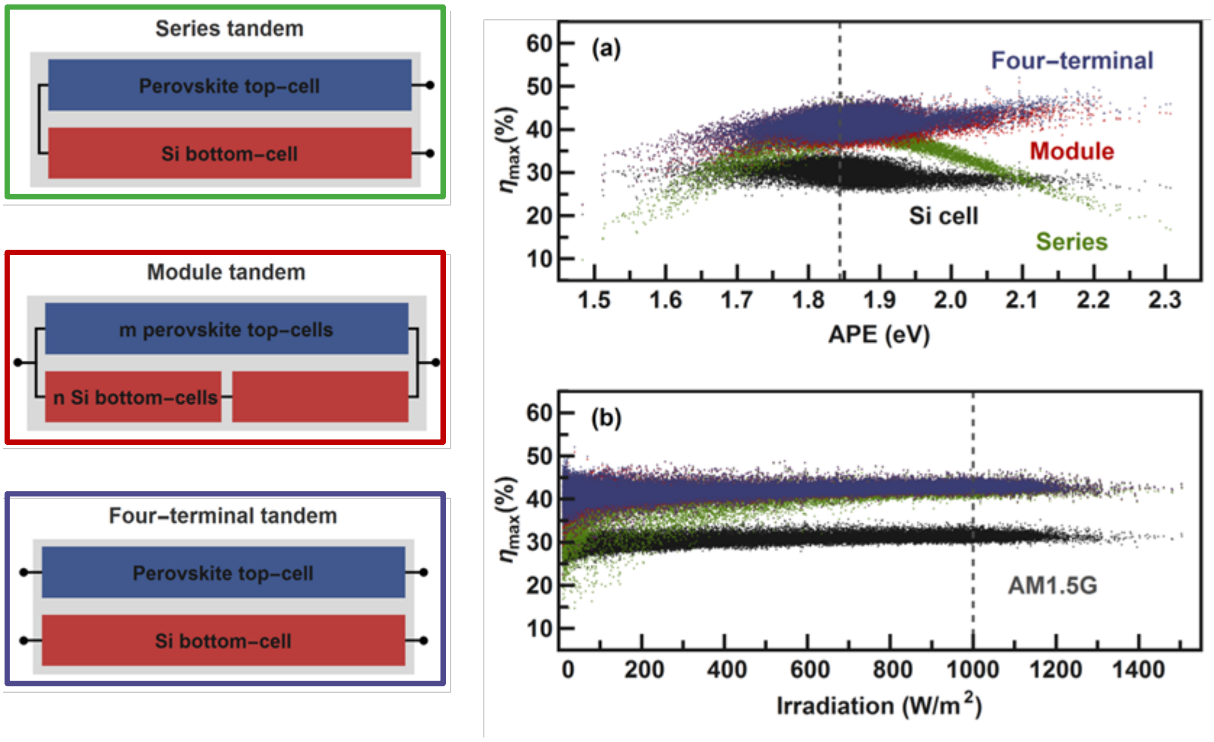


Figure 23 Schematic illustration of perovskite/Si TSC configurations. Top left: monolithically integrated two-terminal tandem in which the perovskite top cell and the Si bottom cell are electrically connected in series. Middle left: mechanically stacked two-terminal module tandem in which the perovskite top cells and the Si bottom cells are electrically connected in parallel. Bottom left: four-terminal tandem in which the perovskite top cell and the Si bottom cell are electrically independent. Right: efficiency limit of the three perovskite/Si tandem configurations and a single-junction Si cell under real illumination conditions as a function of (a) APE and (b) irradiation obtained by detailed-balance calculations. The dashed line indicates the APE and the irradiation of the standard solar spectrum. Note, the wavelength of the APE corresponding to the AM1.5 spectrum differs slightly from Figure 21 presumably because of
d
i
f
f
e

	c-Si cell	$E_g^{Perovskite}$	2T(series)	Module	4T
Utrecht, NL	31.2 %	Ideal	41.6 %	42.5 %	42.6 %
		1.55 eV	38.4 %	39.7 %	41.0 %
Denver, US	32.1 %	Ideal	42.9 %	43.7 %	43.7 %
		1.55 eV	39.5 %	40.7 %	42.1 %

Table 3 Power conversion efficiency limit over an entire year for the three perovskite/Si tandem configurations and a c-Si single-junction cell in NL and US obtained by detailed-balance calculations.

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Synopsis

In summary, for hybrid tandem devices, often two device configurations are considered: two terminal (2T) and four terminal (4T). In literature, the two terminal tandem solar cell configuration is also referred to as the current constrained tandem cell configuration and the 4T as unconstrained. The main differences are collated in Table 4. Current matching is required for 2T tandems. If current matching is ensured, 2T tandems can theoretically reach nearly as high efficiencies as unconstrained or 4T tandems. However, if current matching is not obtained, for example due to a poor match of the band gaps applied in the tandem, the difference in attainable efficiencies between 2T and 4T tandems increases.

If local irradiance and temperature data is available, it is possible to estimate the difference in tandem yearly energy yield for different architectures. It should be noted that most models are not experimentally verified. The yearly energy yield of 2T tandem devices is more sensitive to spectral variations. 4T tandems require more layers in the device stack. The additional layers may lead to additional (parasitic) losses. This may reduce the benefit of 4T over 2T tandems in terms of attainable efficiencies.

The integration of sub-cells in a hybrid tandem module is often different for 2T and 4T devices. 4T devices require a good optical coupling between both sub-cells whereas 2T tandems require, aside from a good optical coupling, also a good electrical connection between the sub-cells. Often 2T tandems are fabricated in a continuous sequence of processing steps. On the contrary, the sub-cells of a 4T tandem are often prepared separately and combined into a hybrid cell or module in an integration step. Combining sub-cells at a late(r) stage in the process sequence typically has advantages in terms of the process yield and the requirements for process compatibility only apply to the step where sub-cells are combined and any subsequent processing steps. It is possible to eliminate the (potential) disadvantages of sequential processing of 2T devices by applying wafer bonding or similar techniques.[33]

	Two terminal	Four terminal
Current matching	**Y**	**N**
Efficiency (Standard Test Conditions; STC)	**(Theoretically) equal within 1-1.5% rel., if band gaps are optimized and assuming no optical loss in non-absorber layers of the multi-junction**	
Annual Yield	**Sensitive to spectral mismatch**	**Forgiving w.r.t. non-optimal Eg combination and spectra mismatch**
Optical losses	**Minimal number of layers**	**Additional transparent electrode(s)**
Interface	**Contact layer processed directly on sub-cell / (textured) wafer**	**Optical spacer / insulator**
Integration	**Process directly on sub-cell / wafer bonding**	**Combine two sub-modules**
Power management	**Connect to ‘standard’ inverters**	**(Possibly) novel inverters / optimizers**

Table 4 **Overview of typical characteristics of two terminal and four terminal hybrid tandems.**

3. Hybrid tandems

4. Status hybrid tandem solar cells

Table 5 presents an overview of the best efficiencies obtained with multi-junction solar cells measured under one sun conditions. Only multi-junction efficiencies of about 10% and higher are included. The top row (blue) gives the PV technology applied as high band gap sub-cell. The number in this row corresponds to the record efficiency obtained with this PV technology in a single junction configuration (one sun, STC). The first column (red) gives the PV technology used for the low band gap sub-cell.

The diagonal (white) in Table 5 gives the efficiencies obtained with 'non-hybrid' multi-junction solar cells. Some combinations do not exist as no suitable band gap combination can be made. It is interesting to note that the efficiencies reported for these tandems or multi-junctions are indeed higher compared to the record value of the corresponding single junction PV technology. Exceptions are CIGS/CZTS and perovskites. For CIGS/CZTS, it is hard to find an efficient high band gap material. Perovskite solar cells are an emerging PV technology and low band gap perovskites for tandem solar cells have only recently been explored. Higher efficiencies could be expected in the near future.

The hybrid tandem based on GaInP / Si reaches an efficiency of 29.8%, well in excess of the corresponding single junction hero cells (20.8% for GaInP and 26.6% for c-Si). This nicely demonstrates the concept of hybrid tandems as technological solution to boost the efficiency of solar cells.

The next highest hybrid tandem efficiency (25.2%) is based on a combination of perovskite and c-Si solar cells reported by EPFL[34]. Although the efficiency is 1.1% (abs.) below the c-Si hero cell efficiency, the c-Si cells used in their study was 22.1%. Therefore, this perovskite / c-Si hybrid tandem helps to boost the efficiency of the c-Si cell by over 3% abs.

Another interesting combination of perovskite on CIGS was reported by Fu et al.[35] The stack is based on two thin-film technologies of which one is already commercially available. Fu reported a 14.2 % efficiency for the semi-transparent top cell and 18.3% for the CIGS (unfiltered) CIGS cell. The 4T tandem stack brings the efficiency up to 20.5%. Recently, this efficiency has increased to 22.1%.[36]

All 20%+ hybrid tandems mentioned above are based on a 4T device configuration. In fact, all hero hybrid tandem cells reported in Table 5 are based on stacked solar cells except best reported hybrid tandems partially based on organic photovoltaics (OPV).

Top Cell *best in class 1J eff. (%)*[37] **Bottom Cell**	**c-Si** *26.6*[38]	**Thin-film Si and alloys** *11.8*	**III-V** *28.8*	**CdTe** *22.1*	**CIGS, CZTS** *22.3*	**OPV, DSSC Qdots** *11-12*	**Perovskite** *22.1*
c-Si	**n.a.**	**16.3 (Zhang)[39] (25 O.S.)[40]**	**29.8 (Essig)[6] (34.5 3J+1J O.S.)[37,41]**			**18 (DSC/c-Si, Kwon)[42]**	**25.2 (Ballif)[34] (28 O.S.)[40]**
Thin-film Si and alloys		**13.6 (3J,)[37]**					
III-V			**31.6 Alta[37]; 38.8 (5J, Boeing)[37]**				
II-VI (CdTe)				**n.a.**			
CIGS, CZTS				**15.3 (Noufi)[31,43,44]**	**9.8 (Noufi)[43,45]**	**15 (Liska)[46]**	**22.1 (Fu)[35,36]**
OPV, DSSC, Qdots		**13 (3J,Zeman)[47–49]**				**13.2 (3J, Heliatek)[50]**	**16 (Liu)[51]**
Perovskite	**-**	**-**					**20.3 (Eperon)[52]**

Table 5 Overview of reported ‘1 sun’ efficiencies of multi-junction solar cells. ‘O.S.’, abbreviates for optical splitter; ‘#J’ indicates the number of junctions in the photovoltaic device when deviating from 2.

5. Combining PV technologies

Hybrid tandems are made by combining absorber layers of different PV technologies. Hybrid tandem solar cell are sometimes considered as an add-on technology to boost the efficiency of a conventional single junction solar cell technology. Often the two PV technologies differ considerably in maturity. The maturity of a technology is often described by its technology readiness level. This chapter starts with a brief description of the technology readiness level of various PV technologies. Next, a method is briefly described which is used to estimate the practically feasible hybrid tandem cell technologies. Then, six combinations of PV technologies for hybrid tandems are discussed in more detail. Finally, the findings are summarized at the end of the chapter.

Technology readiness levels

The maturity of a technology, here a PV technology, can be discussed using the concept of technology readiness levels (TRL). Nine levels are defined ranging from 1 (basic principle observed) to 9 (system proven in operation). The commercial PV technologies (CIGS, CdTe, thin film silicon and c-Si) have a high TRL level of 9. At the low TRL levels one can find the emerging PV technologies as described in 'Approaches to increase the efficiency of solar cells'. Perovskite solar cells are currently at TRL 4. III/V solar cells range from TRL 5 (validation in relevant environment) to TRL 7 / 8 (prototype at pilot scale / system complete and qualified).

Hybrid tandems often require modifications of the technology developed for single junction application, this typically results in a drop in TRL level. For example, the current density in the low band gap sub-cell of a tandem is often a factor of two lower compared to the current density in the cell optimised for single junction application. The required modifications may result in a new solar cell design which needs to be validated first in the lab (TRL 4). Developing a semi-transparent top cell based on a commercial PV technology such as CdTe or CIGS is another example.

In the next sections several PV technology combinations are compared. One should be aware that these PV technologies may be at different stages of their development which makes a fair comparison difficult since the uncertainties and risks increase when the TRL level is lower.

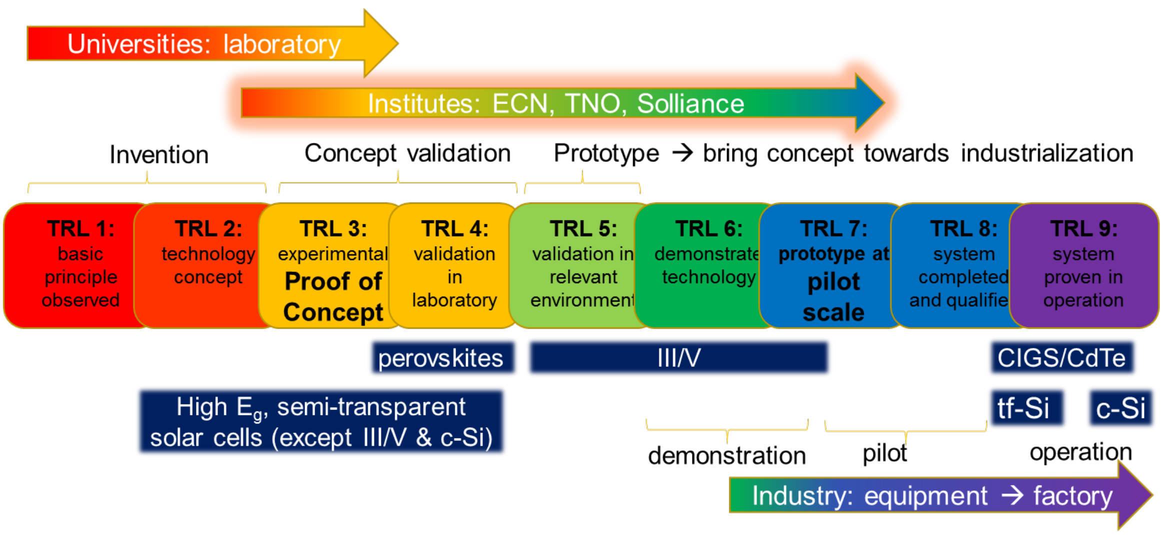


Figure 24 **Schematic overview of the technology readiness level (TRL) of selected PV technologies. Note, high band gap (E_g), semi-transparent solar cells are often at the stage of 'proof of concept'.**

Attainable hybrid tandem device efficiencies

Theoretical calculations about the maximum attainable tandem cell performance have been published by several authors. [32,53–55] Here a summary is presented as to how the practically attainable efficiencies for several hybrid tandem concepts were evaluated. A more detailed description may be found elsewhere.[56] The simulation method has been verified for a-Si:O,H/c-Si and perovskite/c-Si.[39,56] In short, the method is based on advanced optical simulation combined with solving diode equations. With the optical simulation, the reflectance, transmittance and absorptance of each layer of the solar cell can be calculated. It is assumed that the active-area short-circuit current density approximates the current density calculated from the absorptance of the absorber layers in the hybrid tandem.

The current generated by the bottom cell of the tandem is lower as the incoming light is filtered by the top cell. To estimate the performance of the bottom cell, a modified one-diode equation is used to calculate the open-circuit voltage and fill factor of this sub-cell of the tandem. The open-circuit voltage and fill factor of the top cell are taken from literature. With this data it is possible to estimate the performance of a hybrid tandem cell. It is also possible to estimate the performance of a 4T hybrid tandem module. To do so, the trade-off is described between the resistance loses in the TCO on the one hand and active area losses caused by interconnection on the other hand and from this the losses are minimized. Figure 25 shows the result of these calculations for perovskite / c-Si tandems. As can be seen from the graph, a gain in efficiency of 6 to 7 % may be feasible. The optimum band gap for 2T and 4T differs significantly. The sharp optimum for the 2T stack is determined by the current matching requirement. The simulation reveals that the 4T perovskite/c-Si tandems has a weak dependence on the perovskite band gap (optimum is 1.9 eV).

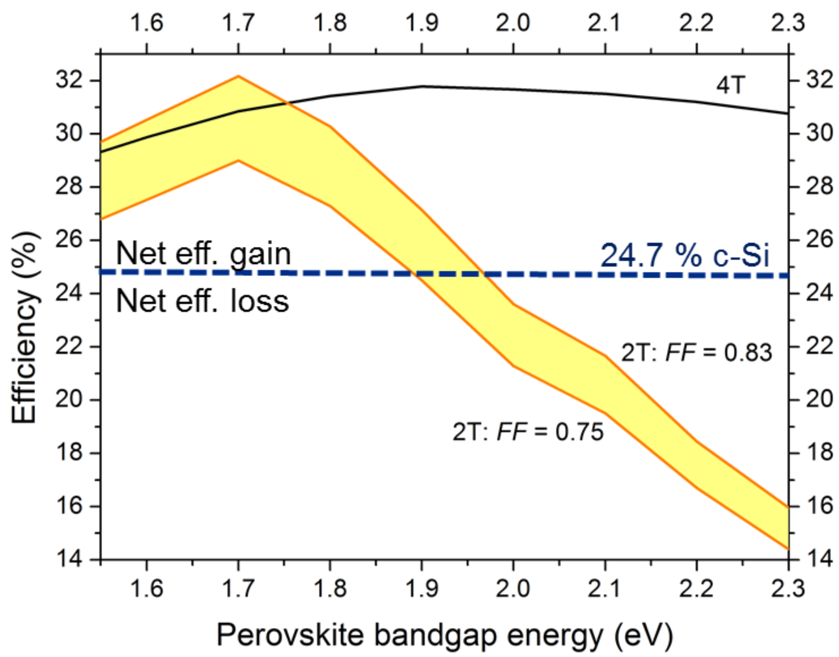


Figure 25 **Estimated practically attainable efficiencies for perovskite/c-Si tandems in either a two terminal or four terminal configuration as a function of the perovskite band gap. The calculations were based on a 24.7% c-Si solar cell and a methylammonium lead triiodide (MAPI) perovskite solar cell. To shift the perovskite band gap, the optical properties of MAPI were shifted accordingly. For two terminal devices the fill factor of the tandem is in between the fill factor of the top and bottom cell, indicated by a bandwidth (yellow area).**

The calculations indicate that 2T devices have a slightly higher efficiency, if an efficient perovskite material with a suitable band gap is available. The efficiency difference is caused by the additional layers present in the 4T device stack, causing optical losses. Note that the optimum high band gap for a 4T device is blue shifted. This relieves the electrical requirements of the transparent conductive oxide (TCO) somewhat as the current generated in the top cell of the tandem decreases when the band gap of the top cell increases. This points to the important role TCOs play in the development of efficient hybrid tandem solar cells.

Selected PV technology combinations for hybrid tandems

a-Si:O,H / c-Si [39]

Parameter	Value
Eg (eV) / band gap tuning	~ 1.6 – 2.1 with slow absorption onset; Si-Ge alloys offer a route to lower the band gap
Sub-band gap absorption	Yes
Semi-transparent (ST) device efficiency / potential efficiency gain (%)	>5 / ~ 2
LCA aspects	OK
Annual degradation rate a-Si:H (%/year)[57] Annual degradation rate c-Si (%/year)	0.9 ± 0.4 0.4 ± 0.2
TRL	High
Additional module cost (EUR/m^2) – preliminary est.	20

Table 6 Overview of key aspects of hybrid tandems based on a-Si:O,H / c-Si.

Remarks

- The band gap of thin film silicon can be tuned to approximately 2.1 eV. However, sub-band gap absorption reduces the IR transmittance to the bottom cell (c-Si). This limits the potential efficiency gain to approximately 2% (with respect to the efficiency of the c-Si bottom cell).

- The performance of the single junction thin-film silicon cell is below 50 % of the Shockley-Queisser limit. Whereas the c-Si hero cell reaches ~ 76 % of the Shockley-Queisser limit, see Figure 9.

- The additional module cost to add a thin-film Si module to a c-Si module are estimated to be approximately 20 EUR/m^2. Although this is a very low number, the limited efficiency increase of up to 2% makes this combination not very attractive.

- Annual degradation rates are based on outdoor data collected on the corresponding single junction technology at PV system level. See also a recent update of this study.[58]

III-V / c-Si [6,59,60]

Parameter	Value
GaInP E_g, lattice matched (eV)	~ 1.7-1.9 (tunable over a wide range for III-V compounds)
Sub-band gap absorption	Low
ST device efficiency (bottom cell eff.) / realized efficiency gain with SHJ-Si (%)	18.1 ≥ 5
LCA aspects	For thin-film III-V solar cells, roughly comparable to c-Si
Annual degradation rate III-V (%/year) Annual degradation rate c-Si (%/year)[57]	Data not available 0.4 ± 0.2
TRL	Medium for III/V on 'large scale'
Additional module (EUR/m^2) – preliminary est., conventional processing	> 1000; significant price reduction expected if a learning curve can develop

Table 7 Overview of key aspects of hybrid tandems based on III-V / c-Si.

Remarks

- This combination shows the best performance for hybrid tandems under one sun conditions.

- It should be noted that the efficiency gain with respect to the sub-cells is high, at least 5%, however, when compared to the III/V hero cell, the efficiency increase is limited (1% abs.).

- Photon recycling is important in III/V solar cells to optimize device performance. This effect should be taken into account when measuring the tandems, but also when designing the tandem stack.[6]

- The cost of III/V solar cells processed with conventional methods is costly. New methods are under development, see for example the work at Sol Photaics.

- Wafer bonding may be a method to integrate sub-cells in a module.

- Unfortunately, no relevant outdoor annual degradation rate data for III/V PV modules or systems was found.

C(I)GS / c-Si

Parameter	Value
E_g (eV) / band gap tuning	~ 1 – 1.7
Sub-band gap absorption	Yes
ST device efficiency / potential eff. gain with c-Si (%)	~ 6 (CGS) / ~ 2 – 3.5
LCA aspects	Depending on material (i.e. Cd, In)
Annual degradation rate CI(G)S (%/year)[57] Annual degradation rate c-Si (%/year)	0.9 ± 1.5 0.4 ± 0.2
TRL	High, however ~ 3 for ST devices
Additional module cost (EUR/m^2) – preliminary est.	30

Table 8 Overview of key aspects of hybrid tandems based on C(I)GS / c-Si.

Remarks

- The C(I)GS band gap is tunable over a range, which makes it an interesting candidate as high band gap sub-cell.

- Unfortunately, it turns out to be extremely difficult to make efficient high band gap C(I)GS. The best semi-transparent high band gap CIGS cells reach approximately 6 %, which is low compared to the Shockley-Queisser limit.

- Because of the lack of efficient high band gap, semi-transparent C(I)GS cells, a breakthrough in cell efficiency is required for this PV technology to enable efficient C(I)GS / c-Si tandems.

- For the life cycle analysis profile, the inclusion and possible replacement of Cd and potentially In is relevant.

- Annual degradation rates are based on outdoor data collected on the corresponding single junction technology on PV system level. See also a recent update of this study.[58] For semi-transparent high band gap CI(G)S, the degradation rate may deviate.

CdTe / c-Si [55]

Parameter	Value
E_g (eV) / band gap tuning	1.5 / possible by alloying CdTe with ZnTe
Sub-band gap absorption	Low
ST device efficiency / pot. eff. gain with c-Si (%)	Not found / Not determined; First solar & MIT estimate a max. efficiency of 26 %
LCA aspects	The toxicity of Cd and abundance of Te is a concern
Annual degradation rate CdTe (%/year)[57] Annual degradation rate c-Si (%/year)	0.4 ± 0.6 0.4 ± 0.2
TRL	High
Additional module cost (EUR/m^2) – preliminary est.	Insufficient data available

Table 9 Overview of key aspects of hybrid tandems based on CdTe / c-Si.

Remarks

- Band gap tuning and grading is possible when combining CdTe with ZnCdTe and CdMgTe.

- Semi-transparent devices were not found in the literature.

- Currently we are looking into the optical constants of CdTe and stack information of semi-transparent CdTe solar cells in order to estimate the performance of these tandems.

- In a recent publication First solar & MIT estimate a max. attainable efficiency of 26% for this material combination.[55]

- Annual degradation rates are based on outdoor data collected on the corresponding single junction technology at PV system level. See also a recent update of this study.[58]

- Annual degradation rates are based on outdoor data collected on the corresponding single junction technology at PV system level. See also a recent update of this study.[58]

Perovskite / c-Si [34,56,61,62]

Parameter	Value
E_g (eV) / band gap tuning	~ 1.2 – 2.3
Sub-band gap absorption	Low
ST device efficiency pot. eff. gain with c-Si (%)	16.4 (EPFL) 6 - 7
LCA aspects	Pb
Annual degradation rate perovskite (%/year) Annual degradation rate c-Si (%/year)[57]	No data available 0.4 ± 0.2
TRL	Low
Additional module cost (EUR/m^2) – preliminary est.	20 – 40

Table 10 Overview of key aspects of hybrid tandems based on Perovskite / c-Si.

Remarks

- Band gap tuning is possible by varying the composition of the perovskite crystal.

- Perovskite solar cells typically have a steep absorption onset and low sub-band gap absorption.

- The efficiency of semi-transparent devices is now ~16-17%, which can give rise to an efficiency gain of over 3%.

- Most perovskite solar cells contain lead. This requires specific attention for the LCA profile of this PV technology.

- The lifetime of perovskite solar cells is increasing. Oxford PV recently announced it passed critical IEC tests with perovskite solar cells.

Perovskite / CIGS [35]

Parameter	Value
Eg (eV) / band gap tuning	~ 1.2 – 2.3
Sub-band gap absorption	low
ST device efficiency pot. eff. gain with CIGS (%)	14.2 (EMPA) (16) 6-7
LCA aspects	Pb
Annual degradation rate perovskite (%/year) Annual degradation rate CI(G)S (%/year)[57]	No data available 0.4 ± 0.2
TRL	Low
Module cost (EUR/m^2) – preliminary est.	20 – 40

Table 11 Overview of key aspects of hybrid tandems based on Perovskite / CIGS.

Remarks

- Band gap tuning is possible by varying the composition of the perovskite crystal.

- Perovskites typically have a steep absorption onset and low sub-band gap absorption.

- The efficiency of semi-transparent devices is now ~16-17%.

- Most perovskite solar cells contain lead. This requires specific attention for the LCA profile of this PV technology.

- The lifetime of perovskite solar cells is increasing. Oxford PV recently announced it passed critical IEC tests with perovskite solar cells.

- a perovskite / CIGS tandem could potentially be light weight and/or flexible.

Final remarks

concerning the bottom cell in hybrid tandem devices
In the above discussed hybrid tandems, c-Si or CIGS was used as bottom cell. It is important to stress that these cells need to be re-engineered to function optimally in hybrid tandem devices. Required modifications include:

- Cell and module design for low injection levels – low currents, maintain high voltages and increase fill factor,
- Light management & surface topology,
- Relaxed constraints for high spectral response over complete solar spectrum; potentially reduces the cost of the bottom cell,
- Integration in modules.

Synopsis

Table 12 summarizes the main aspects of the selected PV combinations considered for hybrid tandems as discussed in this chapter. The first three technology combinations each have one aspect which prevents market introduction of the technology. This hurdle requires a technological breakthrough. Example cost of III/V is currently high through a breakthrough like Sol Voltaics could potentially remove this barrier for market introduction.

In the case of CdTe / c-Si insufficient data is currently available for the evaluation. Perovskite solar cells have an issue with lifetime. However, since Oxford PV recently passed an important IEC test the symbol '-' was replaced by '+/-'.

Combination (hi Eg/low Eg)	Eff. gain	lifetime	Cost	Remark
a-Si:H / c-Si	--	-	+	(Too) limited eff. gain potential
GaInP / c-Si	+	?	--	High cost, up scaling required, importance of photon recycling
CGS / c-Si	--	-	?	No high Eg, semi-transparent, efficient cell
CdTe/ c-Si	?	+	?	No high Eg, semi-transparent, efficient cell
Perovskite / c-Si	+	?	+	Lifetime, up scaling, low TRL
Perovskite / CIGS	+	?	+	Lifetime, up scaling, low TRL

Table 12 Summary of key aspects for hybrid tandems based on various PV technology combinations. CGS abbreviates for copper-gallium-sulfur or selenium, a group of materials with similarities to CIGS, but with a higher band gap. Symbols indicate "--" major hurdle for commercial application; "-" needs significant improvement for commercial application; "?" this aspect is uncertain/unknown, further work is needed to prove this parameter does not prevent market uptake of the technology; "+" aspect is proven at a low TRL (Technology Readiness level) additional work may be needed for up scaling, or to optimize performance, etc.

The efficiency gain is an important factor for hybrid tandem solar cells. This gain should be sufficient to bare the extra cost of an additional sub-cell. Note that the additional cost should be considered at module or system level.

To maximize the gain in tandem efficiency, the band gaps of the sub-cells should be preferably close to the (theoretical) ideal pair of band gaps.

6. Cost of hybrid tandems

As mentioned in section 2, the cost of a PV system is often split in module cost and the cost of the balance of system (BoS): the necessary components (and optional: including also labor) besides the module which are needed for a working PV system.[63] The ratio between module cost and BoS cost depends on the specific PV system and may vary. A typical PV system may have a cost breakdown of 2/5th for the module and 3/5th for the BoS. A large part of the BoS cost scales with the system area and a small part depends on the output power of the system.

Solar cells in a PV module convert light to electrical power. To a first approximation, the cells determine the output power of the PV system. The cost fraction of crystalline Si cells to the module cost is approximately 1/2 and thus the fraction of the cell cost of the overall PV system cost is often around 1/5. As the fraction of the cell cost is small compared to the system cost, an increase in the cell cost has a limited effect on the PV module and PV system cost.

As discussed above, the BoS cost can be divided in area-related BoS cost and power-related BoS cost. Area-related BoS cost include for example the cost for module mounting structures and cables, while the cost of inverters belong to power-related BoS cost. Hybrid tandem modules allow to increase the efficiency of PV systems. This allows to generate the same amount of power from a smaller (less square meters) PV system. The smaller footprint of the more efficient PV system does not affect the power-related BoS cost, but lowers the cost of area-related BoS component (like mounting structures and cables).

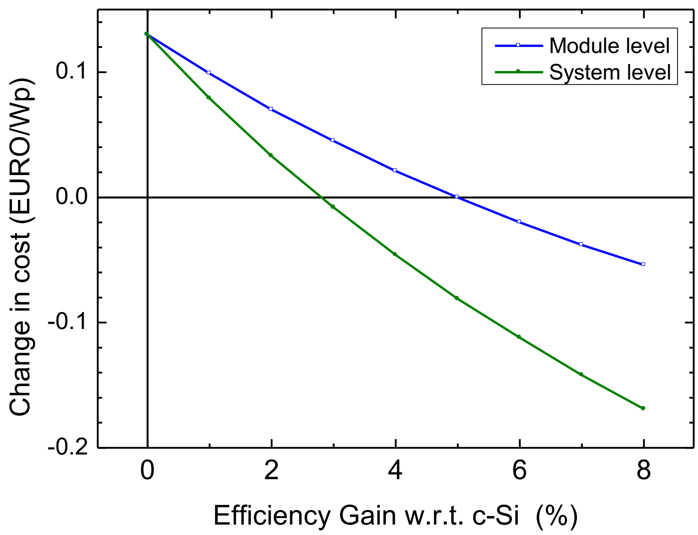


Figure 26 Example of a relation between the efficiency gain of a hybrid tandem PV module (blue open symbols) or system (green closed symbols) expressed in terms of EUR/Wp. The efficiency gain is with respect to the efficiency of a c-Si module. For the calculation, the following assumptions were made: c-Si module power 300 Wp (1.62 m²) with a cost of 0.4 EUR/m². The net additional cost to add a high band gap top module was estimated to be 20 EUR/m² (this is excluding 5 EUR/m² for a glass substrate). A seller margin of 20 % and an area related BoS cost of 70 EUR/m² was assumed.

Figure 26 gives an example of how the additional cost in EUR/Wp of a high band gap top sub-module may be compensated by the additional power generated from the hybrid tandem module as compared to a state of the art single junction c-Si module. In this example, the cost of the c-Si module is 73.9 EUR/m^2; the additional cost to add a high band gap top module is estimated to be 20 EUR/m^2. In this example, the cost of a hybrid tandem is lower as compared to a c-Si module if the efficiency (with respect to the stand-alone c-Si module) is increased by about 5 % absolute. At PV system level, the break-even already occurs at an efficiency increase of 3%.

This ‘back of the envelope calculation’, indicates an opportunity to reduce cost on module level and a significant cost reduction on PV system level. Note, for a hybrid tandem PV system some modifications at module and BoS level are required which are neglected in this example for simplicity.

An upper limit for the cost reduction of (hybrid) tandem solar systems can be estimated by considering the maximum increase in performance of a tandem solar cell compared to a single junction. For efficient solar cells, the efficiency increase is roughly a factor of 1.37, see for instance Figure 15. If we assume for the moment the addition of the second cell comes without any added cost and that the utilization remains the same, the power output increases by a factor of 1.37. Expressed in terms of EUR/Wp, the cost is reduced by a factor of 1.37. If the number of junctions increases, the cost reduction potential may be larger.

Detailed cost of ownership calculations on PV systems require a large set of reliable input data, or a distribution thereof (for example: material cost, (tandem) cell processing cost, cost for integrating cells in modules, process yields, BoS cost, local irradiance levels, local performance ratio data, annual degradation rate(s) and operational and maintenance cost).[63] Because of the low TRL level of hybrid tandems and therefore the lack of reliable input data, there results a large uncertainty in these types of cost calculations. The cost of ownership calculations can also cover additional items like permits, insurances, project (planning) cost and the cost of capital. These items increase the lever of the cell efficiency on the cost of ownership. If more of these items are included, the breakeven point is already obtained at lower efficiency gains.

Recent papers by Peters et al. and Bobela et al. take a different approach.[16,64] The cost of tandem PV systems is compared to PV systems based on the corresponding single junction technologies. From these studies it is noted that if one of the tandem sub-cells is significantly more cost-effective than the other, it would be more cost-effective to use the most cost-effective PV technology stand-alone than adding the more expensive sub-cell. In other words, a tandem must compete against both sub-cells and is most cost effective if both sub-cells have similar costs.

In general, one can say the sub-cells in a hybrid tandem should be rather similar, not only in cost/Wp, but also in efficiency (both sub-cells should be at a similar distance from the Shockley-Queisser limit), and lifetime. In chapter 2, reference [16] was quoted, ‘hybrid tandem solar cells should be based on a ‘marriage of equals’’. If the lifetimes of the sub-cells are dissimilar, it may be more attractive to choose for the more stable single junction PV technology instead of the tandem technology. A similar reasoning holds for the efficiency. If the sub-cells operate at very different distances from the Shockley-Queisser limit, it will be hard to develop a tandem cell with a large gain in efficiency compared to the efficiency of the most efficient single junction.

7. Projections for the next 5 years

Over the last few years impressive progress has been made in the development of efficient hybrid tandems, specifically on III-V / c-Si, perovskite / c-Si and perovskite / CIGS. It is important to put these results in the right perspective. Nearly all work was done on cells and most cells have active areas of 1 - 100 mm^2. It is expected that in the next 5 years the efficiencies at cell level will further increase and one may expect efficiency gains (compared to the best performing stand-alone system) of 5-6%. The increase in efficiency will be enabled by improved TCO's, optimized contact layers and absorber layers with optimized band gaps. Implementation of light management strategies, including photon recycling, is also expected in the next years. These developments offer new opportunities for materials companies to develop new (pre-cursor) materials and deposition tools equipment. At the same time, fundamental knowledge is needed to understand how phenomena like photon recycling affect the architecture of hybrid tandems.

Also at module level one expects to see efficiency gains for hybrid tandem modules in the next five years, however, this requires significantly more effort. Firstly, making modules requires more resources (materials, equipment and person hours) as compared to making cells. Secondly the uniformity becomes much more important and typically requires a baseline process on a pilot line. These lines do not exist at the moment, but are expected in the next year(s). An example of this development is the recent acquisition of a former CIS module manufacturing facility of Bosch by Oxford PV.[65] Oxford PV aims to realize a modern, pilot-scale process line to manufacture industry-standard wafer sized perovskite devices. Similarly, the Swedish company Sol Voltaics is investing in upscaling their III-V technology to enable III-V / c-Si hybrid tandems. These developments again offer again good prospects for material providers and equipment manufacturers, as well as for companies selling characterization equipment and installation services.

Concurrently, bottom cells (CIGS, c-Si) need to be optimized to maximize the power output of hybrid tandems and to minimize the cost of these multi-junction devices. Examples here include novel cell designs, for example, optimized for low injection levels, optimized red response, and improved passivation. These optimized cell technologies could be addressed by companies like Tempress, Smit Thermal Solutions, and various spatial-ALD companies.

Integration activities will become increasingly important starting in 2017. Here two development lines are expected: one for 2T tandem modules and another development line for 4T modules. The two integration processes are expected to differ significantly since the 2T tandems are most likely directly processed on top of the first cell or module leading to a 'monolithic' tandem device. The integration of 4T tandems is expected to occur at a later stage of the fabrication process, i.e. when both sub modules are combined in, for instance, a single lamination step to realize the hybrid tandem module. If wafer bonding is economically feasible for 2T tandems, the difference between the 2T and 4T integration processes may fade. The wiring in 2T and 4T differs and new strategies will be developed to optimize interconnection schemes at module level.

Another aspect is the introduction of ultra-barrier materials to protect sensitive materials against ingress of foreign chemicals into the module, such as moisture and oxygen, and the egress of elements from active components of the module. The above-mentioned activities lead to new markets for material companies, producers and corresponding equipment manufacturers of (conductive) back-sheet foils, ultra-barrier foils, laminators and module assembly lines.

Once hybrid tandem modules become available, a market for a new generation of inverters for hybrid tandems develops, possibly in conjunction with a new generation of junction boxes and connectors.

First outdoor measurements are expected in the next two years. More long term indoor and outdoor measurements are needed in the proceeding years to collect more statistics on these systems. The hybrid tandem devices most likely require high-end characterization tools which offers opportunities for companies like Eternal Sun. It is also expected that existing IEC standards may need to be adapted, extended or even drafted.

Pilot projects where first hybrid tandem modules are applied by customers may, in a positive scenario, be expected in the next five years. This could include high-end building applied PV systems. Building integrated solutions are expected to follow and at a later stage, PV power plants. It should be noted that a strong synergy is expected between the development of novel single junction PV technologies and novel hybrid tandem technologies.

Besides technology development, academic research is needed to better understand how to reduce the gap between the Shockley–Queisser limit and the practically attained efficiencies and how to realize more efficient hybrid tandem devices. The challenges here are to identify new chemical routes for efficient and stable absorber and envelope layers. The envelope layers are contact layers typically located on either side of the absorber layer. Once the absorber layer is optimized and bulk recombination is minimized, these contact areas often have a decisive role in the device performance. High level multidisciplinary material research will elucidate the correlations between (local) material properties and device performance. These correlations will enable accurate device simulations to optimize complete device stacks.

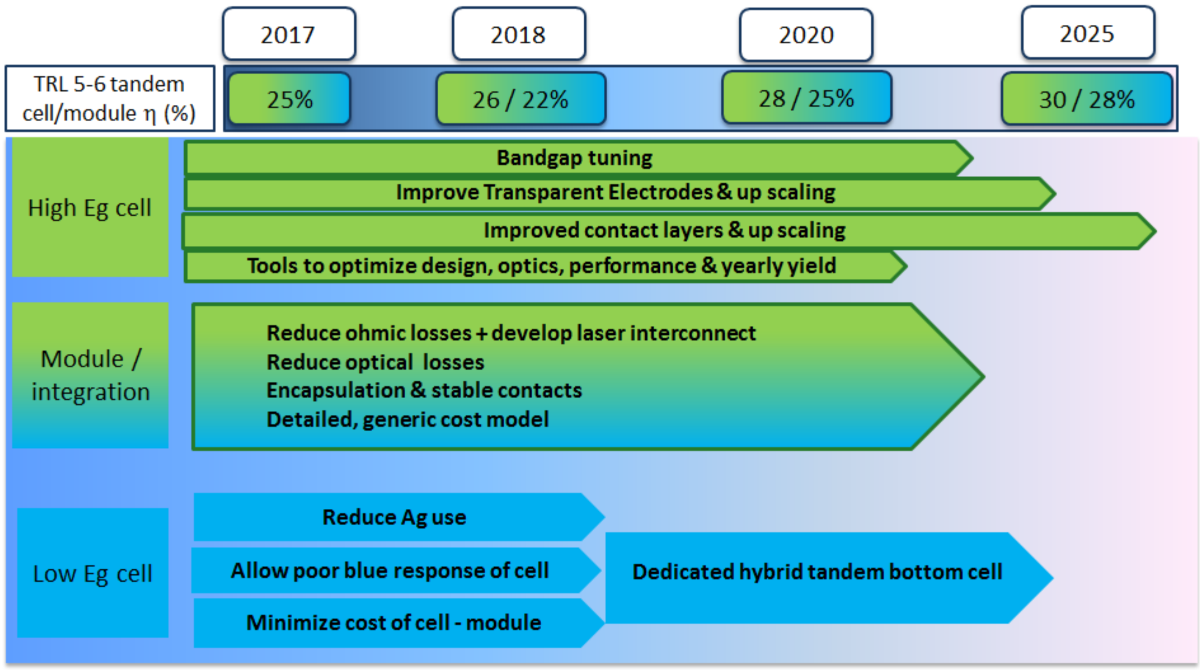
New technologies are also expected in the next years, although at a low TRL level (~ 2 - 3). These new techniques may be based on advanced photon cutting and pasting. Another development that should be mentioned here is the use of high level computer calculations to identify new material leads for PV application. One may expect results (on cell level) from these projects in the next five years. Efficient tandem device based on similar processes and materials, as well as non-hybrid tandems, are also expected in the next five years.

Finally, a major result of hybrid tandem research could be the fact that it brings together PV researchers from different PV technologies and as such, it may help the ‘ontzuiling’ of the Dutch PV community.

8. Recommendations

This sections provides an overview of the activities necessary to develop the field of hybrid tandems in the Netherlands to support the Dutch industry by enabling a leading global position in this new field. Scheme 1 gives the main topics which enable highly efficient (26% - 27%) hybrid tandem *modules* by 2025. This scheme is followed by Scheme 2 and Scheme 3 detailing the roadmap to develop efficient, stable and cost effective bottom and top cells and their integration in hybrid tandem modules. Finally, Scheme 4 addresses the developments needed at system level.

Enabling research



Scheme 1 Roadmap for generic, enabling research activities needed to support the development of hybrid tandem solar modules and systems.

The top row provides the time axis. The second row gives the projected efficiency at cell and module level for hybrid tandem devices. The activities are split into actions focusing on high and low band gap cells and the work needed to integrate these cells in modules.

Band gap tuning towards an optimized match within the hybrid tandem device is work which often has only limited overlap with absorber development for single junction applications and is therefore important to include here. Transparent conductive oxides (TCOs), or more generally transparent electrodes, can increase the efficiency by approximately one percentage point (absolute) in the next 5 years. The further development of TCOs will therefore be important in order to fully exploit the potential efficiency gain of hybrid tandems compared to single junctions.

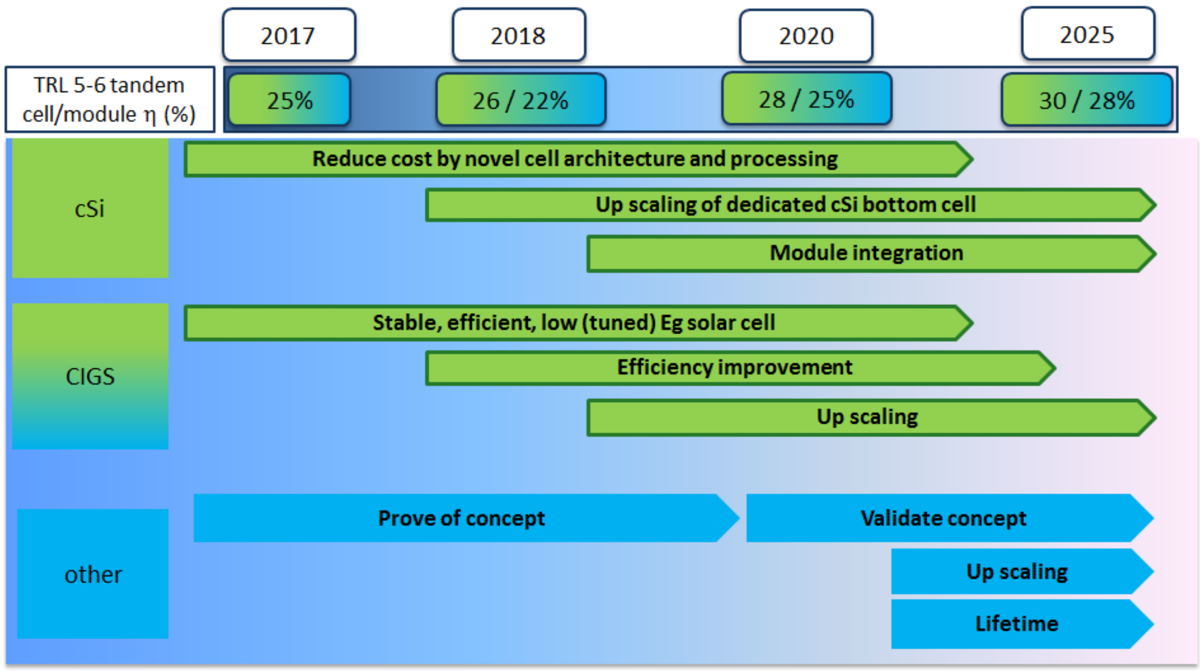
Similarly to TCOs, contact layers which electrically and optically couple to the absorber layer are very important in the optimization of efficiency, lifetime and economic viability of hybrid tandem devices. Important aspects involved in this include energy level alignment, surface recombination, transparency and selectivity of the contact layers. The optimization of the cell stack requires verified and accurate electrical and optical simulation models which need to be developed further.

The optimization of the bottom cells is typically along two lines: exploiting the relaxed constraints concerning the blue response of the bottom cell, and the lower current density in the bottom cell. This work will lead to novel c-Si cell designs for tandem application with a better spectral response in the (infra-) red part of the spectrum, lower electrical losses and lower material cost.

The integration activities aim at minimizing electrical losses and smart ways of interconnecting cells. Optical layers help to reduce reflection losses and to increase the optical path length through the absorber layer, as well as optimizing photon recycling. For stable device performance under harsh conditions, the typical encapsulation method for CIGS and c-Si solar modules may not be sufficient for hybrid tandems. Finally, cost modeling is required to closely monitor the economic viability of hybrid tandems.

Bottom cell

Scheme 2 presents the high level roadmap for activities to improve selected bottom cells for hybrid tandems in the next five years. For c-Si, this includes work to improve the (infra-) red response and to minimize Ohmic losses in the cell. This will lead to new processes and cell designs which need to be scaled up and integrated into modules. For CIGS the activities are similar, however, CIGS offers the additional possibility to tune the band gap by modifying the chemical composition. These new compositions may require optimization to reach high efficiencies, followed by upscaling.

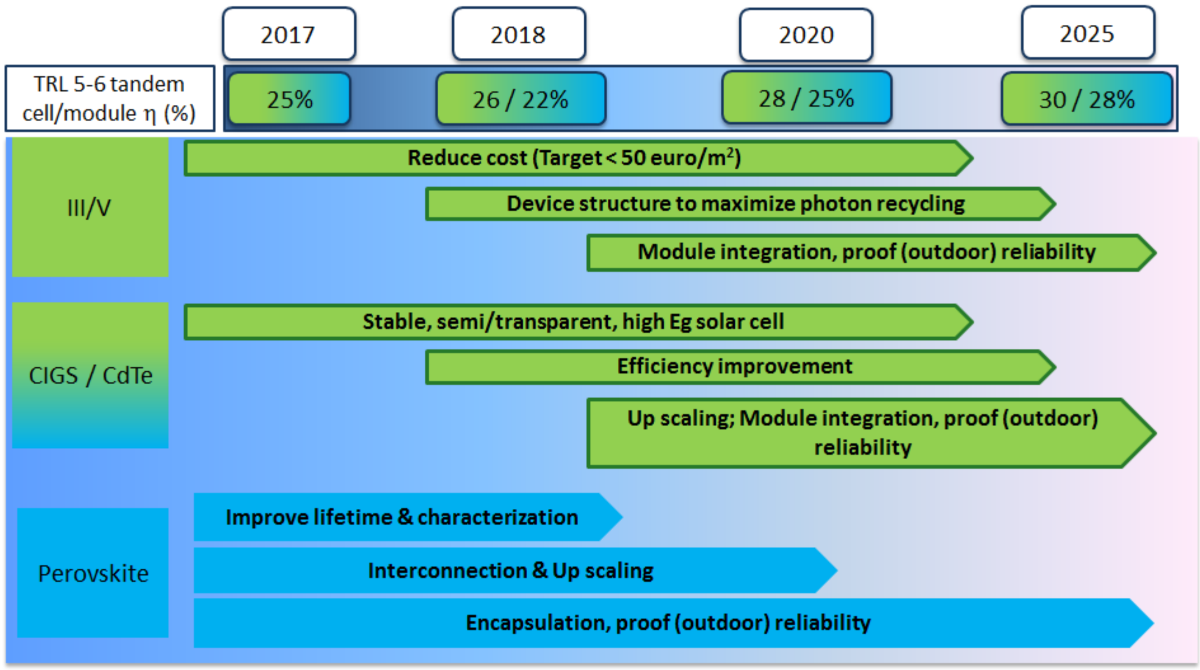


Scheme 2 **Roadmap for research activities to develop the existing single junction technologies CIGS and c-Si towards optimized bottom cells in hybrid tandems.**

It is possible 'other' new materials and material combinations become available to be applied as absorbers in bottom cells. These materials may be based on developments ofexisting materials such as III-V's, CIGS and perovskites or based on novel materials which, for example, may be identified by computer aided screening of large libraries of materials. Once new leads are found and validated, upscaling of the material and device stack needs to be proven together with long lifetime.

Top cell

Scheme 3 gives the roadmap for selected PV technologies which could be applied as top cells in hybrid tandem modules. The main aspect for the III-V's is to develop a technology to reduce the cost to levels which are comparable to c-Si in terms of EUR/m^2. Another aspect is to maximize photon recycling in the top cell. Photon recycling is essential to maximize device performance in efficient direct band gap solar cells. In tandems, it is important to trap emitted light in the same cell. A third aspect is module integration and outdoor reliability.



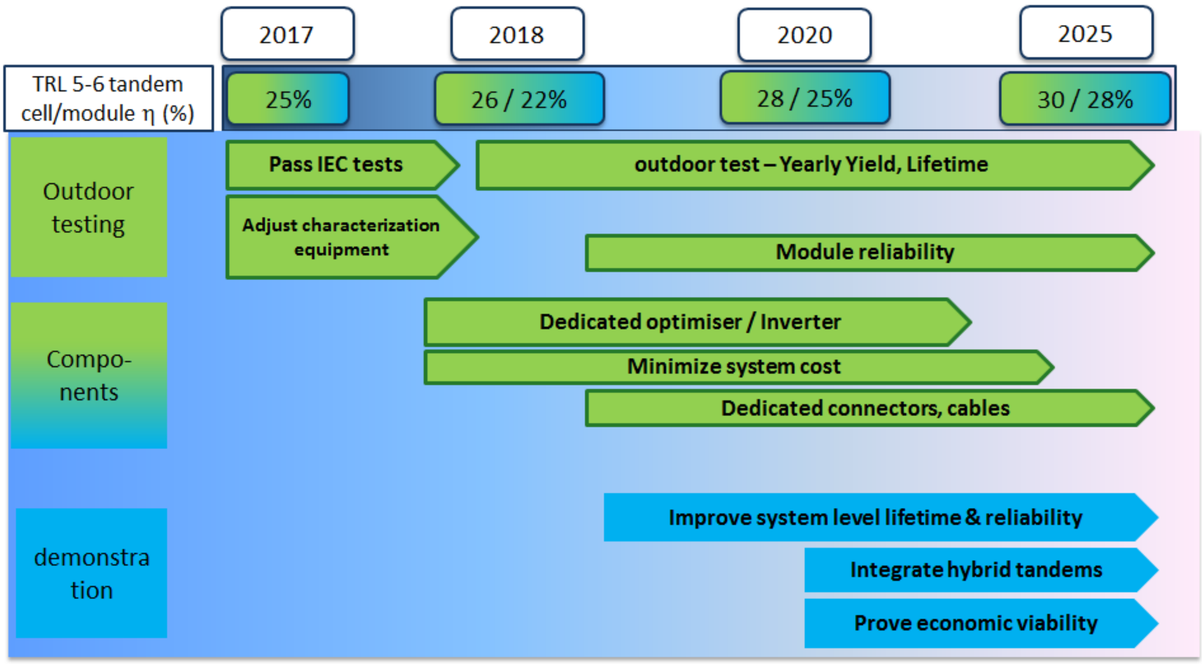
Scheme 3 **Roadmap for research activities to develop semi-transparent, high band gap, efficient, stable and economically viable top cells for application in hybrid tandems.**

CI(G)S may not seem to be a promising candidate as absorber material in the high band gap sub-cell of a hybrid tandem. A semi-transparent variant of CdTe may be more promising due to the possibility of modifying its band gap by tuning the chemical composition. Once the efficiency and lifetime are sufficient, the next step would require scaling up of the process, outdoor reliability tests and life cycle analysis.

For perovskites, the focus is on proving the stability and upscalability (including a suitable interconnection technology) of the technology, whilst at the same time continuing efficiency improvements remain important. Special attention is to be paid to encapsulation and the complete life cycle analysis of the technology. An interesting development here is the realization of an efficient (non-hybrid) tandem solar cell by U. Hasselt, Oxford University and Stanford.[52]

System level

At system level, it is important to pass the relevant IEC tests. Hybrid tandems may also require adjusted characterization equipment for indoor and outdoor measurements. Once consensus is reached on characterization, outdoor tests are needed to better predict yearly yields and the reliability of the system.



Scheme 4 Roadmap for research activities at system level needed to develop economically viable hybrid tandems.

Several components may require modifications such as optimizers / inverters, connectors, etc. Another activity is to identify and eliminate any redundancies in the system with the overall aim of minimizing system cost.

Finally, hybrid tandems need demonstration projects to evaluate the technology under real life conditions. Demonstration could be on the levels on building applied, building integrated and even PV power plants.

Policy

Hybrid tandem PV modules offer a clear route to increase the efficiency of PV systems significantly. Increasing the efficiency of PV systems is important for two reasons. Firstly, it allows to install more Wp if area is limited or expensive, and secondly, it will likely result in a cost reduction for PV systems. Several PV technology combinations can be made. This report provides an overview of, and a roadmap for, the most discussed technology combinations for hybrid tandem PV systems.

To further develop this technology, small and medium sized companies are willing to be involved in the innovation process, however, due to the very tight margins in the PV industry the horizon for innovation is typically in the order of a year. For these companies, the government needs to play an important role to facilitate the development of this technology in a way that companies can participate and ultimately take over.

Large companies see the PV market as an attractive growth market. Further they typically have medium (month - year) or even long term (years) research programs. Topics for these long term research activities need to be generic: when the technology is suitable for only one specific market (like Solar), there is a risk the investment in research will not pay off. So also the large companies will not develop such a technology by themselves. Clearly, there is an important role for the government to enable the development of this technology. A roadmap is presented here.

The strong position of the Dutch academic groups working on solar energy combined with institutes like ECN, TNO, and their ‘daughter organizations’, Solliance and SEAC, gives the Netherlands a good position to play an important role in the development of hybrid tandems. Both SMEs and large companies see a role for themselves, if supported by the government, in the development of this sustainable energy technology.

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Appendices

A1. Overview consulted companies:

DSM

Dyesol

First Solar

Heliox

Heraeus

Manz

Panasonic

ReraSolutions

Shell

Tempress

A2. Overview of relevant expertise for hybrid tandems in the Netherlands

Topic & Organisation	Thin film Si	III-V	C(I)GS	CdTe	perovskite	cSi	Q-dots	photon cutting/ pasting	Adv. electrical & optical char. & modeling	Light management	modules	Indoor ALT	Outdoor testing & perf.	Systems & PV integration	economic analysis	LCA
AMOLF					x		x	X		X						
Avans														x		
ECN						x			x	X	x	x		x	x	x
FONTYS														x		
H v Amsterdam														x		
HAN														x		
Hanze H														x		
NH Leeuwarden																
Radboud		x							X			x	x	x		
RuG					x		x		X							
SEAC											x			x	x	
Solliance	x		X		x				X	x	x				x	
TNO														x		
TU/e	x	x			x				X					x	x	
TUD	x				x	x								x		
U. Utrecht													x			x
U. Twente													x	x		x
UvA							x	X	X							
VU					x				X							
WUR														x		
ZUYD													x	x		

Table A 1 **Overview of Universities and research organizations in the Netherlands with relevant expertise for the development of hybrid tandems. Colors indicate type of organization: red, academic; green. 'Hoge school'; blue, research or TO2 organization.**