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SOLLIANCE REPORT

THIN FILM PV ROADMAP

TKI Urban Energy

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CONTENTS

List of abbreviations

PV	PhotoVoltaics
BIPV	Building Integrated PV
I2PV	Infrastructure Integrated PV
VIPV	Vehicle Integrated PV
LCOE	Levelized Cost Of Energy
c-Si	Wafer based crystalline silicon
mc-Si	Wafer based multi crystalline silicon
a-Si	Thin film (amorphous/microcrystalline) silicon
CIGS	Thin film Copper Indium Gallium Selenide
CdTe	Thin film Cadmium Telluride
III-V	(Thin film) III-V multijunction: GaN, GaAs, InP, AlGaAs, etc.
GaAs	(Thin film) III-V single junction Gallium Arsenide
PSC	Thin film Perovskite Solar Cells
DSSC	Thin film Dye Sensitized Solar Cells
QD	Quantum Dot solar cells: e.g. PdS-QD
R2R	Roll to roll
S2S	Sheet to sheet
PECVD	Plasma Enhanced Chemical Vapour Deposition
PVD	Physical Vapour Deposition (evaporation or sputtering)
AP	Atmospheric Plasma
CPV	Concentrator PV
BI-CPV	Building Integrated Concentrator PV
UAV	Unmanned Aerial Vehicles

List of symbols

TC	Temperature Coefficient	% / K
WVTR	Water Vapor Transmission Rate	$g/(cm^2\ day)$
DNI	Direct Normal Irradiance	$kWh/(m^2\ yr)$

1 Samenvatting in het Nederlands

Dit rapport geeft een toepassing- en marktgerichte roadmap voor onderzoek en ontwikkeling op het gebied van dunne film zonneceltechnologie in Nederland.

De roadmap is gebaseerd op internationale ontwikkelingen, groeiscenario's en technische stand van zaken, maar beschrijft deze vanuit het perspectief van specifiek Nederlandse maatschappelijke uitdagingen, marktkansen en sterktes in kennis en onderzoek.

Het dient als één van de vier componenten om te worden samengevoegd tot een algemene Urban Energy "Roadmap voor PV". De andere roadmaps betreffen Kristallijn Silicium zonnecellen, Hybride tandem zonnecellen, en PV Systemen en Toepassingen. Deze drie onderwerpen, en een algemeen overzicht van de ontwikkelingen rond zonne-energie worden hier daarom slechts als context vermeld.

1.1 Nationale missie en ambities

Tezamen beschrijven deze vier roadmap elementen een research agenda voor Zonne-energie, onder meer als input voor de Kennis- en Innovatieagenda "Grootschalige opwekking van duurzame elektriciteit" en gerelateerde Meerjarige Missiegedreven Innovatieprogramma's en als uitwerking van de Uitdaging "Ieder oppervlak wekt duurzame energie op" van de Route Energietransitie van de Nationale Wetenschapsagenda.
Deze duurzame stroomopwekking zal op uiteenlopende plaatsen in onze leefomgeving en in toepassingen geïntegreerd worden, en dit programma zal daarom raakvlakken hebben met andere van zulke meerjarenprogramma's, zoals voorzien voor Gebouwde omgeving, Mobiliteit en Vervoer, Industrie, Agro, en Infrastructuur.

Leidende thema's voor Duurzame Stroomopwekking zijn:

- Optimalisatie en kostenreductie
- Innovatie energiesysteem (conversie, opslag)
- Integratie in leefomgeving

Ambitie voor zonnestroom in Nederland is om rond 2050 te komen tot een niveau van 100-200 GW_p opwekkingsvermogen, en daarmee in tientallen procenten van onze toekomstige elektriciteitsbehoefte te voorzien. Dit komt overeen met een oppervlak van 500-1000 km^2 aan zonnepanelen. Een dergelijk ruimtebeslag is slechts denkbaar door multifunctioneel land- en watergebruik, en door vergaande integratie van zonnecelmaterialen in bouw- en constructiematerialen in de gebouwde omgeving en infrastructuur.

1.2 Het belang van dunne film zonneceltechnologie

Het eerste van de drie thema's impliceert op zichzelf al dat zonneceltechnologie nog lang niet "klaar" is. De stroomopbrengst per vierkante meter kan en moet hoger, omdat dit zowel kosten als ruimtebeslag kan verlagen. Dit betekent dat de efficiency van stroomomzetting verder omhoog moet, vrijwel zonder de productiekosten van celmateriaal te verhogen.

De huidige kostenverlaging in de silicium zonneceltechnologie is voor ruwweg 80% het gevolg van opschaling, en "slechts" voor 20% het resultaat van innovatie. De mogelijke kostenreductie door opschaling is echter begrensd, en de betekenis van innovatie zal toenemen. Hierbij begint de optimalisatie van silicium zonnecellen op natuurlijke grenzen te stoten, die volgens de huidige inzichten overwonnen kunnen worden door het combineren (stapelen) met dunne lagen van andere zonnecelmaterialen, elk speciaal gevoelig voor een ander deel van het zonlichtspectrum.

Dunne film zonnecel technologie (en dunne film technologie voor PV modules in het algemeen) is een onuitputtelijk bron van innovaties gebleken, maar is in opschaling (en daarmee tempo van kostenverlaging) gehinderd door het feit dat er vele technologieën naast elkaar naar de markt zijn gebracht. In deze tijd van opschaling is het relatief aandeel van dunne film PV in de zonnecelmarkt weliswaar gedaald, maar absoluut productie volume, kwaliteit, en snelheid van innoveren nemen alleen maar toe. Het eerste thema richt zich echter niet alleen op verlaging van de financiële kosten van moduleproductie, maar tevens op reductie van maatschappelijke kosten. Daarbij zijn belangrijke voordelen van dunne film PV de kortere energie terugverdientijd en een kleinere ecologische voetafdruk in verhouding tot silicium technologie.

Voor het derde thema, integratie in de leefomgeving, is het voordeel van dunne film PV dat het als een pakketje van dunne lagen op folie of rechtstreeks op constructie materialen (glas, metaal, kunststof) geproduceerd kan worden. In geautomatiseerde productie specifiek op maat gemaakt ("mass customization") kan het worden toegepast in lichtgewicht folies en geïntegreerde producten. Dunne film is minder afhankelijk van mechanisch robuuste verpakking dan (brosse) silicium wafers, maar meer gevoelig voor atmosferische factoren zoals water en zuurstof. Voor het uiteindelijke marktaandeel van dunne film PV zal daarom veel zal afhangen van de mate van succes in het ontwikkelen van goedkopere barrièrefolies (of glasfolies) die in kostprijs kunnen concurreren met het nu toegepaste moduleglas, of het zodanig intrinsiek stabiliseren van de cel dat deze minder gevoelig wordt voor atmosferische invloeden. Niet alleen zou dat de mogelijkheid creëren voor lichtgewicht, maat- en vormvrij produceren tegen lagere kosten, maar de ecologische voetafdruk zou aanzienlijk afnemen als geen vlakglas meer nodig is voor module encapsulatie. Als de PV-ambities voor 2050 gerealiseerd zouden moeten worden met modules uit vlakglas, zou dat een vertienvoudiging betekenen van de huidige totale wereldproductie aan vlakglas voor alle bouwtoepassingen tezamen.

1.3 Focus op drie soorten dunne film zonnecellen

Hoewel er heel veel verschillende materialen in ontwikkeling zijn voor toepassing als actieve zonnecel-laag, focusseert de roadmap op slechts drie typen van materialen, te weten: PSC, CIGS, en III-V (GaAs). Daarnaast worden CdTe en a-Si als referentie beschreven: de eerste

omdat het momenteel het grootste marktvolume heeft (maar nauwelijks kennispositie in Nederland) en de tweede juist omdat er een grote en waardevolle Nederlandse kennispositie aanwezig is die generiek benut kan worden (ook al loopt het ooit beduidende marktaandeel nu sterk terug).
Dit is geen waardeoordeel over andere typen (zoals OPV, DSC, QD) maar is bepaald door huidige belangstelling vanuit de markt en de sterkte van de Nederlandse kennispositie. Oftewel, de aanwezigheid van voldoende stakeholders om de roadmap mogelijk te maken en te motiveren. Bovendien zijn veel aspecten die deze roadmap adresseert zodanig generiek voor alle typen dunne film zonnecellen dat het hele veld hiermee gediend is, en een goede uitgangspositie creëert als een ander type PV actieve laag belangrijker wordt.

CdTe: Vooral voor grootschalige PV
Slechts één fabrikant van dunne film zonnecellen produceert een volume van meerdere GWp per jaar (First Solar, VS). Tot rond 2015 was dit ook de producent met de laagste productiekosten, totdat het schaalvoordeel van silicium te groot werd. CdTe wordt vooral toegepast in grootschalige projecten, met name in zonrijk en heet klimaat, maar ook kleinschaliger op daken en zelfs als semi-transparant vensterglas. De omzichtigheid die betracht moet worden om een cadmium houdend product in de markt te zetten heeft geleid tot een zeer beperkte toepassing op de consumentenmarkt. Enkele Aziatische partijen bouwen momenteel op basis van westerse (waaronder ook Nederlandse) technologie productiefaciliteiten voor CdTe.

CIGS: Vooral voor integratie, dicht bij de consument
Eén fabrikant (Solar Frontier, Japan, type CIGS) produceert rond 1 GW_p per jaar, en een aantal Chinese initiatieven met GW ambitie zijn in opschalingsfase (nu honderden MW_p elk, met westerse technologie partners, waaronder NL). Een vijftiental producenten is actief, zonder uitzondering met focus op integratie, en voor meer dan de helft met flexibele producten (staal of kunststof folie); met name voor in de bouw (gevels, daken). Cellen en modules kunnen gemaakt worden in vrijwel elke denkbare vorm, van grootschalige energie opwekking tot consumenten-producten. Het is het werkpaard van de huidige Nederlandse dunne film PV roadmap.

PSC: Veelbelovende ontwikkeling voor alle toepassingen
Perovskiet maakt een snelle ontwikkeling door waarin Nederland (Solliance) tot de wereldtop behoort; en is daarom paradepaard in de roadmap. Het heeft naast nog op te lossen grote uitdagingen vooral ook enorme potenties (record lage kosten, hoge efficiëntie, en bij uitstek geschikt als tandem met silicium). Het verkeert nog in ontwikkelfase. Het zou de goedkoopste PV-technologie kunnen worden, en zou ook boven TW-schaal niet gehinderd worden door schaarste van grondstoffen. Veel zal afhangen van voortgaande stabiliteitsverbetering, goede encapsulatie tegen lage kosten, en de mate waarin toxische componenten een rol zullen spelen.

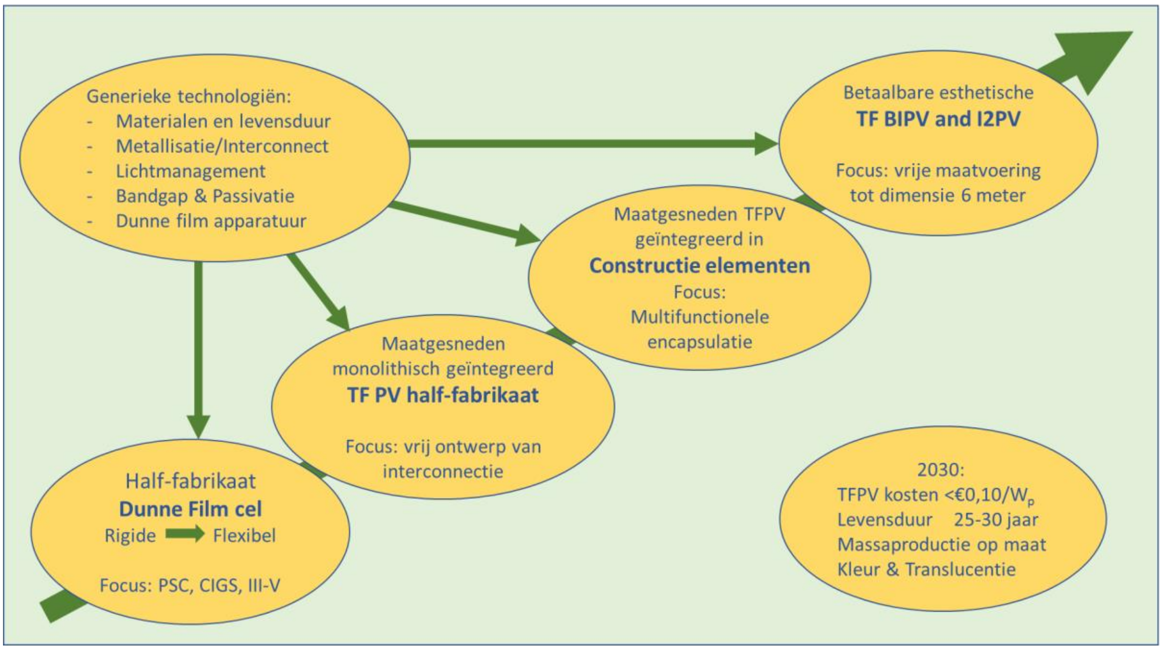
III-V: Hoogste rendement, maar uitdaging in opschaling
Het raspaard in de roadmap, met verreweg het hoogste rendement en een bewezen betrouwbaarheid en levensduur, vooral in ruimtevaart toepassingen. Intrinsiek zeer goed bestand tegen grote temperatuurwisselingen, en geschikt voor gebruik onder geconcentreerd zonlicht. De momenteel maatgevende III-V multi-junctie zonnecel is de tripel-junctie InGaP/(In)GaAs/Ge cel. III-V zonnecellen worden geproduceerd op 4 inch diameter Ge halfgeleider wafers, omdat alle samenstellende lagen in een kristalstructuur “groeien” die zijn ordening ontleent aan de kristalstructuur van deze ondergrond. Omdat deze kristallijne Ge wafers niet alleen relatief klein,

maar ook kostbaar zijn, bleek een Nederlandse vinding om het zonnecelmateriaal na productie los te maken van deze ondergrond ("lift off") een route naar opschaling en flexibele producten te openen door het substraat telkens opnieuw te gebruiken. Deze opschaling is een uitdaging, maar komt steeds dichter bij commercieel relevante productiesnelheid. Naast toepassing van III-V op Ge substraat onder geconcentreerd zonlicht (NL module concepten) zullen eerste integratietoepassingen van folies vooral hoogwaardige producten met beperkt beschikbaar oppervlak betreffen, zoals auto's.

a-Si: Ooit de grootste in dunne film PV, maar onvoldoende rendement
Het vorige werkpaard, zowel voor grootschalige toepassingen als voor integratie. Geen beperkt beschikbare grondstoffen nodig, geen toxische bestanddelen, en een potentie voor lage kosten door het produceerbaar te maken op grote substraten (2,2x2,6 m^2 glas en roll-to-roll folies). Enerzijds door de onverwacht snelle kostenreductie van kristallijn Si cellen, en anderzijds door een combinatie van opbrengst (yield) problemen met kostbare productie apparatuur, en een beperkt module rendement hebben de meeste producenten zich teruggetrokken van de markt. Nederland heeft echter een sterke kennispositie opgebouwd, zowel publiek als privaat (zoals HyET). Deze kennis is generiek waardevol voor dunne film PV in het algemeen, en tevens voor toepassing in kristallijn Si PV.

1.4 Roadmap voor geïntegreerde dunne film PV

Op basis van de maatschappelijke behoefte aan grootschalige geïntegreerde zonnestroom-opwekking (BIPV, I2PV, VIPV), de economische kans en wenselijkheid om eigen lokale PV productie in Europa en Nederland te ontwikkelen in de vorm van slimme modules, integratie van maatgesneden PV in bouwelementen, constructiematerialen en producten, én de aanwezige sterktes in de Nederlandse kennispositie (zowel publiek als privaat), is de hier schematisch weergegeven "Roadmap voor geïntegreerde dunne film PV" ontwikkeld en in detail uitgewerkt.



2 Summary

2.1 Goal of this roadmap document

This document provides an application- and market driven roadmap for research and development on Thin film Photovoltaics in the Netherlands.
It describes this development in technological terms, aiming at international application-driven targets and specifications for thin film PV, but from the perspective of the Dutch national research and market environments.

Scope
It will serve as one of the four components that will be synthesized into an overall TKI Urban Energy “Roadmap for Photovoltaics”. The other roadmap topics will be Crystalline silicon PV, Hybrid tandem solar cells, and PV Applications. This Roadmap should steer and focus the research that will be performed in the coming years under the Dutch Top sector Energy, and provide targets and international benchmarks that can be used to measure progress.
The synthesized Photovoltaics roadmap will provide a general introduction how Climate goals motivate the development of methods for durable Energy generation, how Photovoltaics can develop to provide a serious contribution to a future durable energy mix, and how the PV research agenda relates to the *Nationale Wetenschaps Agenda*. The PV Applications roadmap will describe in which modes PV should be integrated in our environment. These topics are therefore not addressed here, and this roadmap document is limited to the technological and market economic aspects of the Thin Film PV Roadmap.

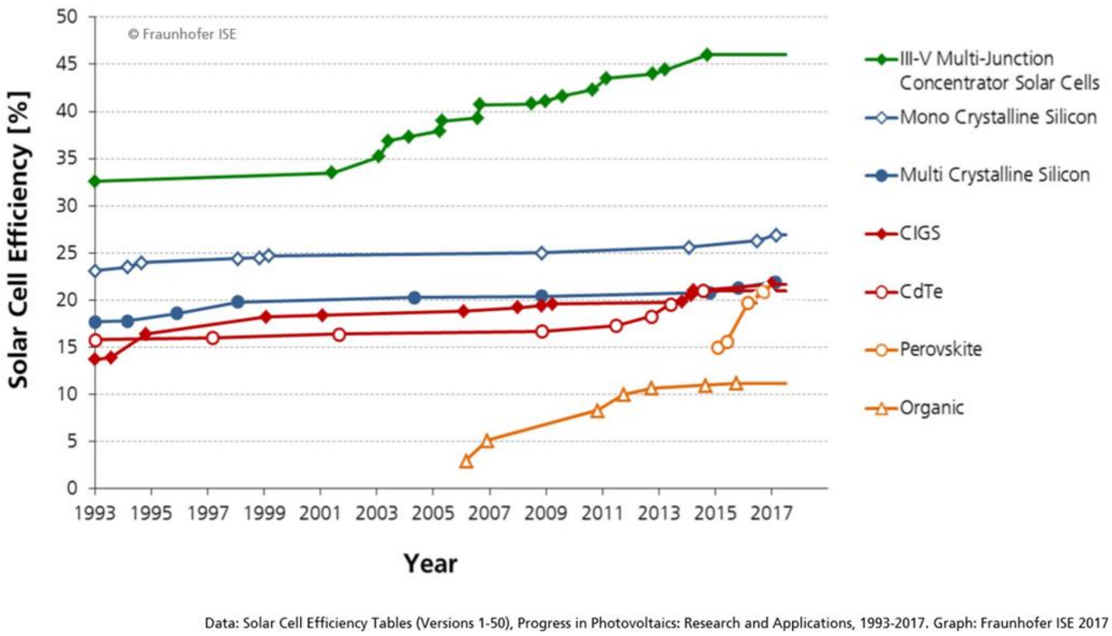


Figure 1: Solar cell efficiency records for several types of absorber material.

2.2 Motivation of technology focus

The definition of technology-specific time lines will be focused on three of the four types of presently commercial relevant thin film PV technologies, all of which enable competitive efficiency levels with respect to silicon (Figure 1). They are characterized by the type of absorber material: CIGS, PSC and III-V, respectively.
The selected focus on these three thin film PV technologies is by no means meant as any disqualification of the others (history has learnt and may learn again that both market relevance and applied/scientific research interest vary over the years). But the combination of these two, current market relevance and research strengths (Table 1), motivates the current focus:

- PSC: Recent rapid increase in research cell efficiency, low cost potential and suitable band gap for tandem formation with crystalline Si result in very high market- and research attention. Dutch knowledge position is strong (utilizes OPV experience), and through highly innovative Solliance facilities realized by Dutch R2R-equipment, NL/B research attracts worldwide market attention as it uniquely combines world class efficiencies and (S2S and R2R) upscaling capabilities. In 2017, world record efficiency for low cost R2R solution processed PSC was achieved, and tandem efficiency of semitransparent PSC on glass with crystalline silicon came very close to the current world record.
  Involved NL research groups: Solliance partners TNO, ECN, HolstCentre, TU/e, TUD + RUG, RU, UvA, AMOLF

- CIGS: At present the commercially most relevant demonstrator for thin film module formation. Efficiency is higher than a-Si, and it is more suited for integration than CdTe. A variety of producers is active in the market, several with GW-scale ambitions, more than 50% with flexible product ambitions, and 100% with BIPV ambitions. CIGS market share in Dutch installations is one of the highest in the world, and market interest for customized and integrated CIGS production in NL is growing. Although Dutch academic background in CIGS is not leading in terms of cell efficiency records, expertise on equipment and processing for customization, s-ALD barriers, -passivation and -buffers, sequential CIGS processing, and also reliability research is world class.
  Involved NL research groups: Solliance partners TNO, ECN, HolstCentre, TU/e, TUD + RU

- GaAs / III-V: The class of PV materials with highest conversion efficiencies. Dutch research not only held previous world records for epitaxially grown thin films on wafers, but it also was the cradle of thin film formation by Epitaxial Lift Off (ELO), which is now leading to industrial development of flexible III-V module formation, and might open new high end markets. III-V is unrivalled in space applications, and Dutch commercial and research activity on integration in spacecraft is strong. It is also extremely suited for solar concentrator applications, also for BI-CPV in NL. And technically, it is the winner in VIPV.
  Involved NL research groups: RU, Solliance-TNO (Integration), TUE (nanowires).

The selected thin film routes can thus be characterized as: PSC with focus on scaling and durabiltiy research, CIGS with focus on customized module research, and III-V with focus "transfer to thin film" and multijunction research. In this sense, together with the presented roadmaps for enabling technologies, they are generically relevant also for other types of thin film PV (CdTe, a-Si, OPV, DSSC, QD).

TF type	Technology status world wide	Technology status Netherlands	Specfic strengths of Dutch ecosystem
CdTe	Mature (GW); growing; competitive in utility scale	Equipment manufacturing *No production development* *No module integration* Installation: in solar farms, BAPV roofs, BIPV windows	Thermal processing *No research*
CIGS	Mature (GW); growing; close to competitive in integration; widest variety of module concepts and demonstrated application in every PV market domain	Equipment manufacturing 20 yrs Industrial process development (Scheuten*, Dutch Space*, Solliance) Module integration start ups Business cases for semi fabricate production Installation: in solar farms, BAPV roofs (also flexible), BIPV roofs and facades	2step absorber processing; Customized module formation; ALD; Reliability testing; Integration (free form foil; I2PV road surfaces Research: TNO, TU/e Kessels (ALD), TUD Zeman (Reliability), AMOLF (plasmonics), ECN (device physics)
GaAs III-V	Mature; growing; unrivalled in space; competitive in CPV; pilot TF production	Very small scale production Integration for space; CPV module integration startups	Research: RU Schermer (former effic record; ELO) AMOLF (photon recycling), TUE Haverkort (nanowires)
a-Si	Mature (100MW); declining; potential relevance for flexible and semi-transparent PV applications	Equipment manufacturing 20 yrs industrial process development (HyET), <1MW production capacity. Few installations (glass); pilot installations (flexible)	Absorber and multilayer processing; Low cost R2R flex module concept (HyET); Research: TUD Zeman (Light trapping, multijunction), RUU* Schropp, TU/e vdSanden, ECN (absorber deposition)
OPV	Pilot production; stable; close to competitive in niches; color attractiveness	Equipment manufacturing *No production development* *No module integration* *No installations*	Research: TU/e Janssen, RUG vHummelen (former effic record), TNO (precursors*); HolstCentre (R2R proc), ECN (cell development)
PSC	Low TRL; growing: high efficiency with yearly improving stability; low cost potential; potential tandem with cSi.	*Equipment manufacturing industrially viable process development (>1 km produced) by VDL-ETG, STS, Bosch-Rexroth and Maan*	Research: TNO HolstCentre +ECN (S2S and R2R prod dev; record eff's), TU/e, RUG (material), TUD (nano), RU (optical char)
DSSC	Niche production (demo facades, roofs, products); stable; color attractiveness	*No commercial activity*	Research: ECN*, TU/e Kessels (interfaces)
QD	Low TRL; increasing record efficiencies; potential for photon splitting/multiphoton;	*No commercial PV activity*	Research: TUD (Siebeles), RUG, RUU, TU/e, AMOLF

Table 1: Summary of technology status and national strengths for different types of thin film PV. *"Mature" indicates that products are (or were) commercially available on the market with sufficient* reliability. *)Terminated activities which had international impact of which expertise is still available.

This TKI Urban Energy Roadmap thus substantially supports these technologies, but the definition of these absorber-specific research lines is left to fundamental university research programs. It is noted that although in recent years focus of the thin film roadmap switched from OPV to PSC because of the much faster progress of the latter, very recent advances in OPV (13% cell record) and long term developments in QD are followed with great attention. Although not specifically addressed by research under TKI Urban Energy, on relevant aspects reference is made to CdTe (First Solar, US), as it is an important reference for all commercial thin film PV technology. And although worldwide thin film a-Si production has greatly declined, the specific flexible a-Si concept of HyET (NL) is an important asset for the flexible thin film roadmap goals, and continued research on thin film silicon is not only justified by the thin film market, but even more by the wafer based Si market.

Before limiting the scope to thin film PV and focusing on only a few selected thin film PV technologies, the first paragraph of this roadmap starts from a wider perspective. Thin film deposition and patterning are highly generic technologies, and Dutch industry and research acquired leading positions in this field, built on many decades of experience. Continued R&D on these equipment and process technologies is also supported under the Dutch Topsector HTSM. As they are generically applicable to both crystalline wafer based PV and thin film PV the most relevant topics are discussed in paragraph 2.1.

Therefore, this document starts from the viewpoint of thin film technology in general. After that, it focuses on specific thin film PV technologies. And it resumes a more generic approach as the roadmap for thin film PV technologies in general is described in terms of four generic enabling PV technologies: Materials & Reliability, Metallisation & Interconnection, Light management and Passivation & Bandgap control, which are the same generic enabling technologies both for crystalline and thin film PV.

2.3 Roadmap and targets Urban Energy program Thin Film PV

Based on the global status of the technology, the specific strengths of the Dutch industry and research environment and on market demands, this roadmap proposes to focus the Urban Energy program Thin Film PV as follows (see Figure 2):

- Goal:

Low cost production of high quality (efficiency, life time) low carbon footprint PV cells in the form of large area (glass and flexible foil) semi-fabricates, designed for customized module production that is aimed at optimized PV-integration in construction elements for BIPV and Infrastructure Integrated PV.

- Roadmap:

From mass produced standard glass modules towards automated production of BIPV and I2PV construction elements by integration of customized flexible PV-semi-fabricates.

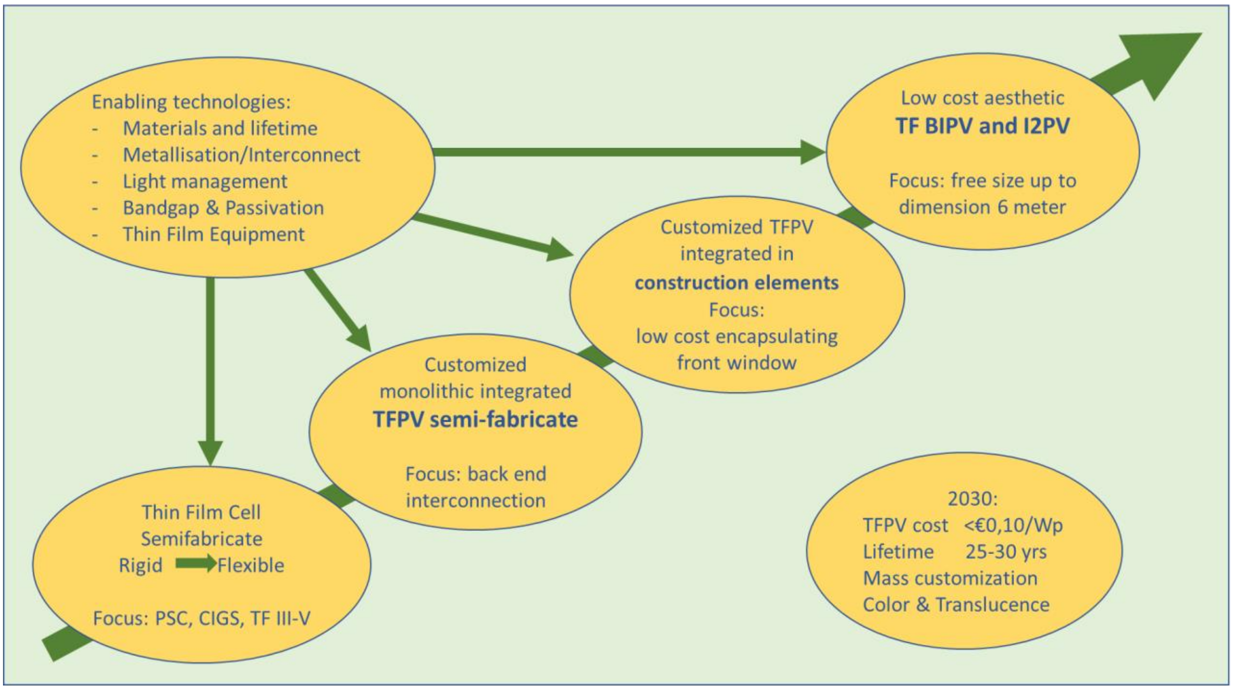


Figure 2: TKI Urban Energy thin film PV roadmap towards 2030

Focus will be on:

- thin film PSC, CIGS and III-V (multijunction and single junction GaAs)
- improved efficiency and durability at reduced cost
- flexible semi-fabricates for BIPV, I2PV, VIPV, with freedom of shape and color
- customized monolithic interconnection after completion of active layer stack
- cost reducing multifunctional front window encapsulation
- improved understanding of TF degradation and prediction of reliability and life time
- shadow tolerant and aesthetic design
- recyclability

High level targets:

- 2030 target: TF flexible PV: cost <0,1 €/W_p, (aperture area) module efficiency >20%, lifetime >25 years.
- Perovskite PV: 25% small-area champion cell efficiency @TRL4; 22% medium/large-area rigid modules and 20% medium/large-area flexible modules from pilot production lines
- TF semi-transparent PV for windows with 50% transparency (VIS) and >10% module efficiency
- TF flexible, low-weight PV for Unmanned Aerial Vehicles (UAV) and other Vehicle Integration (VI) of 600 gr/m^2 and >30% module efficiency.
- Enhanced acceptance of PV in public space by design at all levels.

Operational targets 2020:

- Proven material compositions, processes and device designs for roll to roll PSC module formation on flexible polymer foils (2020: 17% module efficiency on 15x15 cm^2 size and 15% on 30x30 cm^2).
- A flexible low-cost substrate, containing an electric barrier to allow for monolithic (back-end) interconnection.
- A customizable digital back-end interconnection process and equipment (S2S and R2R).
- A low-cost flexible front sheet and/or packaging technology which allows for sufficient water protection as well as outdoor weathering and physical protection for the (integrated or to-be integrated) PV module element (50% cost reduction for CIGS encapsulation by improved inherent device stability and alternative encapsulation strategies).
- Proven material compositions and processes and device designs for CIGS module formation on steel foils (2020: 16% module efficiency on 30x30 cm^2 size)
- Shunt-free CIGS (sheet to sheet) and PSC (roll to roll) back end interconnected modules with reduced dead zone (<200 μm) and free size customization capability
- Proven material compositions, device designs and processes for III-V module formation on metal foils (2020: 22% module efficiency on 24x24 cm^2 size).
- Demonstrators of multifunctional front window encapsulation: use of construction materials to replace module front window materials (e.g. glazing, molded polymer elements, transparent bitumen road surfaces).
- Development of industrially viable wafer separation and reuse for III-V, and optimization of multijunction cell efficiency
- Free shaped and free colored modules
- Modules with improved recyclability

3 Roadmap for thin film PV in general

The field of thin film PV is characterized by a very large variation of products, which are generally characterized by the type of absorber material that is applied as the active layer. The commercially most relevant types will be discussed in chapter 3. Here in chapter 2, important general aspects that define the thin film roadmap as a whole are discussed, and they are input for the enabling roadmaps in chapter 4.

However, as thin film technology is an enabling technology in itself, the first paragraph will reflect on the Dutch position on thin film technology, and its relation to PV production in general.

3.1 Thin film technology for PV

The European framework technology programs of the last decades, and also the present Horizon 2020 program, are focused and organized along lines of enabling technologies. Industrial thin film technology first strongly developed in Microtechnology in the last decades of the previous century. Micron-scale semiconductor technology was the driving force to develop process equipment for highly controllable deposition of thin films from the gas- and liquid phase. Chemically resistant vacuum pumps, gas and liquid delivery systems, as well as product positioning and handling were made available and produced at lower cost, thereby also allowing thin film technology to spread to less added value markets. In this period, the Dutch ecosystem developed its strong position in this field. Not only a wide variety of thin film companies on silicon based semiconductor technology (like Tempress, ASMI, Philips semiconductors) and coating equipment (e.g. PMF/VDL-ETG, NTS, MECO, IHI Hauzer Technocoat) developed, but also on glass coating (e.g. Philips lighting and displays, Scheuten, VDL ETG, Smit Ovens), magnetic and optical recording (PDM, Toolex/OTB, OM&T/Morphotonics, Anteryon), wear resistant coatings (Bodycote), photographic materials (FujiFilm), precursor- and material chemistry (DSM, AkzoNobel), thin film lithography (ASML, MAPPER) and thin film analysis (FEI) evolved.

This thin film ecosystem with its long history is a major asset for the continued development of PV technology in the Netherlands, both for crystalline based and thin film PV.

Around 2010, when mass production of PV started to take off, Dutch equipment manufacturers had about 5% of the world equipment market for photovoltaics (Table 2, Roland Berger, with data from 2010). When the world market peaked in 2011 (Table 3), unpublished background information to the Roadmap “Zon op Nederland” (Berenschot, 2011) revealed a Dutch turnover in the order of 500 M€/yr, which was especially remarkable as it seemed to defy the economic crisis that started in 2008. At that moment in time, the Dutch turnover in equipment was tenfold the turnover in Dutch PV installations
A major part of the total 500M€ turnover concerned thin film equipment: SiN for the crystalline market, and tools for major suppliers in aSi, CIGS and CdTe. Also, at that time there were four or five Dutch companies with PV (cell) manufacturing ambitions, three of which on thin film, and all three with a focus on roll to roll production: Helianthos/HyET (aSi), Scheuten Solar (CIGS), and Dutch Space/Airbus (CIGS). As it was expected that both aspects of PV (equipment as well as installations) would show explosive growth, 30 M€ was invested in the Solliance platform for thin

film PV equipment and process development. Two Dutch Topsectors, High Tech Systems and Materials (HTSM) and Energy, acknowledged the importance of photovoltaics, and cofinanced the thin film equipment, process, and device development through a dedicated Roadmap (HTSM) and a TKI (Energy).

	HIGH TECH					ENERGY	
	Research & development/ consultancy	Production equipment	Silicion, wafers and other materials	Cells / modules	BOS materials	Installation & maintenance	
GLOBAL MARKET SIZE [EUR Bn]	0.5-0.8	4.5-7.2	7-8	14-16	3-5	11-13	∑ 40-50
TURNOVER NL [EUR m]	30-35	250-300	-	350-375	50-75	25-50	∑ 700-800
MARKET SHARE NL [%]	4.5-6%	4-5.5%	-	2-2.5%	1.5-2%	0.2-0.4%	∑ 1.6-1.8%
EMPLOYEES NL [FTE]	200-250	700-750	5-10	900-1,000	225-250	100-200	∑ 2,100-2,500

Table 2: The Dutch PV solar energy sector in 2010, at the first definition phase of the Top sector Energy and the TKI Solar (adapted from: A Vision for the PV sector – update April 2011, Roland Berger; input document for the Top Team Energy).

However, the PV equipment market declined by almost an order of magnitude due to the overcapacity that had been created, and remained low for several years. Moreover, due to the rapid price erosion of PV, to date none of the Dutch production facilities has come to maturity. In that period of recession however, it was noted that one of the few types of equipment still being sold were pilot production (spatial-) ALD tools (SolayTec, Levitec, ASMI, Roth&Rau/Meyer-Burger); one of the core thin film equipment technologies of Solliance (TNO and TU/e). As well as selenisation equipment for CIGS and tools for CdTe.

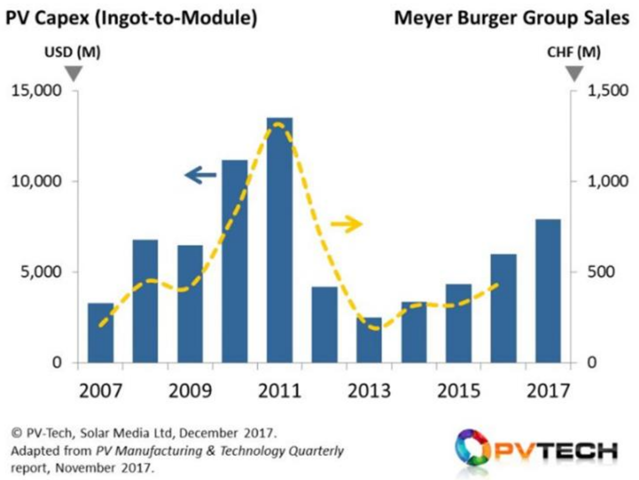


Table 3: Worldwide spending on PV equipment up to 2017, peaking in 2011 (which was also due to major investments in thin film), and recovering towards 2017. Further increase in 2018 is expected, due to a combination of technology upgrades (e.g. n-type Si and bifacial) and capacity increase. [1]

From 2015 the equipment market started recovering, although not to the level of 2011. Most recently, it was reported (VDMA 2017 [1]) that the strongest sales segment in the second quarter 2017 for German PV manufacturers was the production equipment for cells (59%), followed by Production solutions for thin-film PV (24%). Although the production of modules based on CIGS and CdTe thin-film technology is less than 7 percent on the world market, the thin film PV equipment part of the market has been larger than that for the past few years. In the last year (2017) about 500M$ of new investments in CIGS equipment were announced, while also CdTe market leader First Solar is adapting its factories to larger module size, and Chinese CdTe manufacturers like CNBM open new factories.

Government policies in countries with a high level of PV production also aim at an increasing level of locally produced equipment. This has a negative effect on Dutch or European job creation in PV equipment building. In terms of value creation it depends whether the equipment manufacturer shifts part of its production to the nation of its customer, or that they are taken over by investors from these nations.

For this roadmap, following aspects are most relevant:

1. As described above, the PV equipment market is growing again. Dutch equipment manufacturers and supply chain are in a competitive position to participate in this growth. But for many of these companies, the opportunities for high revenues in the PV market are declining because of fierce competition and interfering national policies. Therefore, they are not as much the drivers for this roadmap as they were at the beginning of this decade.
2. The foreign (thin film) PV manufacturers however, are stronger connected to the Dutch roadmap than 5 years ago. Virtually all thin film PV manufacturers recognize this roadmap as relevant for their own development, and they are particularly attracted by the fact that thin film process and device development in this program is performed in close cooperation with (Dutch) equipment manufacturing capabilities. The needs for process innovation of the PV producers have become the new driving force. In other words, the innovation drivers have changed from (local) PV-equipment driven technology push to (foreign) PV-production market pull.
3. The technologies that are addressed by this thin film PV roadmap are in line with the enabling technologies as addressed by the roadmap of the current European Framework Program. The most relevant are Renewable Energy, High End Equipment, Smart manufacturing (Industry 4.0), Nano-photonics, and Materials. Apart from their relevance for PV production, most of the technology developments required for PV are of generic relevance an contribute to progress in these enabling technologies. (In fact, in the competition for human talent, renewable energy and PV research act as an important societal motivator to contribute to the development of these enabling technologies).
4. Contrary to the situation in 2011 described above, at this moment Dutch economic activity in PV installation has become much bigger than in production and production equipment. In this growing installation market, it is noted that thin film PV is more popular on the Dutch market than in most other markets. In 2015, CIGS market share exceeded 10%, while it was 3-4% worldwide. In 2017, thin film was present in all Dutch PV market segments: private homes, industrial roofs, facades, windows, ground installations and even in road elements.

5. PV production is returning to Europe in the form of added value module design and PV-integrated construction elements, based on import of PV cell materials mass produced elsewhere. Also for thin film, and especially in the Netherlands where it is more than average appreciated by (BIPV) integrators and customers. Driving ambition for this roadmap is therefore to serve the growing installation market, and especially BIPV and I2PV with (locally produced) customized module formation, based on (possibly elsewhere) mass produced cell materials.
6. The nature of thin film production technology will develop to adapt to the scale of PV production.

To explain this last point, which motivates the choice to focus the roadmap on roll to roll flexible PV production, the development of the scale of PV is described in orders of magnitude, with reference to the scales of other thin film markets.

Year	PV production capacity (order of magnitude)	Total area of PV
2000	0,1GW/yr	3 km^2/year
2010	10 GW/yr	100 km^2/year
2020	100 GW/yr	1000 km^2/year
2035	*1000 GW/yr*	*10.000 km^2/year*

Table 4: Order of magnitude of total area of photovoltaics worldwide produced per year.

Year	Thin film product	Thin film processing size	Total area of thin film coated product
2010	Silicon for IC manufacturing	0,3 m diameter wafer	6 km^2/year
2010	LCD screens	2,2x2,6 m^2 (GEN 8)	300-500 km^2/year
2010	Optical data storage	0,12 m diameter CD (>10^{10}/year)	400 km^2/year
2017	Float glass	6m wide Jumbo glass 1 floatline: 25-40 km2/year	10.000 km^2/year
2017	Coated packaging foils	Several m wide	>100.000 km^2/year

Table 5: Order of magnitude of total area of thin film products worldwide produced per year.

At the turn of the century, worldwide production of silicon solar cells (Table 4) represented a total surface area which was of the same order of magnitude (but smaller) than the total area of wafers that was processed for semiconductor integrated circuit manufacturing (in the order of 6 km^2/year; Table 5) and Tempress decided to use it's background in thin film technology for silicon-IC production to enter the silicon PV market. In the decade that followed, PV started to consume more silicon than semicon. At first, this led to a silicon shortage, and the high cost of wafers was one of the drivers for thin film PV to emerge with a clear cost advantage. This was foreseen also by Dutch AkzoNobel (aSi) and Scheuten (CIGS), both starting their thin film PV pilot production developments at that time, by in-house developed processes with a focus on low cost substrates. But after that period, dedicated wafer manufacturing for PV-grade silicon became available, and prices steeply declined.

Around 2010, the yearly produced area of PV passed 100km^2/year, and approached the volume of LCD manufacturing at that time. As Applied Materials was frontrunner equipment supplier in

this field, it launched LCD manufacturing technology as a means to build turn key thin film aSi factories, and introduced the scaling laws of price-experience curves for thin film products to the PV world. Their prediction in 2011 for the thin film PV cost reduction roadmap (expectation $0,30-0,70/Wp in 2020) was not far off, but their estimate for silicon wafer based PV betrayed them (expectation was 0,60-0,80/Wp in 2020) and in 2012 they withdrew from the market, mainly because of limited cell efficiency, yield problems and high equipment cost (low pressure PECVD). Now in 2017, First Solar (US) and CNBM (China), both originating from an architectural glass processing background, are entering the PV market with similar size but 70% higher (CdTe) module efficiency and lower cost technology. Where customers of Applied Materials had to feed their aSi-production lines with specially fabricated textured-TCO coated glass, the TCO for CdTe is now mass produced at the glass float line at extremely low cost.
Thin film optical data storage (CD, DVD) manufacturing was at the same level (400 km2/year), and every company in this field entered the PV market around that time (Toolex/OTB assisted Shell Helmond in upscaling; its close relation Midsummer (Sweden) still builds CIGS systems for cells of CD-dimensions (module production starting in China). OM&T was successful in upscaling of nano imprint technology from CD level to textures for light management on large glass size for Applied Materials customer Moser Baer (India). After that, it continued as Morphotonics.

Now in 2017, a level of 100GW/year is in sight, corresponding to some 700km^2/year. The biggest producers operate at n-GW scale, corresponding to nx7km^2/year volumes. Where Scheuten had the right vision and ambition to build a dedicated PV glass float line for ultra-clear low iron glass in Germany, but could not foresee that most PV production would have left Germany so rapidly, and where Applied Materials had predicted that one dedicated glass float line with in line APCVD coated F-SnO_2 could serve 4 thin film GEN8 production lines, it is now the Chinese who have made this step. China (CNBM) produces 60% of all ultra-clear PV glass, and the worldwide installed production capacity approaches 1000km^2/year. The majority of PV cover glass is coated with a thin film antireflection layer. And Dutch DSM made public that it serves more than 50% of the world market for such antireflection coated glass.

Dutch Company	TF Strength / expertise	PV thin film application
Tempress SolayTec	LPCVD, PECVD s-ALD	cSi cell manufacturing cSi Passivation
Meyer Burger NL	PVD, PECVD, ALD, Jetprinting Integrated process lines	cSi AR and passivation TF interconnect, TCO, R2R barriers
Smit Thermal Solutions	Thermal processing	CIGS selenisation, CdTe, TCO
Levitech, ASMI	s-ALD, ALD	
MECO	Electrochemical deposition	Metallisation (cSi, glass, foil)
Fuji Film Tilburg	R2R printing, AP deposition	Barriers
Scheuten	PVD on glass	Customised PV integrated glass, AR, CIGS,
AkzoNobel/Helianthos/HyET	Flex module encapsulation, R2R a-Si, R2R APCVD TCO	R2R a-Si, TCO, metallisation, interconnection, encapsulation
OM&T/Morphotonics	Nano imprint	Light management, trapping
DSM	Wet chemistry nano coating	Module glass AR, light trapping
VDL ETG	Process chambers, handling, integration	(Sub)systems for cSi and TF glass and R2R
NTS	High precision equipment	s-ALD
Maan	Advanced plasma reactors	Plasma processing and gluing

The next step towards 2030 is the theme of this roadmap.
It is generally expected that PV will continue to grow to multi-TW scale, and thus, in terms of thin film coated area, towards an order of magnitude of 10.000 km^2/year. In terms of glass, this would correspond to the current total volume of the global architectural glass market. In general, the area of PV will reach an order of magnitude which is substantial in relation to total areas of built environment. For the Netherlands, 300GWp would correspond to a PV area >5% of the nations' land area, while currently 10% of the land area is built environment.
In terms of thin film coating technology, the only domain where such volumes are already common practice, is roll to roll coating of flexible foils. Apart from the high volume potential, inherent advantages of foils are ease of customization and integration, reduced weight.
As it is desired to reduce the embodied energy and material consumption of the built environment, PV should be integrated in the construction materials that are applied there. A flexible PV semi-fabricate not only allows for low cost ease of integration, but may also be designed for ease of disassembly to allow for circular economy and retrofitting in case of differences between economic lifetimes of PV and construction elements.

Thin film equipment roadmap	Status 2017	Target 2018	Target 2019	Target 2020	Target 2030
Spatial ALD - Thermal ALD - (Atm) Plasma Enhanced ALD - Patterned ALD - Atomic Layer Etching (ALE)	TRL8 Si wafer Al2O3 TRL6 R2R 50cm wide TRL4 Float glass 30cm TRL3-4 Plasma ALD TRL2-3 ALE	Uptime and process control; reliable gas heads → Pinhole free barriers; controlled nm holes for passivation → Plasma activated ALD for passivation/light management layer formation → Demo ZnOS on CIGS on glass	TF passivation	Nanoscale surface etching/cleaning →	
Printing - In line jet printing (R2R) - Screen/stencil printing - Slot die coating (R2R)	Iso line print Metal line print R2R30cm PSC stack	Thinner lines; Reduced dot spreading → Rheology and wetting; thickness control; quenching/curing →		R2R 50nm deadzone	
Nano imprinting - Texturing (R2R) - Nano transfer printing - 3D nano imprint	Light mgmt. texturing 100nm on 1m wide glass or foil	Control CIGS selenisation/sulphurisation → Imprinting contact holes →	Upscaling for plasmonic devices →		
Thermal processing - RTP alloying - Thermal quenching (R2R)	RTP Se/S 30cm wide Concept (for PSC)	Control CIGS selenisation/sulphurisation → Accelerated quenching / curing →			
Laser treatment - Scribing/ablation (R2R)		Free form laser scribing: in line glass and roll to roll → Fast laser scribing: semi transparent PV concepts →			
Epitaxial lift off	Accelerated release rate and improved control →				

Table 6: Thin film equipment roadmap for general technologies that are/will be needed for PV, and are supported by strengths of Dutch equipment manufacturing. Most of these topics are also recognized in the 2017 application for joint equipment investments in SOLARlab.

Therefore, this thin film roadmap will be aimed at high volume, low cost, roll to roll thin film processing for high efficiency flexible PV semi-fabricates, optimized for on demand customization, reduced sensitivity to climate conditions and mechanical loads, high aesthetics, and designed for disassembly and circular use. All of these to comply with the desire to integrate ubiquitous PV in multifunctional building and construction elements.

Dutch equipment manufacturers are well positioned to play a substantial role in this market. An indicative roadmap for R&D on (R2R) thin film manufacturing technologies required for PV

production, and which can be supported by specific strengths of the Dutch HTSM ecosystem is given in Table 6. With a consortium of Dutch partners, a versatile roll to roll thin film processing facility has already been made operational and shown to produce research samples at lengths of hundreds of meters.
All solution processed PSC will be the focus, while gas phase processed CIGS is currently the most market relevant demonstrator for module development. Upscaling and acceleration of lift off processes and interconnection strategies for thin film GaAs and III-V multijunction cells are a desirable case for high end VIPV and airborne systems. Flexible CdTe is not an industrial topic. aSi suffers from low-end performance but provides a valuable background of proven flexible device processing solutions. Apart from the crystalline absorber, most of these thin film processing capabilities will be equally important as enablers for the cSi roadmap.

3.2 Thin film PV market

At present, thin film PV has a PV market share of about 6% (data 2016). Cumulative installations of thin film PV are in the order of 23 GW, corresponding to 7,6% of the total PV installations worldwide.

In the previous decade (2000-2010), more than 100 thin film companies and startups have been on the market, and in 2009 the thin film share of the total PV market peaked at 17%. It was the time of silicon shortage and relatively expensive IC-semiconductor grade wafer production, giving thin film a cost advantage that enabled good business opportunities many of these companies.

In the present decade however (2010-2020), when dedicated high volume low cost production of PV-grade silicon wafers came to the market and PV production shifted to Asia, PV price erosion occurred so fast that most thin film companies failed to sufficiently speed up their simultaneous quality improvement and cost reduction. Strategies that were based on system cost reduction by compromising on module efficiency failed. At present, the balance of system cost does not lead to viable business cases for module efficiencies below 12%. As a consequence, thin film silicon (either in the form of a-Si, microcrystalline Si, tandem of triple junctions) is rapidly declining in the market, despite the multi-billion investments in upscaled mass production facilities led by Applied Materials and Oerlikon at the turn of the decade. Also dye sensitized solar cells and (DSSC) and organic photovoltaics (OPV) so far failed to take this 12% hurdle, and up to this date no substantial scale production was achieved.

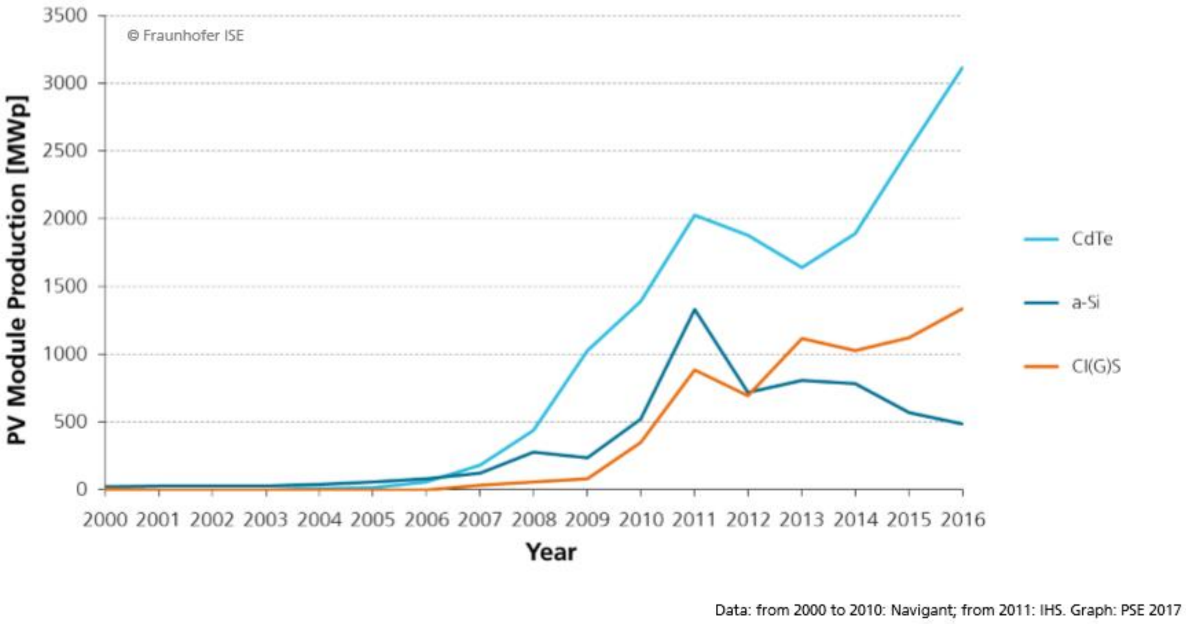


Table 7 Historical overview of PV module production volumes for CdTe, CIGS and a-Si (from Photovoltaics Report 2017, Fraunhofer ISE)

Thin film technology	Accumulated installations up to 2016	Installed in 2016
CdTe	14,7 GW	2,6 GW
CIGS	5,3 GW	0,9 GW
a-Si	2,9 GW	0,1 GW

Table 8: Market relevance of thin film technologies in terms of cumulative and present yearly installations.

At this moment, there are only two thin film PV producers on a GWp/year scale: First Solar (US) with CdTe on glass, and Solar Frontier (J) with CIGS on glass. Both are in the process of restructuring their production, aimed at short term cost reductions of 20-40%, such that thin film market share is expected to reach a temporary low. At some distance to these market leaders, a number of producers is on the market with individual manufacturing capacities up to hundreds of MW_p/yr. However, it should be noted that thin film PV is a declared part of the Chinese PV roadmap, and companies like CNBM, Hanergy and Shanghai Electric are leading a larger group of emerging thin film investors. CNBM alone expressed a 15 GW_p ambition based on CIGS and CdTe for the coming years, and started up production on several 100MW scale in the last quarter of 2017.

GaAs and III-V multijunction devices in general do not yet contribute substantially to earth bound PV electricity production, but have a dominant and proven market position for space applications. Thin film production based on III-V may be brought to larger scale through lift-off techniques enabling re-use of expensive substrates for epitaxial growth. Notable example of such an attempt is the development of a roll to roll lift-off process by Hanergy owned Alta Devices (US). Another route for more substantial earth-bound application of III-V utilizes their high conversion efficiency

under concentrated sunlight conditions, by incorporating them in low cost solar concentrator devices.
Perovskite based thin film PV is not yet in production, but this technology has made remarkable progress in the past few years. Because of its potential of very low cost production, and it's suitable bandgap for tandem formation with crystalline silicon, it could be (or pave the way for) a gamechanger in PV energy generation.

Therefore, this roadmap will focus on (in order of present market relevance) CdTe, CIGS, PSC and III-V in Chapter 3.

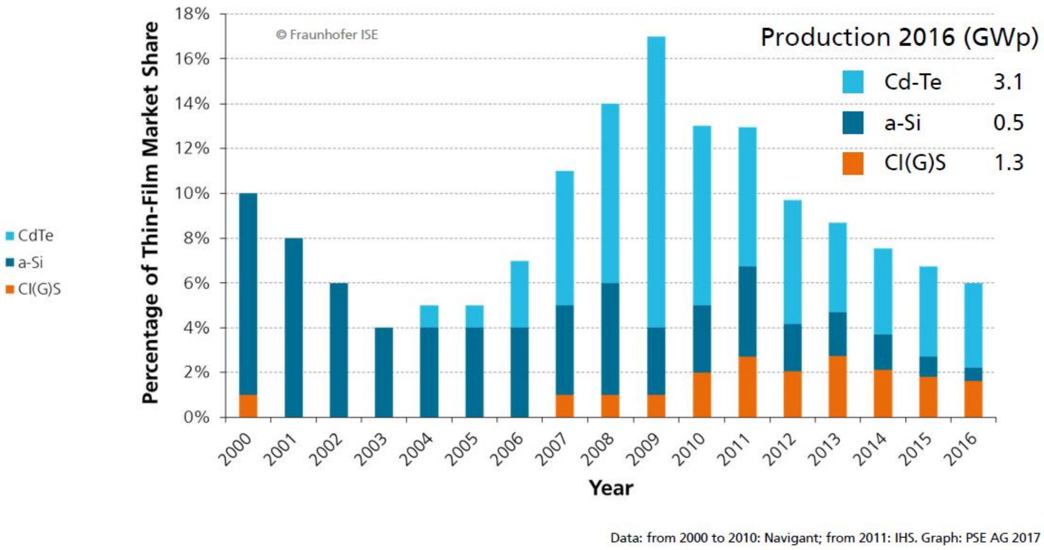


Table 9 Market share of thin film technologies in percentage of the total PV market (from Photovoltaics Report 2017, Fraunhofer ISE)

Another general characteristic of thin film technology, discerning it from current practice in crystalline silicon, is that the entire production flow from incoming substrate to outcoming completed module takes place at one single production location. This "one roof" approach, where a producer is able to control and optimize the entire production sequence was long expected to develop also for the c-Si PV production chain when it reached a sufficient scale, but so far this has not happened. Of the top ten (multi-GW) PV producers, only First Solar fully exploits the concept of "one roof" production at single sites. After the years of upscaling, the roadmap of PV as a whole is now at a point where quality control becomes an even more important issue; both in terms of bankability and as a discriminator in commercial competition. Thin film PV manufacturers may take advantage of their inherent potential for end to end production control and dedicated focus of optimizing all production steps towards one single product.

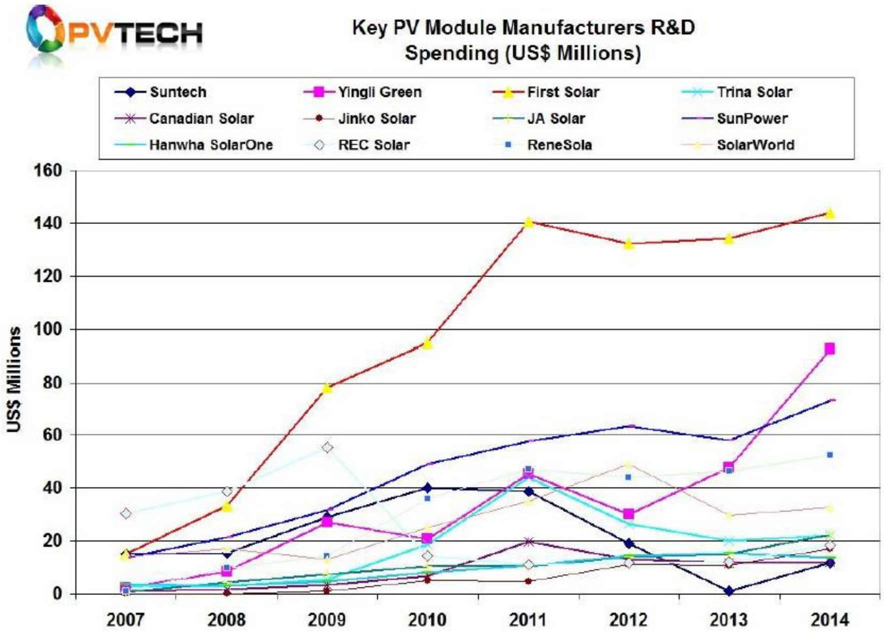


Figure 3: R&D spending of key module manufacturers over the last few years. First Solar, and also SunPower, have the highest level of control and focus over the production chain for their PV product [2].

This difference in approach is also reflected by Figure 3, which presents R&D spending of the top PV producers. It could be argued that First Solar, as the only thin film producer in this group, has the disadvantage of carrying the total financial burden of its own proprietary technology development. But it also reflects the advantage of total focus and control of the entire production sequence towards one single product. In the current PV market with its fierce price competition, this advantage may be exploited by capturing a higher market value through superior quality control.

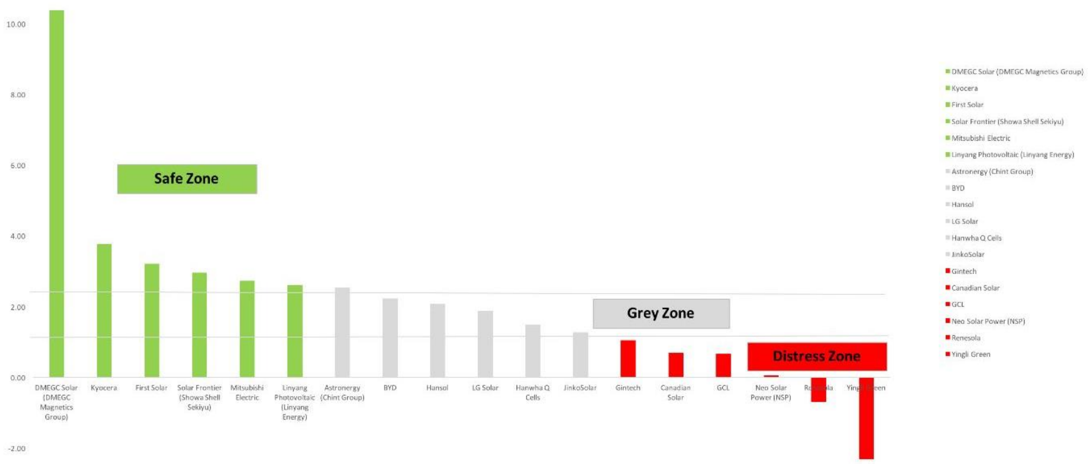


Figure 4: Altman-Z scores (in Q3 2017) of some major PV manufacturing suppliers. Grey and red zones indicate an increased chance on financial problems or bankruptcy.

Currently, all major PV manufacturers guarantee a module lifetime of 20 years or more. Nonetheless, for PV installers and buyers it is also important to have more certainty whether the the supplying manufacturer will be able to maintain this product warranty on its PV modules. Module failure is typically limited to two periods in the product lifetime: early failure due to imperfections in production or handling, and end of life failure after decades of slowly progressing limited degradation. An indication about the chance that warranties(at least on early failure) are not maintained because of an insolvency of the supplying manufacturer is given by the Altman-Z score. In Q3 2017, a considerable number of major crystalline silicon PV suppliers were in the grey or distress zone, while the two major thin film PV suppliers were in the safe zone. Moreover, First Solar as one of these two was in the past few years the only major PV manufacturer actually earning money.

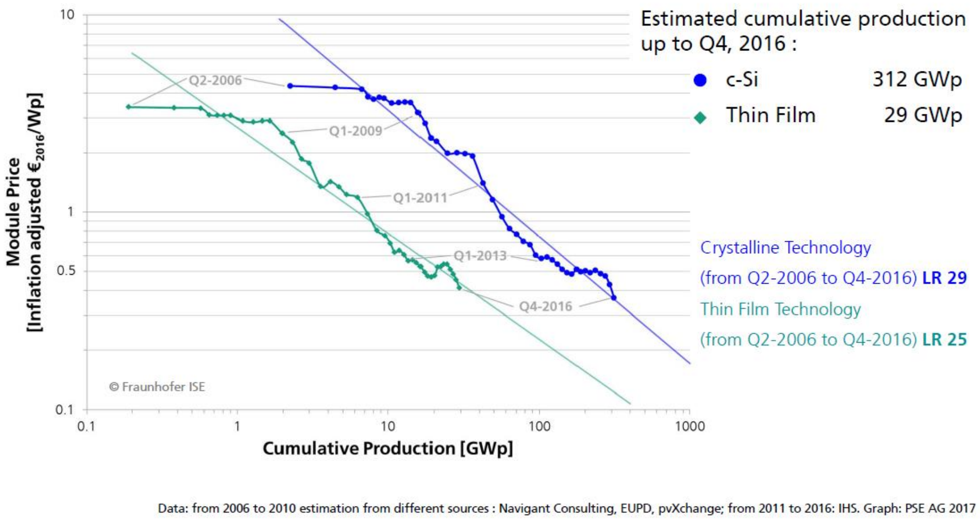


Figure 5: Price learning curves of wafer based silicon PV, and (CdTe) thin film PV (from Photovoltaics Report 2017, Fraunhofer ISE)

A last, but not least important aspect on the market position of thin film PV, is the much debated price learning curve. Figure 5 shows that, on a log-log scale, the module price of both crystalline and thin film decreases linearly with cumulative production. However, the thin film PV cost reduction is already realized at a production scale which is an order of magnitude lower than crystalline silicon technology. This strongly suggests that it has a potential cost benefit when it would be produced at a similar scale. The thin film line is in fact the CdTe price learning curve, dominated by First Solar. Drawing a similar line for CIGS is not really possible, as almost every CIGS manufacturer uses its own proprietary technology; as such, it does not really follow a collective technology learning curve, although major breakthrough improvements and insights are shared in the field. However, as a number of CIGS suppliers currently produce at a cost between $0,50 and $0,60, and the cumulative production of CIGS is 5-6 GW_p, this indicates a datapoint on the left hand side of the green CdTe line. Expectations of PSC solar cells, when stability issues can be solved, are that even lower module costs can be realized. When thin film PV industry would be more able to work out a shared technology roadmap, and collectively achieve a higher production level, it is expected to have a serious cost advantage with respect to silicon.

3.3 Thin film PV technologies

Thin film technologies are commonly referred to by the type of active absorber material that is applied. For all types of absorbers, NREL keeps track of the history and present status of record cell efficiencies that were confirmed by certified institutes.

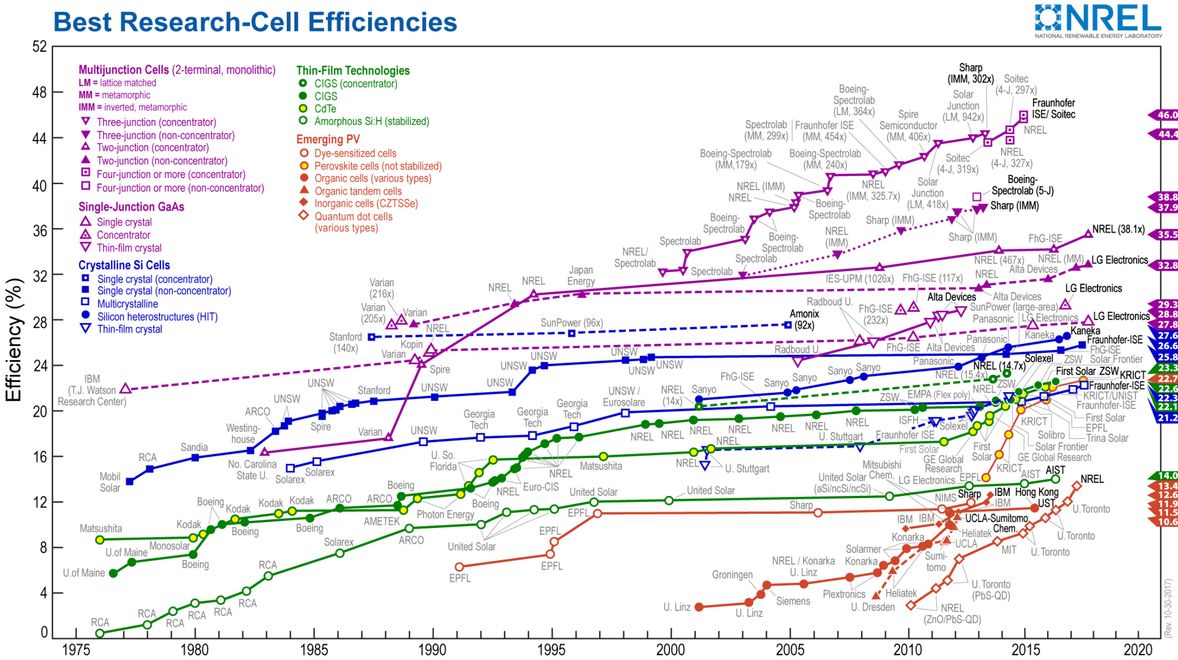


Figure 6: Certified cell records for all PV technologies (NREL website, December 4, 2017)

In the following graph, a selection of the same cell records is visualized with their development over the past 10 years in 5 year steps. Here, (multi)crystalline silicon (mc-Si and c-Si) are the only non-thin film materials, included for reference. The GaAs cell record was obtained by lift off processing (Alta Devices, US), and thus actually thin film. A new cell record for CIGS of 22,9% was confirmed while issuing this report (Solar Frontier, November 2017), and obtained by a novel Cs-treatment of the absorber.

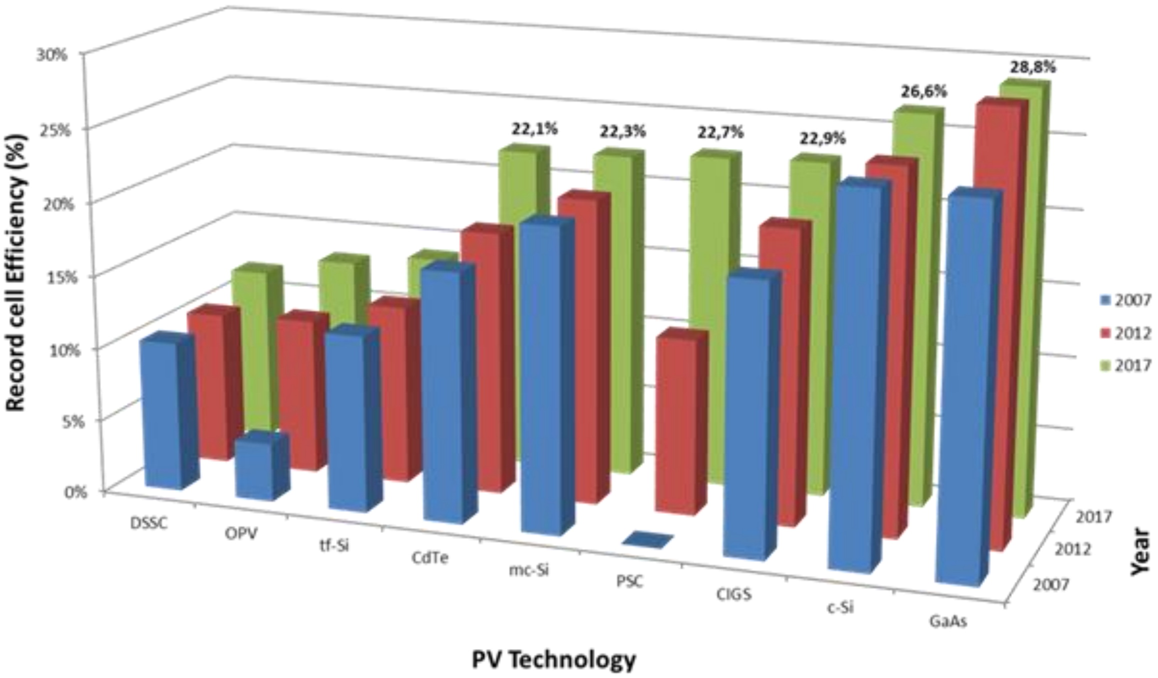


Table 10: Recent development of cell efficiency records for the most relevant PV technologies (status December 20, 2017).

In Table 11 (taken from literature, and thus not including latest announcements) also some of the key properties (open circuit voltage, short circuit current, fill factor) of the record cells are listed. Roadmaps for optimization are often structured attempts to optimize these voltage and current characteristics. The upper part of the reproduced table (marked Table 1) represents confirmed cell records, while the lower part (from the same publication) also takes the “notable exceptions” into account, which were obtained by other test centers or different sample sizes and do therefore not appear in the certified list.

Future developments of cell efficiencies of individual thin film technologies are presented under their respective roadmaps in chapter 3.

TABLE 1 Confirmed single-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill Factor (%)	Test Centre (date)	Description
Silicon							
Si (crystalline cell)	**26.7 ± 0.5**	**79.0 (da)**	**0.738**	**42.65[a]**	**84.9**	**AIST (3/17)**	**Kaneka, n-type rear IBC[5]**
Si (multicrystalline cell)	**21.9 ± 0.4[b]**	**4.0003 (t)**	**0.6726**	**40.76[a]**	**79.7**	**FhG-ISE (2/17)**	**FhG-ISE, n-type[6]**
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687[c]	38.50[c,d]	80.3	NREL (4/14)	Solexel (35 μm thick)[7]
Si (thin film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[c]	29.7[c]	72.1	FhG-ISE (8/07)[e]	CSG Solar (<2 μm on glass)[8]
III-V cells							
GaAs (thin film cell)	28.8 ± 0.9	0.9927 (ap)	1.122	29.68[f]	86.5	NREL (5/12)	Alta Devices[9]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)	RTI, Ge substrate[10]
InP (crystalline cell)	**24.2 ± 0.5[b]**	**1.008 (ap)**	**0.939**	**31.15[a]**	**82.6**	**NREL (9/12)**	**NREL[11]**
Thin film chalcogenide							
CIGS (cell)	**21.7 ± 0.5**	**1.044 (da)**	**0.718**	**40.70[a]**	**74.3**	**AIST (1/17)**	**Solar Frontier[12]**
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25[d]	79.4	Newport (8/14)	First Solar, on glass[13]
CZTS (cell)	**10.0 ± 0.2**	**1.113 (da)**	**0.7083**	**21.77[a]**	**65.1**	**NREL (3/17)**	**UNSW[14]**
Amorphous/microcrystalline							
Si (amorphous cell)	10.2 ± 0.3[g,b]	1.001 (da)	0.896	16.36[d]	69.8	AIST (7/14)	AIST[15]
Si (microcrystalline cell)	**11.9 ± 0.3[b]**	**1.044 (da)**	**0.550**	**28.72[a]**	**75.0**	**AIST (2/17)**	**AIST[16]**
Perovskite							
Perovskite (cell)	19.7 ± 0.6[g,h]	0.9917 (da)	1.104	24.67[i]	72.3	Newport (3/16)	KRICT/UNIST[17]
Perovskite (minimodule)	**16.0 ± 0.4[g,h]**	**16.29 (ap)**	**1.029[c]**	**19.51[c,a]**	**76.1**	**Newport (4/17)**	**Microquanta, 6 serial cells[18]**
Dye sensitised							
Dye (cell)	11.9 ± 0.4[j]	1.005 (da)	0.744	22.47[k]	71.2	AIST (9/12)	Sharp[19]
Dye (minimodule)	10.7 ± 0.4[j]	26.55 (da)	0.754[c]	20.19[c,l]	69.9	AIST (2/15)	Sharp, 7 serial cells[19]
Dye (submodule)	8.8 ± 0.3[j]	398.8 (da)	0.697[c]	18.42[c,m]	68.7	AIST (9/12)	Sharp, 26 serial cells[20]
Organic							
Organic (cell)	11.2 ± 0.3[n]	0.992 (da)	0.780	19.30[d]	74.2	AIST (10/15)	Toshiba[21]
Organic (minimodule)	9.7 ± 0.3[n]	26.14 (da)	0.806	16.47[c,l]	73.2	AIST (2/15)	Toshiba (8 series cells)[22]

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill Factor (%)	Test Centre (date)	Description
Cells (silicon)							
Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7[a]	82.8	Sandia (3/99)[b]	UNSW p-type PERC top/rear contacts[40]
Si (crystalline)	**25.7 ± 0.5[c]**	**4.017 (da)**	**0.7249**	**42.54[d]**	**83.3**	**FhG-ISE (3/17)**	**FhG-ISE, n-type top/rear contacts[41]**
Si (large)	**26.6 ± 0.5**	**179.74 (da)**	**0.7403**	**42.5[d]**	**84.7**	**FhG-ISE (11/16)**	**Kaneka, n-type rear IBC[5]**
Si (multicrystalline)	21.3 ± 0.4	242.74 (t)	0.6678	39.80[e]	80.0	FhG-ISE (11/15)	Trina Solar, large p-type[42]
Cells (III-V)							
GaInP	21.4 ± 0.3	0.2504 (ap)	1.4932	16.31[f]	87.7	NREL (9/16)	LG Electronics, high bandgap[43]
Cells (chalcogenide)							
CIGS (thin-film)	22.6 ± 0.5	0.4092 (da)	0.7411	37.76[f]	80.6	FhG-ISE (2/16)	ZSW on glass[44]
CIGSS (Cd free)	**22.0 ± 0.5**	**0.512 (da)**	**0.7170**	**39.45[f]**	**77.9**	**FhG-ISE (2/16)**	**Solar Frontier on glass[12]**
CdTe (thin-film)	22.1 ± 0.5	0.4798 (da)	0.8872	31.69[g]	78.5	Newport (11/15)	First Solar on glass[45]
CZTSS (thin-film)	12.6 ± 0.3	0.4209 (ap)	0.5134	35.21[h]	69.8	Newport (7/13)	IBM solution grown[46]
CZTS (thin-film)	**11.0 ± 0.2**	**0.2339(da)**	**0.7306**	**21.74[d]**	**69.3**	**NREL (3/17)**	**UNSW on glass[14]**
Cells (other)							
Perovskite (thin-film)	22.1 ± 0.7[i]	**0.0946 (ap)**	1.105	24.97[j]	80.3	Newport (3/16)	KRICT/UNIST[17]
Organic (thin-film)	**12.1 ± 0.3[k]**	**0.0407 (ap)**	**0.8150**	**20.27[d]**	**73.5**	**Newport (2/17)**	**Phillips 66**

Abbreviations: CIGSS, CuInGaSSe; CZTSS, $Cu_2ZnSnS_{4-y}Se_y$; CZTS, Cu_2ZnSnS_4; (ap), aperture area; (t), total area; (da), designated illumination area; AIST, Japanese National Institute of Advanced Industrial Science and Technology; NREL, National Renewable Energy Laboratory; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme.

Table 11: Confirmed cell records (upper part) and cell records obtained on sample sizes that do not comply with rules for official cell records (lower part; *referred to as "notable exceptions"* [3]).

3.4 Future relevance of thin film PV

Roadmaps for all PV technologies aim at increased conversion efficiencies of the respective absorber material, reduced production cost and longer life time. And many technological improvements on module and system level have generic value to reach such goals for all crystalline and thin film PV technologies. However, the decisive relevance of thin film PV for specific applications follows from unique combinations with also other properties. Some of these properties are given in Table 12.

	Cost $/kWh	Energy payback time	Carbon foot-print	Temp coeffic	Stability wrt ambient	Spectral response	Effic 1 sun	Effic <1 sun	Effic >1 sun
++ Optimal when:	low	low	low	low	high	high	high	high	high
CdTe (rigid glass)	+	+	++	+	-	+	O	o	
CIGS (rigid glass)	o/+	+	+	+	-	+	O	+	+
CIGS (flexible)	-/o	+	+	+	-	+	O	+	+
III-V (rigid)	--		-	+	+	++	++	+	++
III-V (flexible)	-		+	+	+	++	++	+	++
a-Si (rigid glass)	o/+	+	+	++	o		-	+	
a-Si (flexible)	o/+	+	+	++	o		-	+	
PSC (rigid glass)	++	++	++	+?	?	+	O	+	n.a.
PSC (flexible)	++	++	++	+?	?	+	O	+	n.a.
	Scarce material content	Hazar-dous material	Trans-lucent	Semi-trans-parent	Stability wrt ambient	Intrinsic Colour	Low weight kg/m2	Power density W/kg	
++ Optimal when:	low	low	y/n	y/n	high	y/n	low	high	
CdTe (rigid glass)	-	-/--	y	n	-	n	o	-	
CIGS (rigid glass)	-	o	y	y	-	n	o	-	
CIGS (flexible)	-	o	?	n	-	n	+	++	
III-V (rigid)	-	-	n	n	+	n	o	+++	
III-V (flexible)	-	-	y	y	+	n	+	+++	
a-Si (rigid glass)	++	o	y	y	o	n	o	--	
a-Si (flexible)	++	o	y	y	o	n	+	+	
PSC (rigid glass)	o	-	y	y	?	y	o	o	
PSC (flexible)	o	-	y	y	?	y	+	++	

Table 12: Unique Selling Points of thin film PV as detailed below in this paragraph. ++ is optimal, o is not distinctive, -- is minimal. Translucence is achieved by local removal of cell material, whereas semitransparency refers to inherent transparency of the complete cell stack.

On the basis of combinations of their general and specific properties, relevance of the thin film technologies to application areas is characterized in Table 13. A distinction is made between thin film produced on rigid (glass) substrates and thin film on flexible (semi-) fabricates. In assessing attractiveness for specific applications, technical, economic (acceptable cost/efficiency ratio) as well as environmental issues (hazardous materials) have been taken into account. Of course, this leads to some ambiguity, but it does not affect the general picture.

	CdTe	CIGS		aSi		PSC Pb free		PSC Pb based		GaAs and III-V		OPV		DSSC	
	rigid	rigid	flex	rigid	flex	rigid	flex	rigid	flex	rigid	flex	rigid	flex	rigid	flex
Utility ground NL	+	+	-			+	+	+	+						
Utility ground desert High insolation	++	+	-	+	o			+		++	+				
Utility floating water		+	+		+	+	+								
BAPV roof	+	++	+		+	+	+	+	+						
BIPV roof		++	++		+	+	+	+	+						
BIPV facade		++	++	+		+	+	+	+					+	+
BIPV semitr window	+			+		+	++	+	+					+	+
I2PV noise barrier		+				+	+	+	+						
I2PV solar road		+	++			+	++		++						
I2PV crash barriers		o	++			+	+								
I2PV streetlights						+	+								
VIPV cars		+	+			+	++		++		++				
VIPV trucks/trains		o	+			+	++		++		++				
Space			+							++	++				
Aircraft/Drones			+				+		++	+	++				
Rapid deploy foil			+		+		+		+		++		+		+
Rapid deploy tent			+		+		+						+		+
Back packs			+				+						+		+
Handheld products			+			+	+					+	+	+	+
Mobile chargers			+			+	+							o	o
Energy scavenging			+		+	+	+		+		+	+	+	+	+

Table 13: Ranking of the attractivity of thin film PV technologies for specific fields of applications. (++ more attractive than others, o equally attractive as others, - - not attractive). Each column: left hand side thin film deposited on rigid substrate (glass), and right hand side thin film deposited on flexible substrate. Flexible CdTe is not in production. For PSC, more fields of application open up when its potential negative environmental impact has been properly assessed and/or remediated or if use of lead (Pb) can be eliminated (Pb-free scenario, but less likely). QD is left out, as no proven applications yet exist, but would be expected to have wide applicability.

For PSC, a distinction is made for a future with or without lead content. A potential disadvantage of perovskite PV modules is that they currently contain a small amount of lead: approximately 0,5 gram/m^2. This is less than the amount of lead in the junction boxes currently also used for crystalline PV. But because lead could end up in the environment if a solar panel were to become damaged, the extent of the resulting harm and how it could be reduced is investigated. Solliance is identifying the various potential risks and investigating alternatives. Tin, and also the less harmful bismuth are investigated as a lead replacement.

As long as toxicity is still considered a risk, perovskite can be ‘wrapped’ in glass panels, and applications would be similar to the current market situation in CdTe. If it can be replaced, it would follow (or outperform) CIGS in its virtually unlimited applicability to all types of use (“Pb free” column in Table 13). In the “Pb based” column a reduced applicability is assumed, depending on the result of future environmental risk assessments comparing the relatively low lead content of PSC to the lead emissions of other energy sources and products.

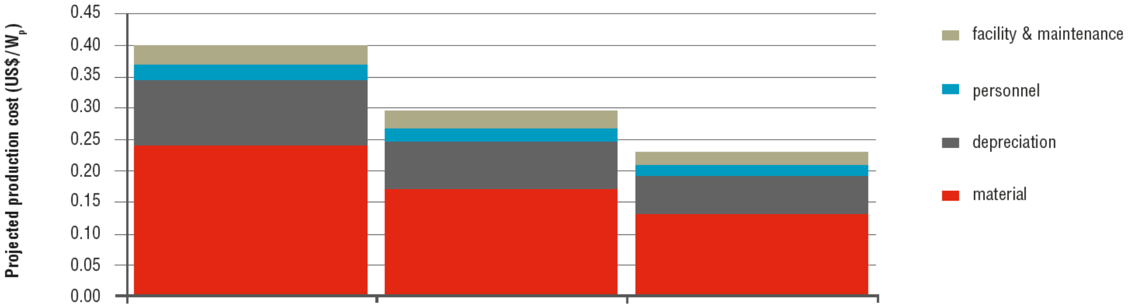
3.4.1 Cost evolution

	2017	2020	2030
Unit	\$/Wp	\$/Wp	\$/Wp
CdTe (rigid glass)	0,31	0,25	<0,20
CIGS (rigid glass)	0,40-0,48	0,30	<0,20
CIGS (flexible)	0,70-1,00	0,30-0,40**	<0,25
III-V (rigid)	-	-	?
III-V (flexible)	-	-	?
a-Si (rigid glass)	0,40	?	?
a-Si (flexible)	0,60-0,70	0,40*	?
PSC (rigid glass)	-	-	0,10
PSC (flexible)	-	-	0,10

Table 14: Cost development of encapsulated modules or several thin film technologies. *) flexible a-Si cost estimate based on new 25MW facility **) flexible CIGS cost estimate based on new 400MW facility.

CIGS

Current price on the market is in the order of € 0,50-0,55 /W_p for standard sized CIGS glass-glass modules, €1,30 /W_p for custom sized glass glass, and €1-3 /W_p for flexible CIGS modules (for important part determined by the cost of flexible encapsulation foil and substrate). In terms of LCOE, standard CIGS modules can be produced theoretically (i.e. not demonstrated, but based on COO analysis of newly built >200MW factory) at a module cost that is comparable to crystalline silicon. Potentially, it is even somewhat lower, as the lower temperature coefficient and the light soaking effect result in higher kWh/W_p. However, to date none of the CIGS companies managed to reach competitive pricing to c-Si or CdTe in terms of \$/W_p. In 2015, CIGS market leader Solar Frontier publicly announced its effort to reduce its present module cost level on short term by 20% (to \$0,40/W_p within 2 years, excluding depreciation) and longer term by 40% (to \$0,30/W_p), with improved production technology that should be demonstrated in their newly added 150MW plant that started operation in 2016.
In the meantime, CNBM/Avancis is starting up new facilities in China. Their first phase of 300 MW is starting in 2017, in addition to an existing 200MW capacity in Germany, and they publicly announced their ambition to reach 1,5GW capacity on midterm, and 5-15GW on longer term. Hanergy (Miasole, Global Solar, and Solibro), are expected to deliver a few hundred MW capacity on short term, and also Shanghai Electric is building capacity on several hundred MW scale.
In flexible CIGS (i.e. companies like MiaSole, Global Solar, Flisom) current Cost of Goods for cell production are about 40% of total costs, and another 40% for module formation (interconnection and encapsulation). Cost reduction potential up to 2020 is largest in module formation (-40%); for cell production it is about -20%. Resulting aim is 40% cost reduction on module level for 2020. As detailed in the enabling technologies (chapter 4), currently applied flexible encapsulation barrier materials are on the market for \$30-40/m2, corresponding to a cost contribution of \$0,18-0,25/W_p whereas for recent developments in alternative barriers (2017) cost reductions of more than 50% are reported.



	Present fab	Next gen fab	Upgrade & scale next gen fab
Capacity	150 MW_p/a	250–500 MW_p/a	500–1000 MW_p/a
Average efficiency	14.3 %	16 %	18 %
Reductions versus present fab		material -20 % capex -20 %	material -30 % capex -30 % f&m -20 %

Figure 7: Projected CIGS production cost using presently available technology and leveraging further cost reduction potential (upgrade and scale phase typically around 2020; towards 2030 further efficiency improvements are generally expected). Source: http://cigs-pv.net/why-invest-in-cigs-thin-film-technology/

PSC

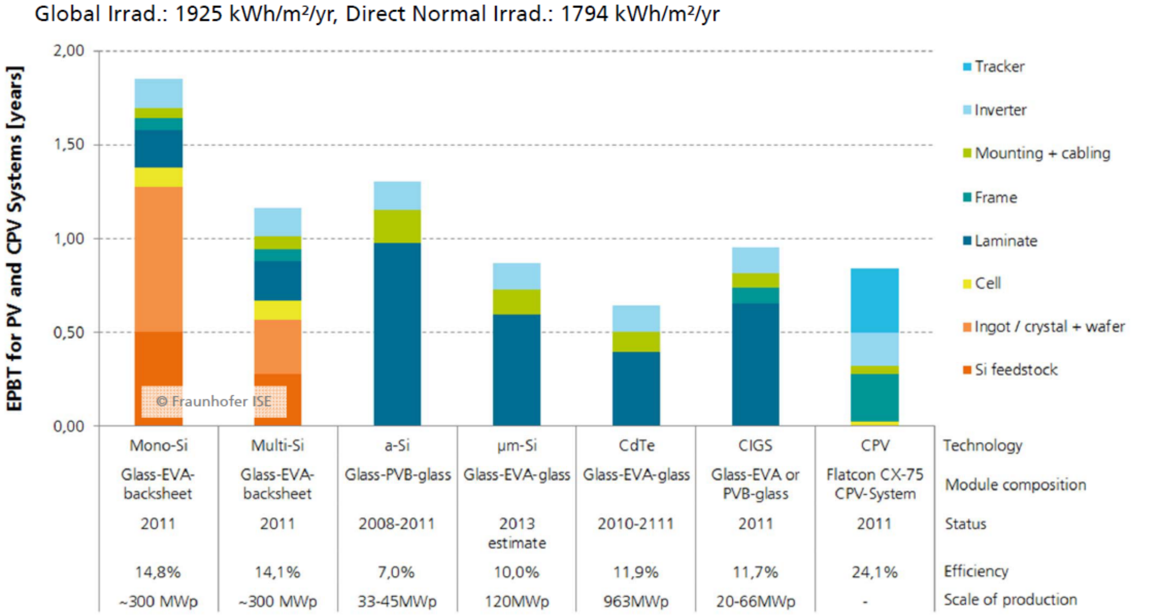
As no commercial production of PSC takes place, costs are estimated on a basis of cost of ownership calculations with assumptions on efficiency, cell stack design, low cost encapsulation, materials consumption and targeted deposition technologies (roll to roll, all solution based atmospheric processing. Inherent advantages like low material cost, relatively low processing temperatures, permitting the use of lower cost substrates, add to credibility that total cost could outperform CdTe and CIGS when module stability can be brought to a competitive level. This is supported by cost of ownership calculations of NREL (L. Tinker, Sunshot 2015): comparing CdTe and PSC a cost reduction for the absorber by a factor of 3, and a 30% cost reduction for TCO and backcontact was predicted.

III-V

No public data on industrially produced III-V are available. Breakthroughs in cost reduction are aimed for by development of lower cost deposition technologies, lift off and upscaling.

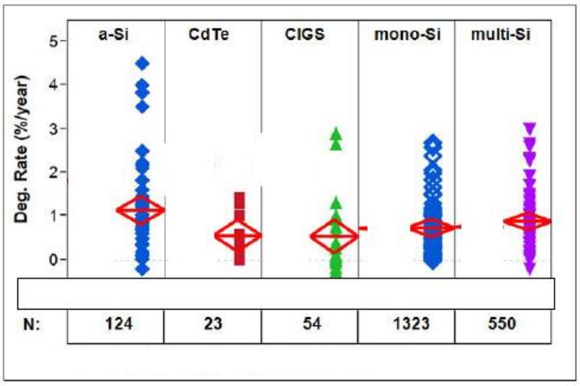
3.4.2 Energy payback time and carbon footprint

The most important value of thin film PV for society unfortunately has (to date) very little market value. Basically, the societal value of any technical means for durable energy generation should be characterized by its ability to “multiply” energy: the amount of energy produced by the technical means during its lifetime, divided by the amount of energy that was consumed to manufacture this means.



Data: M.J. de Wild-Scholten 2013; CPV data: "Environmental Sustainability of Concentrator PV Systems: Preliminary LCA Results of the Apollon Project" 5th World Conference on PV Energy Conversion. Valencia, Spain, 6-10 September 2010. Graph: PSE AG 2014

Typically, the energy payback time of thin film PV is less than 1 year, and lower than that of crystalline silicon. Secondly, the expected lifetime of thin film and crystalline PV are comparable, and thirdly, as a metastudy of 2012 showed, if there is a difference in degradation rate over lifetime, it apprears to be in the favor of thin film. These three factors together indicate that not only the energy payback time, but also the energy "multiplier" is a valuable characteristic of thin film PV in general.



Diamond: 95% confidence interval, means: crossbar

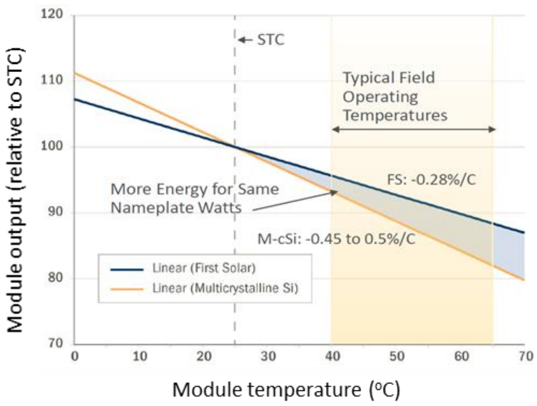
Source: **Photovoltaic Degradation Risk by Dirk C. Jordan and Sarah R. Kurtz, NREL, 2012 World Renewable Energy Forum, Denver, Colorado, May 13-17, 2012**

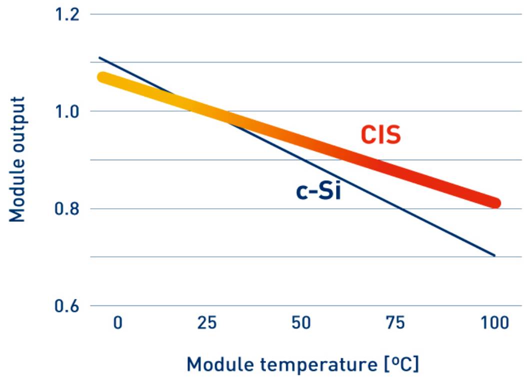
This is also true for the CO_2 footprint. First Solar's CdTe currently has the lowest CO2 footprint of all large scale produced PV technologies. It is followed by the other thin film technologies. PVMC recently calculated an achievable CO_2 footprint of 12,5 g/kWh for optimized R2R production of CIGS on steel by coevaporation (Global Solar, Veeco, SIVA), showing that it could be lower than current CdTe processing. Thin films like PSC and OPV are processed at much lower temperatures than CdTe and CIGS, and when they come to large scale production with good cell efficiencies even lower CO_2 footprints are expected to be achievable.

3.4.3 Thin film advantages for specific applications

3.4.3.1 Lower temperature coefficient

Every PV module shows a decreasing efficiency with increasing operating temperature, described by the (negative) temperature coefficient. In general, all thin film PV technologies have lower temperature coefficients than crystalline silicon. This gives them an advantage in applications with higher average operating temperatures.





The figures above illustrate this for specific products of CdTe (First Solar) and CIGS (Solar Frontier). Depending on average operating temperatures over the year, this leads to higher electrical energy output in kWh/Wp when comparing thin film and crystalline PV with the same nameplate efficiencies under standard conditions (25 degr. centigrade). First Solar reports up to 3% higher output with respect to cSi when averaging over longer periods of time.

The actual value of the temperature coefficient depends on specific cell structure and quality. It follows from device physics that the coefficient generally decreases with increasing bandgap; assuming that the device has been well designed. This is translated to the general experience fact that the coefficient decreases with increasing cell quality and efficiency. An example is CIGS. Fifteen years ago, CIGS temperature coefficients around 0,4 %/C were observed (typically equal to cSi) for cell efficiencies around 10%. At present, typical values are around 0,3.

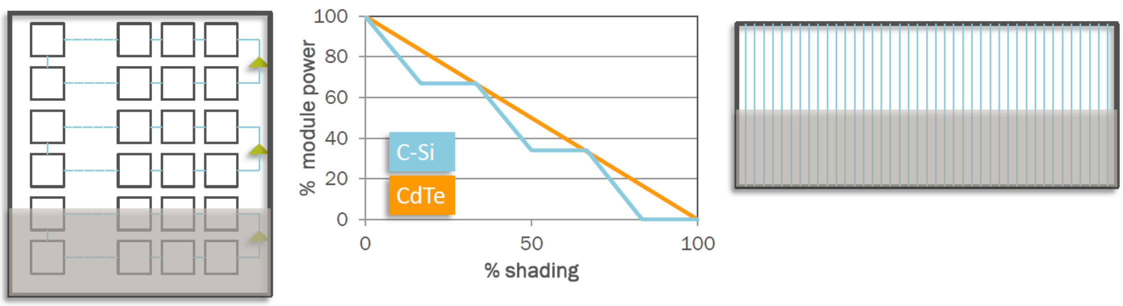
Producer	Absorber	TC (%/°C)
First Solar	CdTe	- 0,28
Solar Frontier	CIGS	- 0,31
Solibro	CIGS	- 0,32
HyET	aSi	- 0,13
Spectrolab/Azur Solar	III-V various	- 0,22/0,30
Reference:	HIT	- 0,29
Reference:	cSi	-0,45 / - 0,50

Table 15: Negative temperature coefficients of several thin film PV products with reference to typical data for crystalline silicon PV.

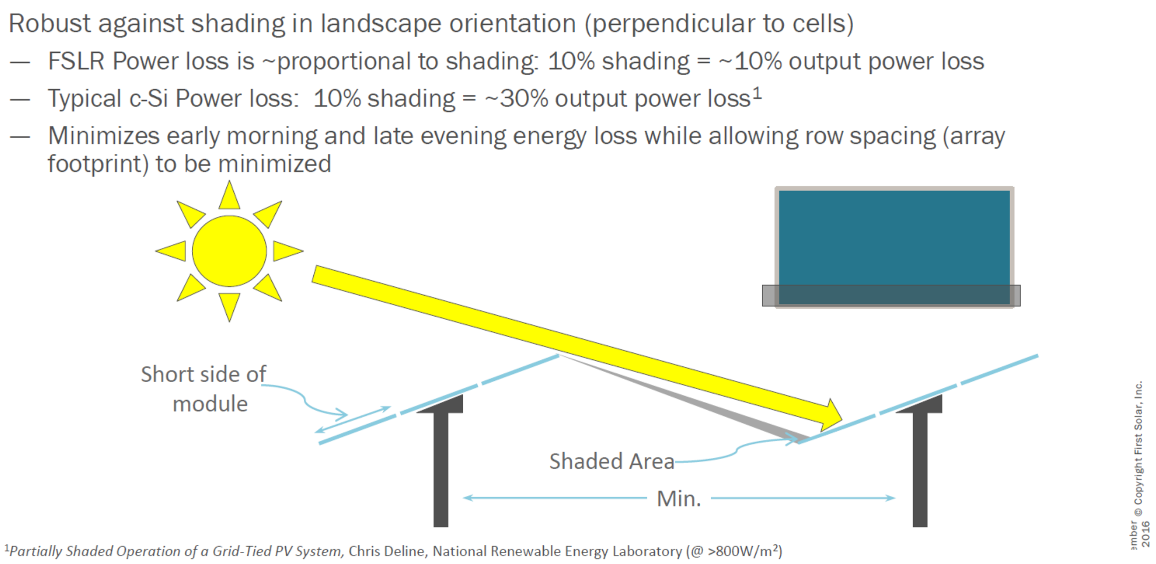
To fully utilize and optimize the temperature coefficient as a market relevant parameter, it could be addressed as part of the technology specific roadmaps as well as the enabler roadmaps. For example: ALD of ZnOS buffer layers is on the enabler roadmap “Junction and passivation”, for Cd-free CIGS, while CIGS bandgap grading/tuning is on the CIGS specific roadmap. By tuning the oxygen content of ZnOS, the buffer layer can be suitably adapted to variations in CIGS bandgap to decrease the temperature coefficient. Target value is 0,3 or lower.

3.4.3.2 Reduced shading loss

A general consequence of monolithic integration of thin film modules, is that they are more tolerant to partial shading than strings of cSi cells. Shading of one single cell reduces (stepwise) the total current of an entire string, while monolithically integrated thin film modules only show gradual decrease of total current when increasing parts of the module are shadowed (as long as none of the cell lines is fully covered).



This effect has been shown to lead to notable advantages in PV application on ground and on roofs. For First Solar (focused on utility scale PV on ground) it is an essential element in their strategic choice to reduce BOS costs by going to more densely packed fields of larger size modules (see figure below)



However, as the roadmap focus of thin film PV (and PV in general) is shifting towards BIPV, also shadowing parallel to the monolithic interconnection lines has to be dealt with. Module problems are encountered in installations where shadowing or complete blocking of light of complete lines occurs (e.g. neighboring building structures or trees in front of PV facades, cleaning of PV windows while they are active, or decorative printings on module front surfaces). Application of bypass diodes and/or segmentation of monolithically integrated modules have recently been introduced on the market in an attempt to deal with such problems, but strategies to deal with partial shadowing have become a focus point of future developments.

Roadmap target parameter
Tolerance to partial shadowing is a roadmap parameter of increasing relevance for specific markets in integrated PV (BIPV, IIPV, automotive and products). On device level, it has been observed that irreversible damage (shunting) may occur upon even very short blocking of light towards individual cell lines. Specific research on underlying mechanisms and potential remedies has recently been started. It is a special focus point in the enabler roadmap for “Metallization and Interconnection”.

3.4.3.3 Spectral response advantage

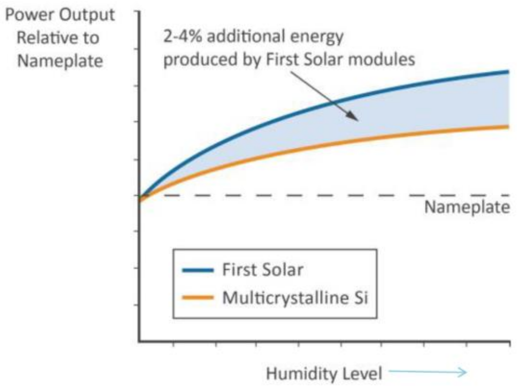


Figure 8: Qualitative comparison of spectral response between CdTe and mc-Si as a function of humidity level (from First Solar company website).

A much debated advantage of thin film over crystalline silicon concerns the spectral response under different illumination and weather conditions, averaged over a year of operation. More statistics and modeling are required, but it is to be expected that specific climate conditions or module orientations lead to power outputs which are higher than would be expected under standard certification conditions, as a consequence of response to varying spectral light compositions and angles of incidence (direct/diffuse lighting).

3.4.3.4 Climate conditions (Solar fields)

Focus of First Solar is on utility scale CdTe based solar fields. For this area of application, much effort was made to integrate the above mentioned specific advantages of thin film with respect to cSi.

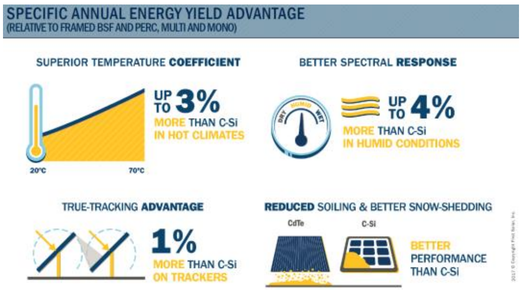


Figure 9 Annual energy advantages CdTe (First Solar)

To market the thin film CdTe product around the globe, First Solar combined these annual yield advantages (see figure) as a function of climate conditions in a world map. It indicates a relative advantage in kWh/Wp energy yield of 0,5% to 7,5 % for important parts of the world.

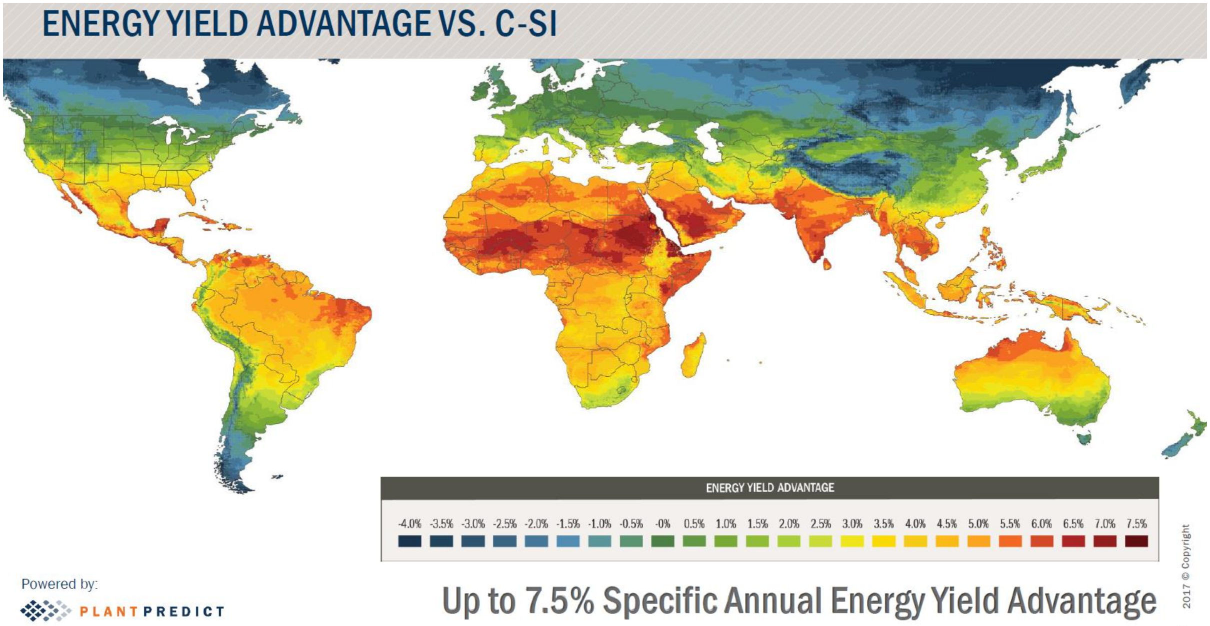


Figure 10: Calculated energy yield advantage of thin film CdTe with respect to c-Si, on the basis of abovementioned generic thin film advantages. It is noted that also NL is light green (+0,5%).

4 Roadmaps specific thin film PV technologies

4.1 Thin film CdTe

Efficiency roadmap (First Solar)

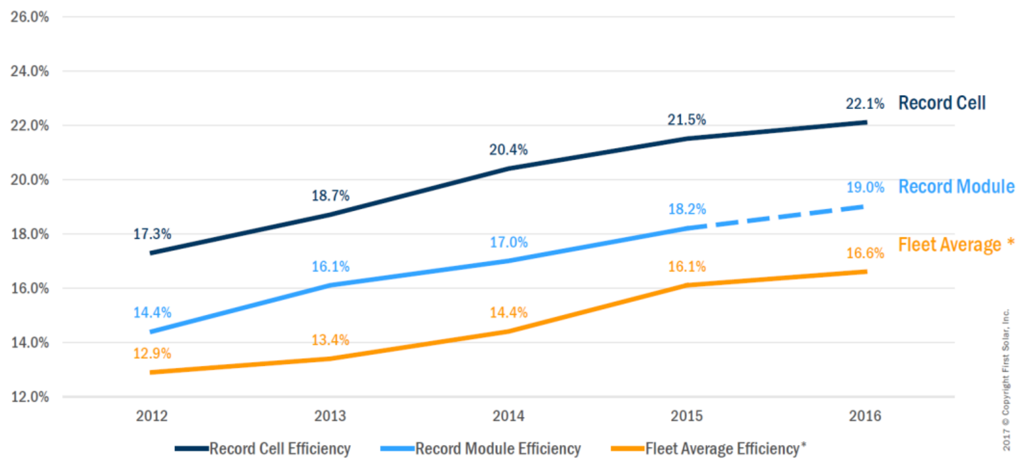


Figure 11 Historic efficiency roadmap for CdTe thin film modules by First Solar.

Record cells and modules by First Solar (Figure 11) are always produced on the basis of technologies that are already used in production. Thus, a consistent development of upscaled products that follows the trend of record cell research could be achieved. This greatly adds to the credibility that the CdTe fleet average efficiency will continue to increase for the coming years. First Solar has demonstrated record cell efficiencies with cadmium telluride (CdTe) of 22% and is increasing module efficiency(record now is 18.6%), with a trajectory to surpass 20%. Recent research has demonstrated photovoltages >1 V. If higher photovoltages can be realized, CdTe efficiencies in manufacturing can increase still further.

Focus for CdTe is on utility scale electricity generation. On the basis of LCOE calculations, it was shown that for solar farms an increase in module size would not only provide cost reduction in production but also considerably on installation level. Therefore, First Solar decided in 2016 to triple the manufacturing size of their modules to 2,47m^2, referred to as Series 6. End 2017, successful first production was made public together with the announcement that a 5,4 GW/year capacity is targeted for 2020.
Also end 2017, CNBM announced successful start of their CdTe production on large glass size.

4.2 Thin film CIGS roadmap

Efficiency roadmap

In 2016, a Whitepaper on CIGS was issued in a joint effort of the global community of CIGS producers and research groups. Although no formal common roadmap was established, it was a generally supported opinion that a number recent of innovative breakthroughs would lead to an efficiency increase of typically 1% per year in the coming years; in terms of small cell lab records as well as in terms of commercially produced modules. The following graph, taken from the collective whitepaper, communicates this general upward trend after a period of modest improvements. In the tables below, the enabling improvement steps that are expected to drive this efficiency increase are listed.

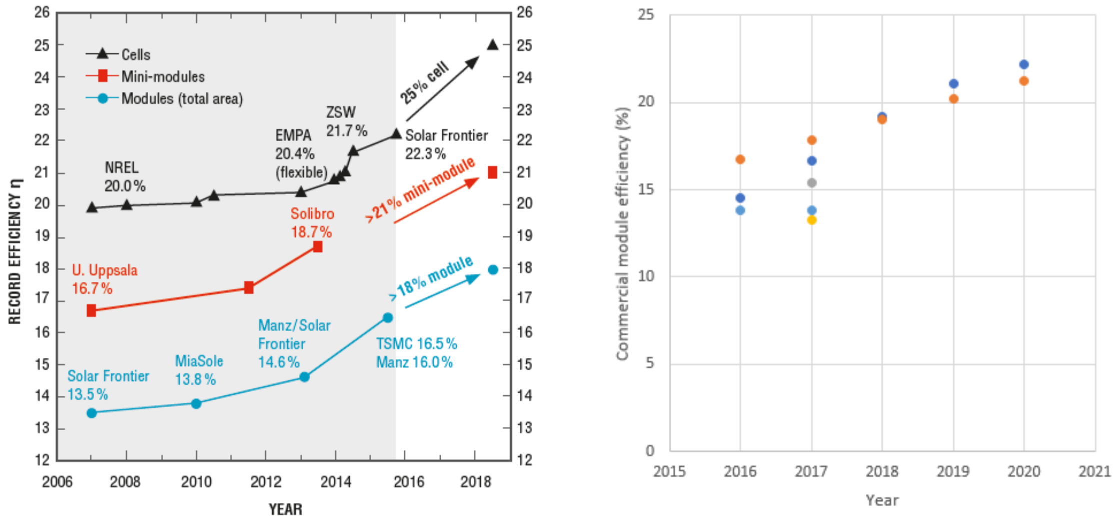


Figure 12: Left: Evolution of record efficiencies, highlighting a steeper increase since 2014. The 2016-2019 projections are based on current R&D projects (CIGS Whitepaper 2016). Right: Evolution of present and expected commercial module efficiencies of several suppliers.

Efficiency enabling targets

CIGS absorber: band gap grading and passivation	Target	Absolute efficiency improvement
K- Post Deposition Treatment (K-PDT)	Reduced ohmic losses	+1%
Sulphurisation after selenisation (SAS)	Higher optical transparency and lower ohmic loss	+1%
Na doping of buffer layer		+x%
Second buffer layer	Higher Voc by reduced interface recombination	+1%
Al-oxide Passivation	Improved charge carrier life time	+x%
Thinner absorber	Reduced cost (higher throughput and lower material use), higher V_{OC} (with passivation)	+x%

CIGS metallization and interconnection	Target	Absolute efficiency improvement
Metal grids	Reduced ohmic losses	+1%
TCO optimisation	Higher optical transparency and lower ohmic loss	+0,5 to +1%
Reduced dead zone classic P1P2P3	Reduce width from 200μm to less than 50 μm	+0,5%
Advanced/back end interconnect	Reduce width from 500μm to less than 200 μm	+0,5%

CIGS materials & lifetime	Target	Absolute efficiency improvement
Polyolefine replacing EVA	Longer lifetime	Reduced efficiency loss ageing
Low cost front sheet encapsulation	Higher optical transparency and lower ohmic loss	n.a.
Low cost flexible substrate	Replace stainless steel	n.a.
Corrosion resistant TCO	Increased shelf time semi-finished product. Longer lifetime	Reduced efficiency loss ageing

CIGS light management	Target	Absolute efficiency improvement
Transparent back electrode	Replace Mo by transparent material for bifacial and tandem applications	+
Nanoscale texturing	Increased optical path length through absorber by diffraction and scattering	+
Patterning of complete stack	Semitransparent modules	-

The Urban Energy roadmap will focus on achieving the indicated improvements with a focus on flexible semi-fabricate CIGS modules for customized integration, and generic low cost production processes and equipment.

4.3 Thin film PSC roadmap

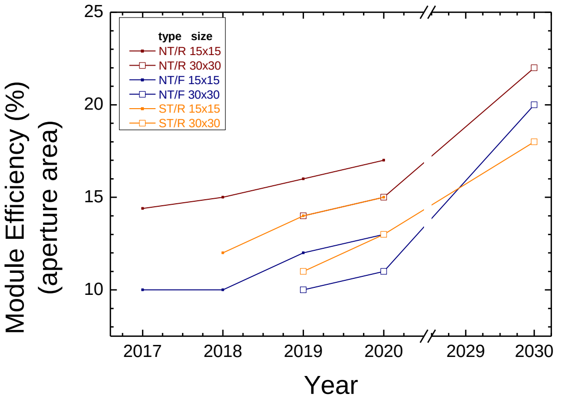


Figure 13: Solliance roadmap of targeted PSC efficiency records on module level (Non transparent rigid, Non transparent flexible, and Semitransparent rigid (tandem compatible) respectively).

The Solliance shared research program currently holds the world record for R2R produced PSC cell and module efficiency, and is close to the world record for PSC (4-contact) tandems with crystalline silicon: 26,1% with respect to 26,4% (December 2017).

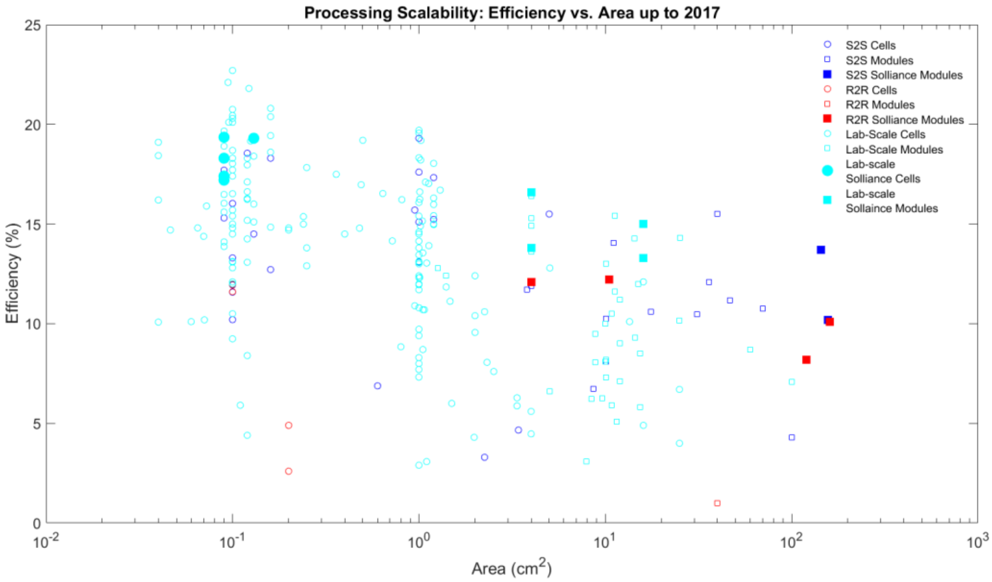
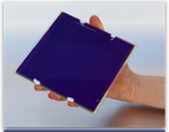


Figure 14 Scatter plot of thus far obtained cell and module efficiencies by Solliance partners. Top cells are not far from world record (vertical axis), but not the focus. Upscaling towards larger module sizes (horizontal axis) without compromising small scale efficiency results, improvement of stability, and commercially viable processing techniques however are of key importance. These criteria are detailed in Table 16.

Scalability	Efficiency	Stability	Cost
Temp. : Compatible with platform processing $T_{process}$~145°C	Value: >16.5% and outlook towards 20% (non-transp)	Temp.: 85°C: T80>1000	Material: Positive outlook to low €/m² (< 30)
Uniformity: Roughness perovskite R_a < 20 nm (?)	Reproducibility: Cell performance between batches	Light : Vis.: T80>1000 UV: filter needed?	Equipment/Process: Positive outlook to low €/m² (< 30)
Equipment: Is equipment in place?	Yield & Distribution: Process has a rather high yield and narrow PCE distribution	Ambient: Unencap. device: T80 at RH<50; 85% T80 at 1 sun	Throughput/Yield: Positive outlook to low €/m² (< 30)
Materials: Are materials sufficiently available; include safety aspects		E-field: Test sensitivity of T80 to J_{sc}, MPP, V_{oc} (LS)	SHE aspects: Positive outlook to low €/m² (< 30)

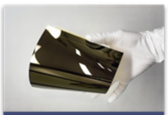
Table 16 Criteria and targets for commercially viable upscaling and module stability of PSC modules.

	2017	2018	2019	2020



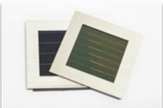
NT/R

	Status M11/17	Target TA18	Target TA18	Target TA 2018
Mod. Size (cm)	**15x15**	**15x15**	**15x15 / 30x30**	**15x15 / 30x30**
Mod. Eff.(%)	**14.4 (ac.a.)**	15	16 / 14	17 / 15
Mod. Stab.: Damp/Heat(85/85); LightSoak (1 sun)	-	D/H T80>1000 LS T80>1000	D/H T90>1000 LS T90>1000	D/H T90>1000 LS T90>1000
Mod. Cost (€/m²)	**152**	?		



NT/F

	Status M10/17	Target TA18	Target TA18	Target TA 2018
Mod. Size (cm)	**15x15**	**15x15**	**15x15 / 30x30**	**15x15 / 30x30**
Mod. Eff.(%)	**10 (160 cm²)**	**10**	**12 / 10**	13 / 11
Mod. Stab.: Damp/Heat(85/85); LightSoak (1 sun)	-	**assessment**	**D/H T80>1000** **LS T80>1000**	D/H T90>1000 LS T90>1000
Mod. Cost (€/m²)	**149**	**?**		



ST/R

	Status M10/17	Target TA18	Target TA18	Target TA18
Mod. Size (cm)	**4x4**	**15x15**	**15x15 / 30x30**	**15x15 / 30x30**
Mod. Eff.(%)	**15.4**	**12**	**14 / 11**	**15 / 13**
Mod. Stab.: Damp/Heat(85/85); LightSoak (1 sun)	**TS:T80>1000hrs@85°C*** **LS:T80>1000hrs@1sun***	D/H T80>1000 LS T80>1000	**D/H T90>1000** **LS T90>1000**	**D/H T90>1000** **LS T90>1000**
Mod. Cost (€/m²)	**57**	**?**	**?**	**?**

* Obtained with different PIN stacks on *cells*

Table 17: Solliance development roadmap for PSC modules on 15x15 and 30x30 cm² size, with specific targets for Non-Transparent Rigid modules (NT/R, as well as for Non-Transparent Flexible (NT/F) and Semi-Transparent Rigid (ST/R) over the coming years.

Towards the Terawatt solar age [4]
A recent review in Science by numerous authors indicated a generic aspect of PSC research that once more confirms that the future of thin film PV still holds tantalizing perspectives (and provides a bridge to the next paragraph) : " Research on perovskites has highlighted how materials can be engineered to be defect tolerant, reducing requirements on material quality and enabling ultralow-cost manufacturing technology for high-efficiency materials. Lessons from perovskites may identify a new class of solar cells that can achieve efficiencies comparable to GaAs but with easily scalable manufacturing."

4.4 III-V roadmap

Current III-V cell technology

Because of the relative ease to combine III-V materials, the conversion efficiency of multi-junction III-V solar cells has been increasing continuously for decades. The present record is over 46% [5] and there are ample opportunities for further improvements to reach efficiencies >50%. The current benchmark III-V multi-junction solar cell is the triple-junction InGaP/(In)GaAs/Ge cell. The cell structure is produced in batches on 4 inch diameter Ge semiconductor wafers utilizing Chemical Vapor Deposition (CVD) systems. The active cell structure is in fact a thin-film with a thickness of about 5 μm. However, for optimal efficiencies these cells need to be produced on a semiconductor wafer with a matching lattice constant. In the current production approach the active cell structure remains on this wafer while it is further processed so that the latter becomes an integral part of the final device. Therefore the present generation of III-V solar cells, just as c-Si, is considered to be a wafer-based device.

Current III-V cell applications

III-V cells have an unchallenged position for spacecraft applications. This is based on their high power to weight ratio and resistance against extreme conditions such as electron, proton and harsh UV radiation as well as cyclic temperature changes between plus and minus 100 ºC. In spacecraft applications (i.e. under AM0) triple-junction III-V cells typically have an efficiency >30%, which corresponds to efficiencies >33% and a record cell of 37.9% under regular AM1.5 conditions (see triple-junction cell development in Figure 15). This space cell market is almost fully served by four producers (Spectrolab, Azur Space, SolAero/Emcore and Sharp).
Because they can handle large thermal loads and have high open circuit voltages (V_{oc}) III-V cells are also highly suited for CPV systems with a large concentration factor (typically 500). With commercially available cell efficiencies up to 40% at 500x AM1.5D. With such high efficiency cells, CPV modules are competitive over regular c-Si modules in areas with Direct Normal Irradiation (DNI) levels above 2400 kWh/(m^2.yr). This concentrator market is served by the four producers for spacecraft cells and about six additional companies and institutes like Fraunhofer-ISE that develop III-V cells and produce them at relatively small scale [6].

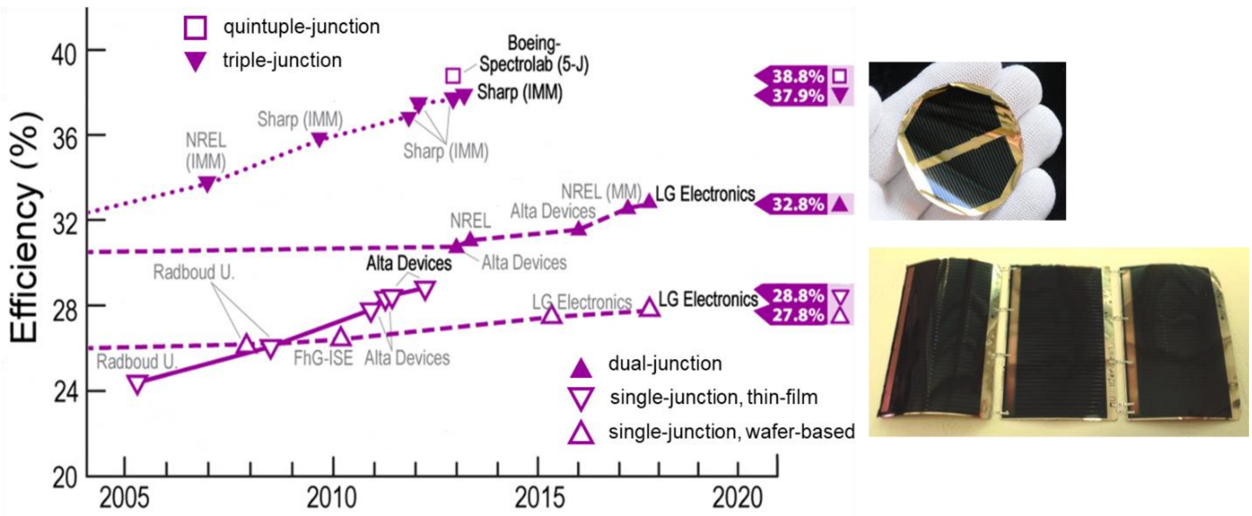


Figure 15: Detail of the National Renewable Efficiency Laboratory (NREL) efficiency chart (also see Fig. 6) highlighting recent non-concentration III-V cell efficiency development. Owing to photon recycling the thin-film cell geometry (images at the right) initiated in 2005 at Radboud University has a superior efficiency over its wafer-based counterparts. Note that both the 32.8% and 37.9% record efficiencies for dual- and triple-junction cells are thin-film devices but are not explicitly referenced as such anymore.

Thin-film III-V cells

With an Epitaxial Lift Off (ELO) approach thin-film III-V cell structures can be separated from their semiconductor wafer [7]. Rather than an integral part of the solar cell, the wafer in this way becomes a reusable production platform for thin-film cell structures [8]. After ELO the thin-films are transferred to a metal carrier foil which simultaneously serves as back contact and a reflector. Owning to photon confinement [9] these genuine thin-film cells can have an enhanced efficiency while their active cell structure is thinner compared to their wafer-based counterparts. The first is reflected by the single-junction efficiency record of 27.8% for wafer-based GaAs cells while it is 28.8% for thin-film GaAs cells (see Figure 15). This thin-film approach for single-junction cells initiated at Radboud University, can also be applied for dual-junction and triple-junction cells with the accompanying gain in cell efficiency. Actually both the 32.8% and 37.9% record efficiencies for dual- and triple-junction cells are thin-film devices but are not explicitly referenced as such anymore.

Research and development challenges on the III-V PV roadmap

I. Improvement of power output by:
a) optimization the efficiency of each individual subcell (eg. by photon recycling),
b) development of alternative subcells with a better responds to the dominant illumination condition,
c) adding more junctions (subcells) to the device.

II. Reduction of production costs by transition to thin-film technology via:
a) development and industrial implementation of an useful wafer separation and reuse technology,
b) reduction of CVD costs (increase cell deposition rate or reduce active cell thickness),
c) development of an alternative (low cost, high throughput) cell deposition technology.

Further application prospects

Given the ample opportunities for further improvements (Ia-c) III-V solar cells are expected to reach efficiencies in excess of >40% under regular and >50% under concentrated light conditions. Based on these efficiency improvements this cell technology has good prospects for a stepwise expansion from the current niche application areas (space and CPV in high DNI areas) in which it has an unrivalled position. With the present wafer-based production technologies this will mainly proceed via field based CPV applications in areas with increasingly lower DNI and building integrated CPV in which the systems have a multiple functionality (like power and heat supply or power and daylight regulation).

If industry succeeds to further improve and implement the ELO based thin-film cell technology, cost reduction associated with wafer reuse (IIa) and reduced CVD costs (IIb) will boost the utilization of III-V cells in its current application areas. More importantly, however, these now flexible, light-weight, high-efficiency cells are anticipated to open an entirely new range of applications in satellite constellations, Unmanned Aerial Vehicles or High Altitude Pseudo Satellites (Airbus), cars (Audi, Toyota), and high-end consumer products (phone and tablet covers). Companies pursuing implementation of this thin-film cell approach are LG Electronics, AltaDevices/Hanergy, Microlink, Semprius, Sharp (via IMM cells) in the USA and Asia and tf2-devices with support of ESA and Airbus in Europe/the Netherlands. Although AltaDevices/Hanergy has already achieved the highest efficiency of any single-junction technology (current champion is 28.8%) and have already demonstrated 24% efficiency for an 850 cm^2 module [10] full Commercial utilization in this respect might take place in 5-10 years..

For large scale application in non-concentrating (flexible) solar modules in the build environment, besides ELO, a low-cost deposition technology (IIc) is required for the production of the cell structures. This should be considered a challenging long term development (15-20 years) but nevertheless LG Electronics and AltaDevices/Hanergy (with reported thin-film tandem cell efficiencies >30%, see figure 15) have already expressed ambitions in this direction.

5 Enabling technology roadmaps

5.1 Materials & Lifetime

Materials and Lifetime	Status 2017	Target 2018	Target 2019	Target 2020	Target 2030
Low cost front window & encapsulation - Rigid - Flexible - PV-Integrated construction elements	Glass + encaps. foil Custom size heat treated front glass; rolled glass Improved corrosion resistance PV cell stack (alt. TCO, ALD barrier) WVTR 10^{-4} g/(cm^2 day) at 30-40 $/m^2 Multifunctional transparent construction materials (moulded polymers, lacquers, bitumen)			Construction glass (window, rooftile, WVTR 10^{-2} g/(cm^2 day) at 15-20 $/m^2	
Substrate foil with barrier - Low cost metal foil + non-conductive barrier - Low cost polymer foil + permeation barrier - Outdoor compatible superstrate foil	PVD oxides/nitrides	Low-C steel with wetchemical dep. barrier ALD barriers / multilayers on polymer foil UV stability; scratch/abrasion resistance		Hybrid barrier	
Rigid glass substrate - Float glass with diffusion barriers/conductors	Sputtered Mo-stacks Jumbo scale sputtered barriers/conductors				Graphene glass
Temporary substrate	Al for SnO2/aSi Lift off III-V Industrially more viable wafer separation methods			Doped tinoxide for other TF absorber	
Reliability and life time - Cell level - Module level - PV-integrated construction level	In situ degradation and life time testing (climate chamber T/humidity) In situ degradation and life time testing (climate chamber); controlled test fields; post mortem Mechanical load testing, bending, scratch/abrasion resistance, fatigue, etc				
Stability improvement - PSC - CIGS	*Days* (PSC) device stability wrt temperature, light and ambient Stability issues of Na/K/Cs addition and bandgap gradients	ALD layers on foil for device stabilisation			*Years*
New materials - Innovative low cost barriers - PSC sequels	Multifunctional construction materials (moulded polymers, lacquers, bitumen) as barrier		Device development for optimised PSC compositions		
Cost of ownership and life cycle analysis Design concepts for recyclability	Reduced use of scarce/hazardous/high footprint materials: thinner CIGS, Pd-free PSC		Design for disassembly in integrated applications		

Table 18: Materials and lifetime roadmap

1. Low cost front window encapsulation

Material costs and limited production capacities present main hurdles on the way towards large-scale deployment of flexible modules. About 1/3 of the flexible CIGS module costs accounts for a transparent front sheet that serves as a high-performance moisture barrier with a water vapor transport ratio (WVTR) of 10^{-4} g/(cm^2 day) and costs of 30-40 $/m^2, whereas silicon wafer-based technology relies on much less expensive polymers with WVTR of 1-0.1 g/(cm^2 day). The need for such a high-performance front sheet is dictated by the chemical instability of the ZnO:Al (AZO) transparent contact, whose degradation is one of the most frequent module failures. Realization of more stable transparent contact layers is targeted to allow for lower cost barriers, specified at 10^{-2} g/(cm^2 day).

2. Substrate foil with barrier

Current flexible thin film (CIGS) concepts are based on polished stainless steel foils with thin film metal barriers to prevent diffusion of elements like Fe which deteriorate absorbers. These metal substrates serve as back electrode, and modules are formed by stringing of separated cell elements. It is desired to use lower cost metal foils (carbon steel) and to develop low cost electrically insulating thin film barriers to enable monolithic interconnection approaches. In recent years, hybrid coatings have been developed to this aim, but these are still subject to further optimization and evaluation by making test cells and -modules (e.g. EU ARCIGS-M). 2020 goal is to demonstrate shuntless high quality monolithic module formation on low cost construction steel foils, by further tuning of barrier layer composition, stability under process conditions, and roughness.

3. Rigid glass substrate

Several thin film producers employ rigid glass substrates that have been coated with back contacts (TCO or Mo) or back contact stacks (contacts with integrated diffusion barriers) directly at the float glass manufacturer. This not only serves to reduce cost, but often improves quality by higher degree of control of the glass surface conditions. Specific optimization, and the location of (most notably Se-) diffusion barriers in the stack are important in relation to back end interconnection processing on glass.

4. Temporary substrate/superstrate

Two very relevant cost reducing Dutch findings are based on temporary substrates:

- Radboud University: Costly substrates for epitaxial growth of III-V absorbers can be reused after the grown layers have been lifted off. Large scale production of high quality thin film is commercially very attractive but requires higher speed lift off processes with improved control.
- HyET utilizes low cost aluminum foil as a temporary substrate for a-Si processing, which is etched off after cell processing. It enables free choice of encapsulation material for additional applications. The concept may be translated also to other types of thin film PV.

5. Reliability and lifetime

Reliability and predictable lifetime are important for bankability of thin film PV installations in general. However, as the roadmap aims at integration in building materials and products, a good match with the envisaged lifetime of the integrated product is even more important. Therefore, aim is to obtain a more basic understanding of loss mechanisms:

- Cell level: for CIGS, where long lifetime and high stability (20yrs) have been achieved in practice, focus is on real time in situ monitoring under controlled temperature and climate conditions, analysis and modeling of degradation effects to study the influence of Na, K, or Cs additions on the absorber stability, and to improve stability of the TCO front contact. For PSC, focus is on inherent stabilization of the absorber material multifunctional transportlayers with barrier properties for gas and/or ions.
- Module level:
    - Reliability of novel interconnection methods (back end laser scribing and printing; metal fingers) and designs
    - Study of basic mechanisms underlying degradation effects under partial shadowing
    - Reliability testing and device optimization under less severe (lower cost) and novel encapsulation conditions

- Integration level:
    - Multi-stress testing of multi-functional PV-integrated components and products. Mechanical stress testing under controlled laboratory conditions of PV-integrated

building components, with a focus on mutual comparison of different PV technologies, substrates and types of front sheet encapsulation

6. Stability improvement

Improve intrinsic stability of front side transparent conductor by change of material composition and/or introduction of built in diffusion barriers (e.g. s-ALD oxides)

7. New materials
- PSC sequels: gradual improvements and new material compositions
- Innovative low cost front sheet encapsulants, based on construction materials for the desired area of application (e.g. transparent pavement/road materials, molded plastics, flexible foils)
- Multifunctional nanostructured front sheet materials: cost reducing/efficiency improving combinations of barrier properties, wear resistance, anti-fouling, light guiding/trapping and aesthetics.
- Graphene as multifunctional front sheet- or back electrode material

8. Cost of ownership and lifecycle analysis
- Continuously updated cost of ownership analyses, to evaluate the effect of proposed innovations
- New cell/module designs aiming at improved recyclability; design for disassembly

5.2 Metallization and interconnect

Metallization and interconnect	Status 2017	Target 2018	Target 2019	Target 2020	Target 2030
Monolithic interconnection: Classic P1P2P3	Reduce dead zone to <50µm → Mech+laser scribe Dead zone 200µm Glass: 1x1 m² Flex foil: 0,5x6 m² Shunt free P3 laser scribing →	Imaging + shunt repair/elimination →			
Monolithic interconnection: Back end interconnect TRL 8 backend for flex aSi (HyET)	All laser scribe + printed iso & metal Shunt free P3 laser scribing → 1000µ 500µ Ag ink: reduced dotspreading 200µ → Flex foil	TCO to replace printed metal → Controlled absorption of ablation pulse → Optimise layer stack to facilitate back end interconnect →			
Monolithic interconnection: Customized/ Free form back end interconnect	Demonstrated on OPV	On demand customisation of semifabricated TF-stacks →			
Advanced interconnection: Combination with finger structures/grids/MWT	Direct patterned metallized foil →			Nano grids →	
Standard module by cell stringing		Wire; mesh →			
Free form module by cell stringing		Automated free form positioning an stringing of TF CIGS →			
Shadow tolerance - Bypass diode strategies - Shadow tolerant interconnection patterns - Identification and elimination of root causes	Module segmentation with diode per segment or cell → Analysis of basic mechanisms reverse bias sensitivity TFPV →		Customised interconnection + diode integration →		
Multijunction/ tandem thin film	High TRL : III-V Low TRL: CIGS-PSC	Transparent interconnects and electrodes →			

Table 19: Metallization and interconnect roadmap

1. Monolithic interconnection

Classic P1P2P3

Current state of the art in monolithic module interconnection (commonly referred to as P1P2P3) is that the three scribing steps are performed as intermediate steps while building up the thin film PV layer stack, Current trend in this state of the art approach is to reduce the efficiency loss that occurs as active thin film PV area is consumed by the electrical series connection of separated cell areas, commonly referred to as the “dead zone”. In the process of monolithic series connection, typical achieved dead area widths are in the order of 70μm (lab) to 200μm (production demo). In combination with typical cell line widths of 5-10mm, this translates into relative efficiency losses in the order of one or several percent.
Aim is to reduce the dead area width to 50μm (lab) in 2020.

Back end interconnect

Apart from the geometrical efficiency loss above, other loss factors occur due to device damage in the form of electrical shunts and defects induced by the interconnection process. Additional cost factors are required cleaning steps after a scribing step, and realignment of each subsequent scribing step. This realignment is also complicated by the fact that deposition of additional layers after a previous scribing step involves high processing temperatures (up to 550-600 C for the CIGS absorber), leading to thermal deformation of the underlying material, which also induces deformation of previously scribed lines. Back end interconnection, taking place after all layers have been deposited, has the potential to reduce these loss mechanisms.
Shunt free P3 scribing is generally recognized as one of the major difficulties, but in 2017 Solliance demonstrated shunt free P3 scribing of CIGS and PSC stacks.
Roadmap is to improve the precision of printed (Ag) metallization to <200μm, to explore transparent conductors to eliminate the need of Ag metallization, and to make combinations with foil based metallized grids (see *Advanced interconnection* below). In addition, to enhance back contact interconnection the cell coating stack will be optimized to control laser light absorption.

Customized free form back end interconnect

But more importantly, by shifting the entire monolithic interconnection process to the end of the production line (back end processing), and performing this in an integrated digitalized setup, it becomes possible to achieve module customization essentially without additional cost. This greatly increases the value of the product, and opens up new possibilities for more efficient integration of PV in building and construction, and in products. And thereby enhances further spreading of PV as an important element in durable electricity production.
Roadmap is to enable on-line scribing of 2D free geometries, also on flexible substrates with diffusion- and electrical barriers

Advanced interconnection

Current state of the art thin film PV modules still suffer significant power output losses:

- 10 – 15% [11] electrical losses in the transparent conductive oxide front contacts due to their inherent trade-off between conductivity and optical transmittance.
- 7 – 10% optical losses in transparent conductive oxide cell front contacts [12] and angular dependent reflection [13] at the module front-side.
- Shading losses due to the restrictions in adapting module design to specific application locations [14]

Roadmap is to reduce these power losses (almost eliminate the 10-15% electrical loss, and reduce optical loss to 3-5%) and to minimize restrictions on thin film PV module design by material, processes and equipment innovations that fit within the current thin film module manufacturing.

At the cell level:

- Boosting the cell efficiency by integrating electroplated metallic meshes, with dimensions, conductivity and transparency far beyond the reach of printing, into the cell front contact.
- Making cell to cell interconnection without the need for a bus bar or accurate alignment between metal meshes and interconnection scribes, allowing narrower scribing.

At the module level:

- Creating adaptable thin film module designs with more flexibility in dimensions and in interconnection and anti-reflection schemes on the module front-side
- Providing an easy way of series and parallel interconnection of sub-modules without changing the current module manufacturing process by integrating interconnection circuits and anti-reflection functionality into the encapsulation foil.
- Develop interconnection schemes that put less severe demands on barrier properties of encapsulating front sheets (prevention of surface topology and wrap through contacts)

Target is to demonstrate plated Ni interconnects in 2018, and to expand to Ni/Cu plating in 2019. Target increase in absolute cell efficiency is +0,5% in 2019; longer term target is +1%.

2. Cell stringing

Standard module

- Contacting and stringing of thin film III-V
- Low cost metal contacting of CIGS-based cells (replace Ni/Ag)

Free form module

- Equipment development for automated free form thin film cell positioning and stringing (demo available 2019)

3. Shadow tolerance

- Design and demonstrate interconnection strategies with improved shadow tolerance

4. Multijunction thin film

- Modeling, design and demonstration of efficiency optimizing strategies for interconnection of stacked cell materials

5.3 Light management

Light management	Status 2017	Target 2018	Target 2019	Target 2020	Target 2030
Transparent frontside conductor - Wider spectral transmission range - Low cost deposition	PVD/CVD doped oxides Alternative TCO compositions; ITO/IZO → Jumbo scale window glass; sol-gel transparent conductors →		Graphene conductors → Metal nanowires →		
Non-transparant backside conductor - Improved optical reflectivity Transparent backside conductor - Compatibility with absorber processing (bifacial and semitransparent applications) - Improved IR transmission (tandems, semitr.)	ALD (oxy)nitrides → Alternative TCO compositions & passivation layers →				
Nanoscale patterning - Light trapping for thinner absorbers					
Colouring Decorative colouring with reduced eff. loss - Absorption layers and patterned structures - Interference - Semi-transparency + colored backreflector - Nanoparticles / MIE scattering	Efficiency loss 10-40% Dot-patterned colour absorbers Multilayer interference	Decorative back end patterning and inteconnect → Patterned absorbers/cells for semi transparency →	Manuf. Technology for nanostructured colouring →	Spectral selective PSC →	
Improved corrosion resistance - Corrosion resistant transparent conductor - Improved encapsulation foils	Alternative TCO compositions & nm-scale barrier layers → PVB, Polyolefines			ionomers	
Transparent construction materials - Moulded plastics; Lacquers; Bitumen; etc	Integrate light management in materials for construction components → Light harvesting, scattering →				

Table 20: Light management roadmap

1. Transparent front side conductor
- Transparent conductive oxides with improved corrosion stability; alternative material composition (e.g. IZO) and added barriers (e.g. nm thickness range ALD barrier layers) Demonstrated in flexible CIGS devices with low cost encapsulation (2019)
- Low cost wet processed, sol gel/slot dye transparent conductors
- Nanowire-based thin film transparent conductors
- Graphene conductors in front sheets or transferred directly onto cell stack

2. Non transparent back side conductor
- Improved optical reflection layers on molybdenum (CIGS) (proof of principle 2019, STW TU/e, TUD)
- Textured back electrodes for improved light trapping (CIGS, aSi)

3. Transparent back side conductor
- TCO materials and (passivating) barriers compatible with subsequent absorber processing; aimed for tandem formation, but also enabling semitransparent PV and (if efficiency can be fully retained) bifacial applications

4. Nanoscale texturing
- Light trapping structures; improved light trapping in CIGS demonstrated in 2017 by CIGS formation on Mo backelectrodes deposited on nano imprinted textures

- Plasmonic structures for light guiding

5. Colouring
- (Patterned) absorption layers included in front sheet encapsulation; on foil or front glass
- Interference layers deposited on front glass (sol gel, sputtering) or incorporated in the transparent conductor of the cell stack (ERANET BIPVPOD)
- Intrinsically colored absorption layers: PSC, OPV with specific bandgap structures
- Resonant MIE scattering (AMOLF/ECN)

6. Improved corrosion resistance
- Transparent conductors or transparent conductive layer stacks with improved corrosion resistance (maintained transparency and electrical conductivity under reduced encapsulation)

7. Transparent construction materials
- Optimized transmission/scattering/trapping of light with multifunctional construction materials (e.g. transparent bitumen, moulded polymers, lacquers) (e.g. PV OpMaat, SolaRoad)

5.4 Passivation and bandgap control

Passivation and Bandgap control	Status 2017	Target 2018	Target 2019	Target 2020	Target 2030
Passivation - Grain boundary passivation - Layer interface passivation	By Na addition By bandgap grading	Na-treatment for monolithic CIGS on insulated steel foil → Al2O3 by ALD for passivation + nanoscale conduction paths for thin CIGS →			
Alternative buffer layers (ALD) - ALD ZnOS	+0,5% demonstrated wrt CdS	Demonstrate ALD ZnOS for CIGS on float glass →			
- ALD ZnMgO - ALD buffer oxide layers for PSC	Second buffer in SolarFrontier record	Demonstrate ALD ZnMgO for CIGS on float glass →			
Bandgap gradient control - Optimisation selenisation/sulphurization - K/Cs post treatment	Ga grading backcontact → Grading by Sulphurisation after Selenisation (SAS) →			+1% efficiency +1% efficiency	
Bandgap tuning - Lower bandgap (red) - Higher bandgap (blue)	PSC device- and material development → Tuning CIGS selenisation/sulphurisation →				
All passivated single bandgap	With imec/Uhasselt (B): ALD passivation for CIGS eliminating necessity for bandgap gradients →				
III-V absorber formation - Reduction of CVD costs - Efficiency optimisation - Alternative or more subcells	Higher dep rate / reduced active cell thickness → Efficiency optimization of individual subcells; Photon recycling →				
Analysis for modeling and control	Time resolved photoluminescence; In situ XRD; Analysis of buried contacts; ... →				

Table 21: Roadmap for Passivation and Bandgap control

1. Passivation

Grain boundary passivation
Grain boundary passivation by Na greatly enhances CIGS cell efficiency. Although in production of CIGS on soda-lime glass Na diffusion from the glass substrate through the back electrode layer acts as a natural supply of Na for passivation, often barriers are used to prevent this diffusion and to add Na in a more controlled fashion. As this roadmap aims for CIGS on insulated metal foils, controlled Na addition is necessary. Liquid Na addition and high temperature Na evaporation are explored in comparison.

Interface passivation
Improved charge carrier life time has been demonstrated by introduction of passivating Al2O3 layers of nm-thickness range at back and front interfaces of CIGS absorbers. Spatial ALD is a fast, effective and low cost method to produce such layers. In this roadmap it's application is explored for two goals.

- Midterm goal is to achieve comparable cell efficiencies with thinner CIGS absorbers (thereby increasing throughput and reducing material cost) by reducing interface recombination. Target is absorber thickness reduction from 1,5 μm to 0,5 μm without significant reduction of efficiency. As typically 1 mm CIGS is required for full absorption, this passivation should be combined with some light trapping or just back reflection (double pass light transmission is sufficient). This is explored in PhD projects (TUD, TU/e).
- Long term goal is to demonstrate interface passivation by deposited passivation layers that should eliminate the need of composition gradients in CIGS absorbers (like present Ga-grading). This would make the absorber not only thinner, but also less complex. This is explored in the Solliance collaboration with UHasselt and imec. In 2017, baseline for 500nm CIGS was established, and first Al2O3 with nm openings was demonstrated. In 2018 both will be combined, and a reflective layer will be added. Target is to achieve 500nm with uncompromised efficiency by two-sided passivation and single reflection in 2020.

In either case, nm scale holes at μm pitch are required to permit local conduction through the passivation layer. Formation of these nm-scale conduction paths is explored utilizing nanoimprint and etching, but also more industrially viable routes involving nanoparticles.

2. Alternative buffer layers

General desire is to replace the classical CdS buffer layer in CIGS modules by alternative buffer layers: both to eliminate the use of Cd, as to eliminate the optical loss by absorption in the CdS layer. Sputtered InS and wet chemical ZnOS buffer layers are applied commercially, and also commercial interest exists for ALD deposited ZnOS. Latest CIGS cell records were obtained by addition of a second buffer layer of ZnMgO (currently in combination with a wet chemical ZnOS). This roadmap therefore focuses on development of s-ALD equipment and processes for deposition of ZnOS and ZnMgO on float glass and flexible substrates.

- In 2016, +0,5% absolute efficiency improvement was demonstrated on CIGS on foil. In 2017, proof of principle of sALD ZnOS on 30cm wide float glass was demonstrated on glass within 1%-range lateral uniformity. In 2018 sALD ZnOS on CIGS on glass is foreseen. Longer term aim is to explore fast ALD combinations of ZnOS/ZnMgO.

3. Bandgap gradient control

By controlling CIGS (where S stands for either selenium and/or Sulfur), Gallium composition gradients as a function of layer depth are created, which act as a back surface field. This is used in current CIGS cell fabrication.

4. Bandgap tuning

Specific integrated applications (e.g. tandems, powerwindows) require tuning of the absorber bandgap to more fully utilize the locally available light spectrum. Improved control of composition (CIGS, PSC) and dedicated multijunction designs (III-V) are aimed for. More specific targets for PSC are for single junction 1.1-1.5 eV, for tandem 1,0-1,2 eV, and for high bandgap 1,7-1,9 eV.

5. Innovative analysis methods for modeling and control

Nano scale control of layer thickness, contact holes, (buried) interfaces, particles require innovative detection methods for analysis. For improved control in industrial processing, modeling and translation into commercially viable control systems is required.

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