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STRATEGIC ENERGY TECHNOLOGY PLAN

Scientific Assessment in support of the Materials Roadmap enabling Low Carbon Energy Technologies

Photovoltaic Technology

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Preamble

This scientific assessment serves as the basis for a materials research roadmap for solar photovoltaic technology, itself an integral element of an overall "Materials Roadmap Enabling Low Carbon Technologies", a Commission Staff Working Document published in December 2011. The Materials Roadmap aims at contributing to strategic decisions on materials research funding at European and Member State levels and is aligned with the priorities of the Strategic Energy Technology Plan (SET-Plan). It is intended to serve as a guide for developing specific research and development activities in the field of materials for energy applications over the next 10 years.

This report provides an in-depth analysis of the state-of-the-art and future challenges for energy technology-related materials and the needs for research activities to support the development of solar photovoltaic technology both for the 2020 and the 2050 market horizons.

It has been produced by independent and renowned European materials scientists and energy technology experts, drawn from academia, research institutes and industry, under the coordination the SET-Plan Information System (SETIS), which is managed by the Joint Research Centre (JRC) of the European Commission. The contents were presented and discussed at a dedicated hearing in which a wide pool of stakeholders participated, including representatives of the relevant technology platforms, industry associations and the Joint Programmes of the European Energy Research Associations.

Chapter on
PV Technology

For the Roadmapping Exercise on Materials for the European Strategic Energy Technology Plan

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1. PHOTOVOLTAIC TECHNOLOGY

1.1.1 Technology and System State of the Art

The scope of photovoltaic (PV) technology to be covered in this scientific summary assessment paper is the PV Module and inverter. It will not cover mountings and frames used for installation. Nor will it include energy storage systems and smart grids, however close collaboration with these sectors will be mandatory in the future as the level of PV penetration rises in the overall energy generation mix.

This paper is a synthesis of the various designated expert's reports that are provided in attachment. For more detail on the subjects and the associated references please refer to these documents.

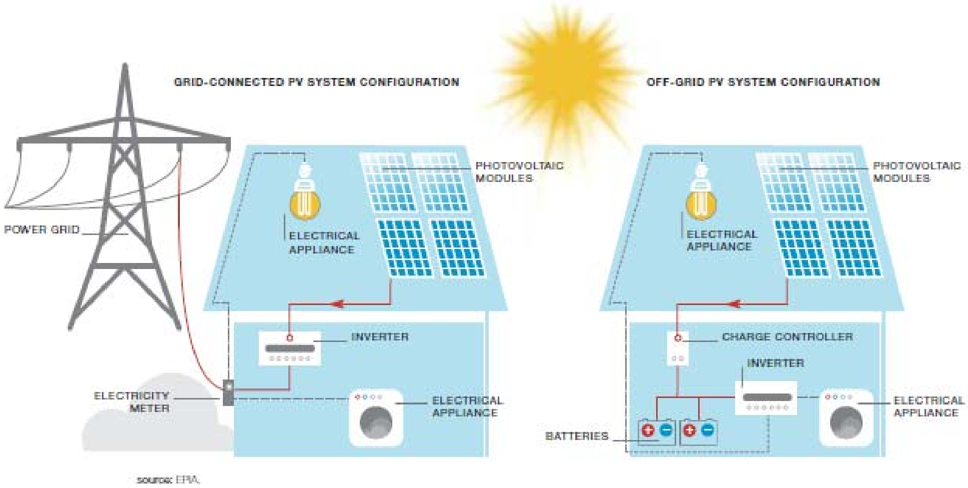


Figure 1. Schematic of PV system connection configurations

The complexity of this assessment paper is that PV technology today covers several parallel technologies that are either competing or are complementary. They vary widely in terms of technological maturity, performance, cost, materials availability and requirements. However this document will review all the relevant PV technologies (listed below) and their development needs to meet the SET Plan objectives for 2020 in terms of energy production cost and materials availability.

- **Crystalline silicon (c-Si)**
  Wafer based c-Si, the most mature PV technology, with high efficiency modules suitable for less price sensitive applications where area restrictions apply.

- **Thin film inorganic PV (TFPV)**
  Have the lowest module cost potential in the near to mid term. There are three broad families
  - **Cadmium Telluride (CdTe)**
    Is the current cost leader PV technology. There are some contested concerns expressed over the future easy availability of tellurium as well as the use of cadmium.
  - **Thin Film Silicon (TFSi)**
    Amorphous Silicon / micro crystalline (TFSi) – Acceptable efficiency cells require sophisticated multi junction device architecture and manufacturing techniques and control. Such multi junction devices architecture will also contribute to device stability.
  - **Copper indium selenide (sulphide) / Copper indium gallium di-selenide (sulphide) (CIS/CIGS)**
    Is the PV technology which has achieved the highest lab based efficiencies of all TFPVs. The active absorber layer material system is the most complex to manufacture which explains the efficiency gap between lab cells and industrial modules. The material system would appear to lend itself to cheaper non vacuum manufacturing processes. There are some concerns about future availability of In, Ga and Se leading to a need for ongoing research in substitute materials systems.

- **Low Concentrator PV (LCPV)**
  Such systems typically use lenses to concentrate the incident light on smaller area c-Si or TFPV cells.

- **High Concentrator PV (HCPV)**
  High Concentrator PV (HCPV): Uses lenses or mirrors to concentrate the incident light on highly-efficient III-V multi-junction solar cells. HCPV systems have great potential for low cost electricity production in solar power stations with 1 to 100 MWp in countries with a large fraction of direct solar radiation.

- **Organic PV (OPV)**
  Organic based thin film PV that have great potential for cost reduction in the medium to long term, however a number of significant scientific / technological hurdles remain to be overcome.

The figure 2 below tracking best lab cell efficiencies shows that all the PV technologies have been improving over recent years and is continuing to do so as science and technology continually push open the envelope.

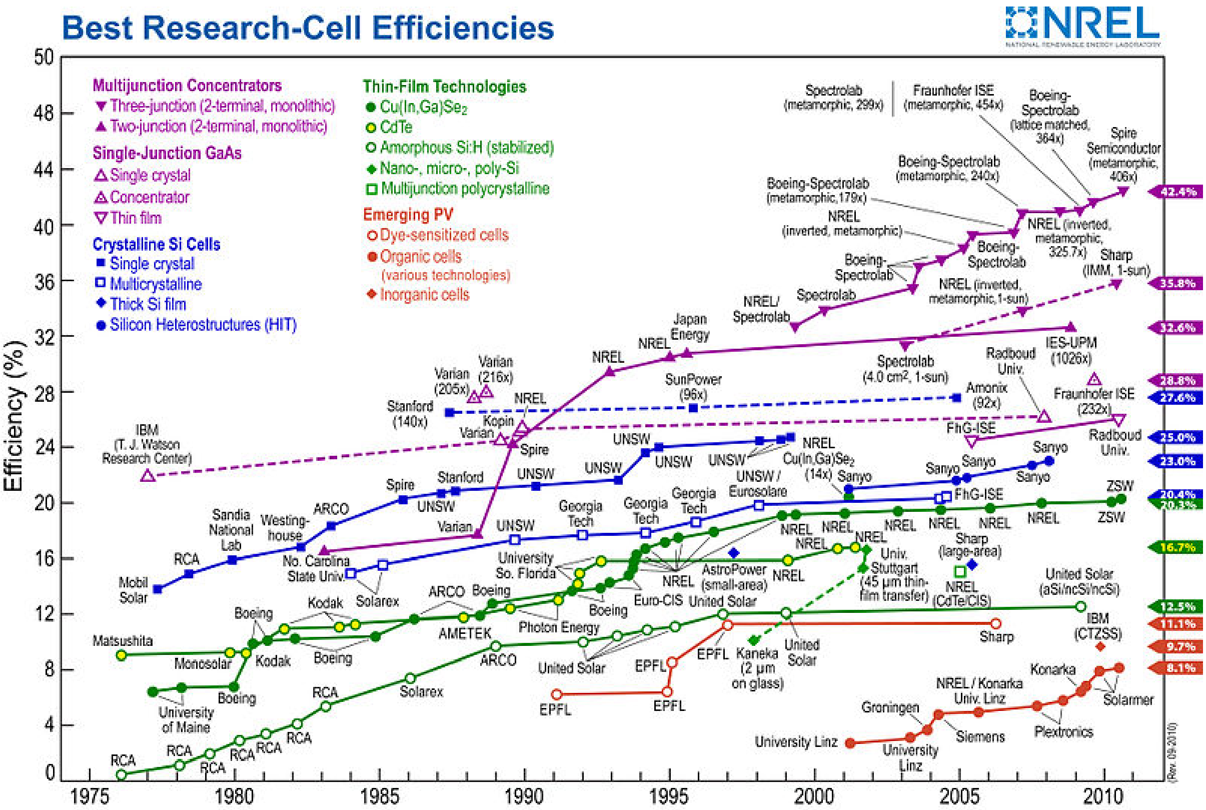


Figure 2. Evolution of best research cell efficiencies

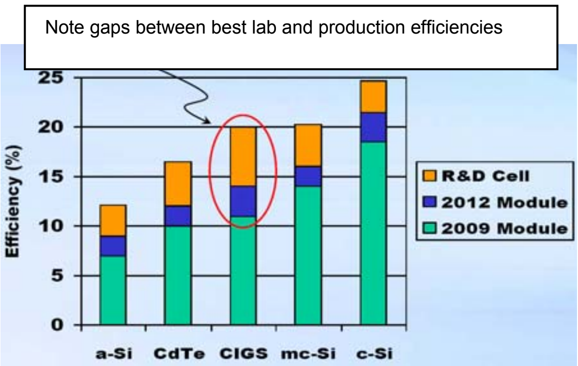


Figure 3a. Efficiency gap between research lab and production (Source Veeco – Photon's PV production equipment conference 2009)

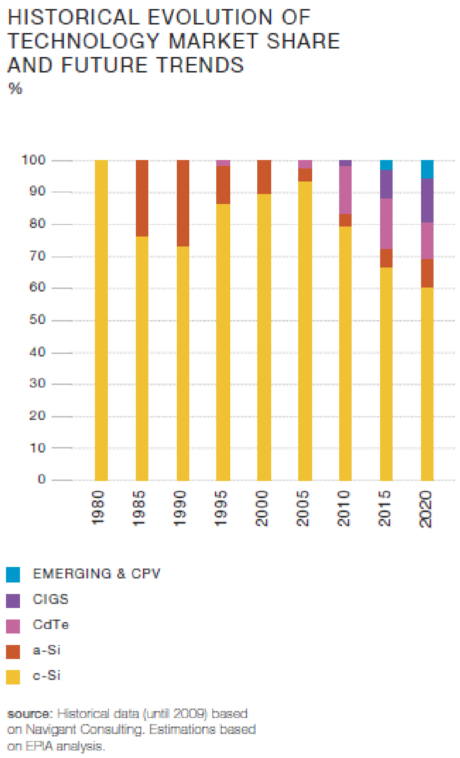


Figure 3b. Historical evolution of technology market share and future trends (Source - Solar Generation IV)

It is important to note the fairly large gaps between best lab cell efficiencies and typical industrial production for all PV technologies (Figure 3a). These gaps are being continually narrowed, however it remains a priority to develop cost effective, reliable processes and technology to minimise them.

The evolution of the different PV technologies illustrated in figure 3b also is an indicator of the early stage of maturity of the different PV technologies.

As a whole, the PV industry has shown tremendous progress in terms of cost reduction.

Figure 4 shows the evolution of c-Si and TFPV prices as a function of the cumulative manufacturing experience. One can note some short term variations above and below the trend line. These are mainly due to the shortage of poly crystalline silicon in recent times (now resolved) as well as brief periods of industry over-capacity. This is normal especially for an industry in its early development stages, but it is important to note that thanks to continuous research efforts and the effects of scale, this price experience curve confirms a consistent trend of 22% reduction in module manufacturing costs for every doubling of cumulative PV production.

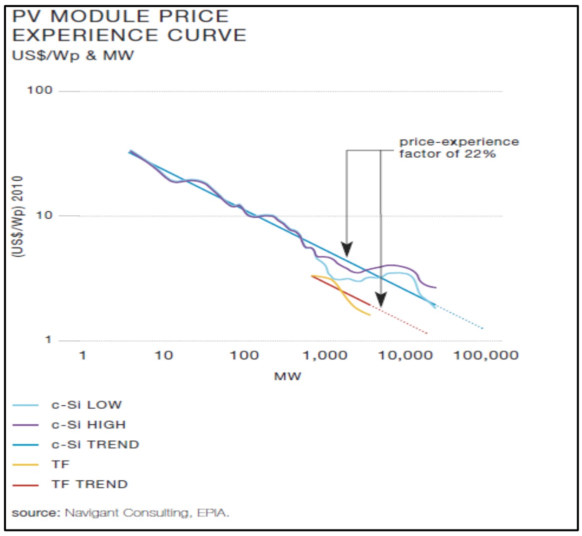


Figure 4. PV module price – experience curve

However, the module is only part of the total cost picture. Additional costs are introduced with the inverter, the Balance of System costs (BOS), installation and engineering / permitting. The module represents typically 50-60% of total installed systems costs (Figure 5).

Simple reduction of module costs is of course beneficial to the installed costs and investment, however improvements on module efficiency will not only impact directly on the module costs but also on the BOS and installation costs i.e. module plus BOS are equivalent to 70 – 80% of total investment costs.
As demonstrated in figure 4, the trend has been for module costs to come down quickly and to continue to do so. As this happens, the non-module costs increase relatively thus increasing the relative impact and importance of the module efficiency. For this reason it is important to focus on developments that will ideally both reduce directly the module costs and especially improve its efficiency in order to have the maximum impact on total installed cost and so the Levelised Cost of Electricity (LCOE).

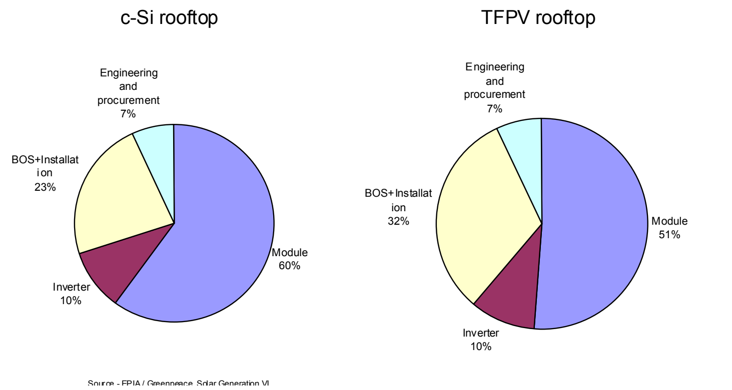


Figure 5. . Cost breakdown for c-Si and TFPV rooftop systems

As outlined above several PV technologies have been developing in parallel. This can be viewed as an underlying strength since it allows the selection of the optimum PV technology as a function of the local irradiation profile and the application constraints. In addition, when one technology is faced with material or technology constraints it allows ready substitution by another.
However, each PV technology does have its own specific cost / performance attributes implying that several but probably not all of the current PV technologies will co-exist in the future. Actual application conditions will determine which ones will be the most adopted through their offer of the optimal solution for a given set of constraints (price sensitivity, space, weight, light conditions, ambient temperatures, aesthetics, longevity ………). Since each of the PV technologies (including even the most mature c-Si) is still exploring the limits of its own attributes, it would be premature today to limit the future options. Consequently, when considering the horizons of 2020, 2030 and 2050 we need to consider the range of PV technologies listed above for further development as it is difficult to foresee today the optimal solution of tomorrow.

KPIs

In the case of PV, the materials focus has to be with respect to their functionality in their activated form. A PV device comprises a series of discrete layers each with its own typical functionalities such as light absorption, semi conducting, electro-optical, optical, abrasion resistance, conductivity……..   The materials actual functionality is most often due to a combination of the material, the manufacturing process and activation steps associated with that material and the behaviour of two adjacent materials at their interface. It is therefore quite often difficult (impossible) to isolate the functionality for measurement e.g. the semi conducting active layer. Others will be relatively easier for example Transparent Conducting Oxide layers (TCOs) in terms of transparency and conductivity. However, even in these cases the interface behaviour will have a significant effect on the device performance.

Consequently in the following pages KPIs for individual materials will be indicated where possible but in some cases and ultimately in all cases it will be necessary to refer to overall device performance and cost.

Based on historical data and looking to the future, we can set the following PV system Key Performance Indicators.

PV performance targets		2007	2010	2015	2020	2030	2050
Typical electricitygeneration costs in Southern Europe (2) (Euros/kWh)		0,30-0,60	0,16-0,36	0,10-0,20	0,08-0,19	<0,07	0,03
Typical turn-key system prices (Euros/Wp) (1)		5	2,26-3,41	-	1,30-2,08	<1,20	0,5
Typical PV module efficiencies (%)	Crystalline Silicon	13-18%	15-20%	16-21%	18-23%	30%	>30%
	Thin Films (inorganic)	5-11%	6-12%	8-14%	10-18%	20%	>20%
	Concentrator PV	20%	20-25%	35-40%	40-50%	50-60%	<60%
	OPV				>10	16	18
	Novel PV technologies		Will need to be competitive with status quo PV systems				
Inverter life time (years)		10	15	20	>25	>25	>25
Guaranteed performance output (years) (3)	Inorganic	20-25	20-25	25-30	35-40	40	40
	OPV				10	>20	>30
System Energy Pay-back time (years)		2-3	1-2	1	0,5	0,4	0,25

Source: Implementation plan for the strategic research agenda / SEII May 2010 - EU PV Technology Platform / EPIA - AT Kearney

(1) Price of system depends on technology improvements as well as market maturity (industry infrastucture and admin costs)
(2) LCOE varies with financing cost and location. Southern EU locations considered range from 1500kWh/m^2 (e.g. Toulouse) to 2000 kWh/m^2 (e.g. Syracusa).
(3) Refers to highest performance guarantees required from the industry but actual figures required will be application dependent.

Table 1. Key Performance Indicators for PV systems

Inherent to all materials developments effective and sustainable resource use should be considered. Recycling will be dealt with in greater depth in section 1.2. Cradle to cradle approach and design for recycling should be an underlying theme for proposed developments where materials can have an influence or enable.

Priorities for implementation of research results

In view of its innate attributes, PV has an assured future in contributing to society's long term energy and environmental sustainability needs; however at present it is still largely relying on external incentives such as Feed in Tariffs to be economically viable. It is of the utmost priority to the industry and society that PV becomes an attractive rational investment opportunity in as short a time frame as possible without the need for such incentives. Once this tipping point has been reached we can expect a self-fuelled rapid deployment of PV for both residential and industrial sectors alike. Reaching this threshold early will be possible provided that the right efforts in research and manufacturing scale effects are implemented.

Figure 6 illustrates schematically the priorities of the implementation objectives for PV over the coming 40 years. The absolute overarching priority between now and 2020 is to bring down the cost of PV electricity generation. Installed cost reduction based on improving current PV technologies will be the key enabler to reach economic autonomy.

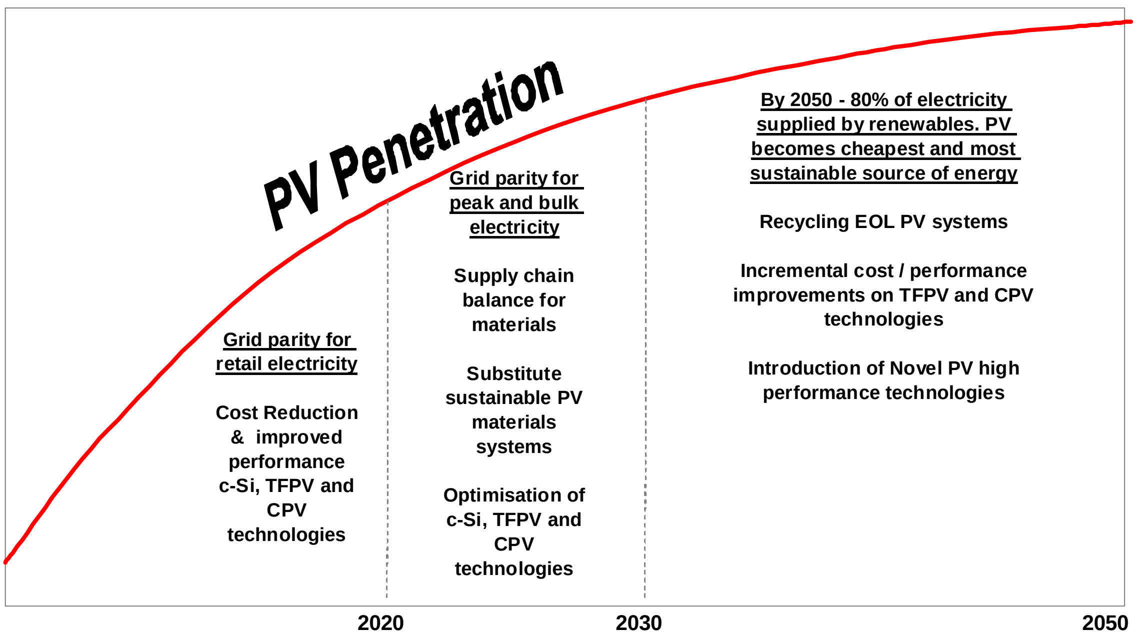


Figure 6. Schematic of PV industry's research priorities / implementation challenges

However, success will bring new challenges in terms of materials availability particularly for the advanced thin film PV technologies. Intensive research into new substitute materials systems with no resource limitations will need to be initiated in the next 10 years so that they may be ready for implementation before 2025. Due to the life time of PV devices, it is not expected that significant volumes of end-of life PV modules will require recycling before 2030, however effective recycling of production scrap will be an important element to ensure sufficient materials availability.

Scenarios and market size

Over the years, the IEA, the EC, the EPIA and independent market forecasters have all regularly increased their predictions of the global PV market size.

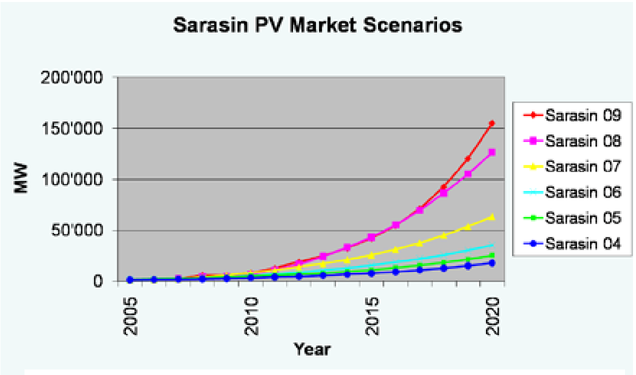


Figure 7. Evolution of PV market estimates – Sarasin Bank (source Stefan Nowak)

The given example is the Sarasin Bank forecasts which consistently increased its 2020 PV scenario in successive years.

This highlights the inherent difficulty of evaluating and defining such scenarios in an early stage high growth industry.

When considering the PV market potential and the pressures placed on the materials supply chain, it is essential to consider the world market. Today Europe is leading the way with more than 70% of the installed PV capacity. However this will most likely change over the next 10-20 years. A recent study on the potential of the "Sun Belt" countries (between 35N and 35S) where the innate drivers in favour of PV are extremely high, suggests that in a Paradigm Shift scenario, the PV potential in such regions would be for an installed base of 1,100 GWp by 2030. In addition, significant growth is expected in populous oil-resource-poor countries such as India and China.

The scenarios suggested in this technology chapter differ slightly from those originally proposed by the EC when defining the project. The world wide annual PV installations in 2010 are now confirmed to have been 16.6 GWp (13.2 GWp in Europe), with estimates for a total installed PV base of 39.5 GWp world wide of which 29.2 GWp is in Europe.

The EC proposed figure in the low case scenario of 84 GWp in 2020 in Europe (coming no doubt from the NREAPs) would appear unduly conservative as it implies an average annual reduction of installation levels of 15 – 20%. Instead we would propose an annual positive progression per annum until 2020 and slowing down progressively after that as PV fills its rightful place in the energy mix.
In the case of the high scenario, rather than introduce a completely new set of figures, we propose to refer to the EPIA's Paradigm shift scenario (Table 2).

We would go further and suggest that provided that the R&D efforts proposed in this document are successful, we would expect the PV industry to be able to meet the requirements necessary for the paradigm shift scenario, but this of course assumes that the other conditions are also met as outlined in the EPIA report.

		2010	2020	2030	2040	2050
LOW SCENARIO						
Cumulative	GWp	39,5	345	1081	2013	2988
Annual	GWp/yr	16,6	59	96	162	175
Ratio of cumulative PV installations World/Europe		1,35	2,5	3,9	-	-
HIGH SCENARIO						
Cumulative	GWp	39,5	737	1845	3256	4669
Annual	GWp/yr	16,6	135	137	250	250
Ratio of cumulative PV installations World/Europe		1,.35	2	2,9	-	-

Table 2. Summary of proposed world wide scenarios (Source EPIA/Greenpeace – Solar Generation IV)

Although the European PV end user market is dominant today, it is expected that the centre of gravity will progressively shift to other regions as costs come down, making PV more affordable for developing regions with great potential (refer to the EPIA's Sunbelt Study). This represents fresh challenges, but great export opportunities for the cost and technology leaders.

A final point is that in spite of Europe's high installation rates, this is not necessarily reflected in the source of manufactured devices. In the last 2 -3 years, China and Taiwan have become dominant forces world wide in the manufacture of c-Si cells and to a lesser extent modules. The reasons for this rapid evolution go beyond a simplistic comparative of labour costs. Further development of cutting edge technology in rhyme with progressive public industrial policy will be needed to ensure that PV is stabilised as a high value added industry in Europe.

1.1.2 Main Challenges for PV Technologies

Materials can be viewed as key enablers in any PV system. In overall terms the key challenges for materials are twofold:

- To design and manufacture PV systems that are efficient enough and cheap enough to meet the grid parity targets (initially residential retail and ultimately utility scale base load) within the next few years as defined in Table 2.
- A materials supply chain that is able to supply sufficient quantities of the required elements (refer to section 1.2).
- Module design and choice of materials that lend themselves to cost effective recycling.
- Developing standardised performance testing and reliability/ageing test protocols that will provide confidence (and so bankability) for PV devices employing newly developed materials in a wide range of operating conditions (from Europe to Sunbelt environments).

Each PV technology has its own specific challenges and will be outlined in the following sections

1.1.2.1 Crystalline-Si

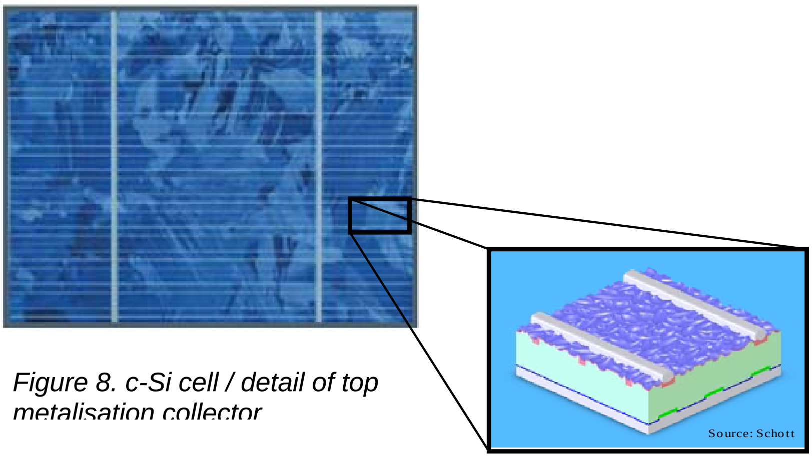
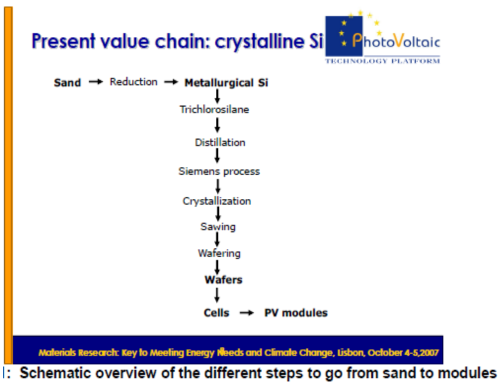


Figure 8. c-Si cell / detail of top metalisation collector



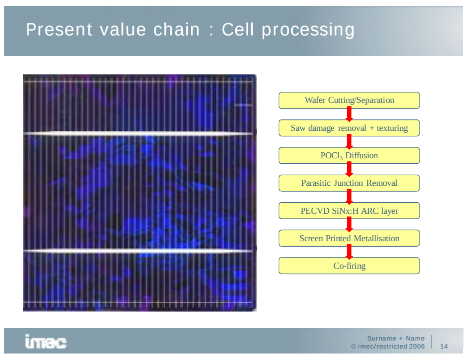


Figure 9a & 9b. Value chain for c-Si manufacturing

Crystalline Si with 80% of today's PV market is the most mature of all the PV technologies having benefited from more than 30 years of development. It is a beacon of what can be achieved in terms of reducing costs and raising efficiency.

The manufacturing processes are well established but still have considerable potential for improvement.

The principal advantages today are that c-Si has the highest production module performance of all flat plate PV modules and the principal semi conducting material (silicon) has no intrinsic material availability issues, although of course industrial investment in refining and wafering capacity will need to keep pace with the market.

New cell architectures, such as hetero-junction technologies originally developed in Japan, are just now starting to be considered by the rest of the c-Si community.

Key challenges for c-Si cells / modules

1.1.2.1.1 The current poly crystalline silicon refining processes require a high level of energy input. So a key concern is to reduce the energy input per Wp of output. In this respect, new process routes with high saving potential (e.g. plasma/segregation purification, Fluidized Bed Reactor) should be investigated to develop feedstock materials.

In parallel, new process routes should be investigated to develop direct epitaxial growth of silicon wafers onto substrates from gaseous phase (silanes, trichlorosilanes, polysilanes or polychlorosilanes…). The resulting material will need to have a very low defect concentration leading to carrier lifetimes of at least 3 times the layer thickness.

1.1.2.1.2 The refined poly-silicon needs to have a cost of less than 20 Euros/kg as soon as possible. New technologies are required to produce solar grade polysilicon.
There needs to be a better understanding on the interaction between metallic impurities, grain boundaries and intra-grain defects in relation to the thermal history of the ingot and wafer for multi crystalline Si. This information is highly relevant to estimate the technical and economic viability of Solar-Si feedstock obtained from alternative routes like UMG-Si.

1.1.2.1.3 Ingot crystallisation has a number of areas for improvement e.g.:

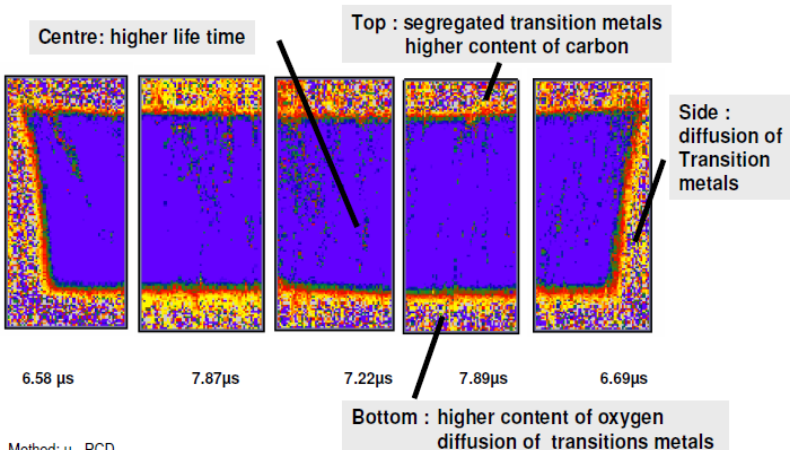


Figure 10. Life time pattern of an ingot cross section, (A. Müller, J. Henker, DGKK Jahrestagung, 7.-9.3 2007, Bremen)

- Crucible material, coating etc. and process development to inert material (Si_3N_4)and reusable crucibles.
- Re-usable crucibles.
- Improvements in silicon yield by avoiding contamination zones around multi-ingots.
- Optimization of ingot volume and geometry
- Maintain the purity of the feed stock to the ingot and wafer.
- Improvement of feedstock yield.

Materials	2010	2020	2020 / 2030	2030 / 2050
mc-/ mono ingots				
oxygen [cm^{-3}]	$< 7,5 * 10^{17}$	$< 5 * 10^{17}$	$< 2 * 10^{17}$	$< 2 * 10^{17}$
carbon [cm^{-3}]	$< 1 * 10^{17}$	$< 5 * 10^{16}$	$< 2 * 10^{16}$	$< 10^{16}$
dislocation density [cm^{-2}]	$\leq 10^{6}$	$< 10^{5}$	$< 10^{4}$	$< 10^{3}$ (mono or multi)
metals [ppbw]	100	< 50	< 20	<10
Crucibles residual metal imurities [ppm]	100	< 50	inert	inert
releasing agent [ppmw]	30	< 10	inert	inert
minority carrier diffusion length [µm]	> 200	300	350	

Table 3. Polycrystalline KPIs

1.1.2.1.4 Blocking and cropping of ingots

- The current process has challenges for geometrical accuracy and surface quality.
- Minimization of cutting losses
- Fully automated in-line production from feedstock and crucible preparation, to ingot blocking and cropping.
- Continuous flow of materials in production, silicon as well as consumables
- The block surface quality should show a good finish after cutting directly, avoiding additional polishing or other surface treatments.
- Geometrical tolerance ± 0,1 mm
- Low surface damage to minimize breakage in later processes (micro-cracks < 20 µm).

1.1.2.1.5 Wafering

Silicon losses due to the slicing process and SiC – slurries are the two major cost items in wafers. Recycling is used to save costs, however for very thin wafers this technology has limits. The challenges in wafering technology can be summarised:

- Reduction of the Si-consumption by thickness reduction. This imposes challenges on thin wafer slicing and understanding of breakage throughout the cell and module process.
- Wafer separation at thin thicknesses.
- Reduction of slurry costs and improvement of TTV and surface defects.
- Reduction of kerf loss to << 100 µm for thinner wafers (< 100 µm).
- Novel technologies to produce thin wafers of < 100 µm thickness and a TTV of < 10 µm up to 2020.
- Control of surface defect morphology to < 10 µm, sufficient for structural etching but avoiding relevant breakage.
- Reduction of chemicals for cleaning and recycling.
- Further thickness reduction to 5 µm – 10 µm with novel technology while keeping the quality level (ion implantation, porous silicon, epitaxial growth) in the timeframe 2020 / 30.
- The scope up to 2050 is a combination of silicon substrate preparation with key elements of the solar cell, like hetero-junction technologies with thin films which are starting already to make inroads.

1.1.2.1.6 Solar cell technology:

- Substitution of Ag (Cu, Al, others).
- Substitution of thermal and chemical processes by laser based process (surface structuring, local diffusion, firing).
- Improved surface passivation with alternative materials, multi layer structures etc,
- Investigating alternative lower cost deposition technologies to PE-CVD for rear emitters. This could include ALD, non vacuum as well as others.
- Because of easier breakage the handling and processing of very thin wafers is crucial. Novel technologies have to be developed.
- Thin wafer based cells will need improved light management / optical engineering for efficiencies of > 20 %.
- Up- or down-conversion requires novel semiconductor materials, band gap tailoring in silicon.
- Greater development of new cell architectures such as hetero-junction technologies (HIT)
- Production lines with a throughput of > 5000 Wafer/h are required

1.1.2.1.7 Chemicals for crystalline solar cells:

- The specification of the chemicals (HF, HCl, HNO3, acidic acid, KOH, NaOH) should be adapted to acceptable levels.
- Reduction of the overall use of volume chemicals to reduce transportation and recycling effort.

1.1.2.1.8 Dopant materials:

- Low cost processes and dopant materials that can be applied easily and result in homogeneous dopant distribution and concentration in volume production are required.
- Novel laser based local diffusion processes require specially designed substances

Materials	2010	2020	2020 / 2030	2030 / 2050
solar cells				
dopants /diffusion	$POCl_3$, H_3PO_4	selective emitters by different diffusion technologies and dopants, doped coatings with laser indused diffusion	locally processed dopants with laser induced diffusion	laser based hybrid processes
etchants	Wet etch: HF, HNO_3, HF	hybride laser induced vapor etch	hybride laser induced vapor etch	hybride laser induced vapor etch
metalization, conductive pastes	Ag w/o lead on lower sheet resistane emitters, low bow high production speed (>3000 wafers/h) substrate size $\geq$ 15,6 cm x 15,6 cm	Ag based leadfree on high sheet resistant emitters, low stresshigh aspect ratio	Cu/ Al instead of Ag printable, dispensible Si, graphite- (nanoparticle) based pastes (inks) on high sheet resistant emitters with good conductivity, low stress	printable, dispensible Si, graphite- (nanoparticle) based paste on high sheet resistant emitters with good conductivity, low stress
barriers	< contact resistance < resistivity > adhesion strength	application for thin, very thin Si-wafers or ribbons		

Table 4. KPIs c-Si dopants, etchants, metalisation, barriers, novel materials

1.1.2.1.9 Metallization:

- Substitutes for the lead containing frits.
- Substitutes for silver as conductive metal inside the pastes.
- Development of new contact materials and application processes based on nano- silicon particles (Innovalight), LRD (laser reactive deposition, Nanogram technology) graphite, fullerenes, graphenes, cyclosilanes or other materials that belong to the 5 most abundant elements on earth.
- Development of non-contact fine line metalisation techniques (aerosol, ink jet…..).
- Adapted contact materials for high sheet resistant emitters.
- Low contact resistivity pastes.
- Low stress at the contact – silicon interface.
- Low shadowing and high aspect ratios in contact lines.
- Stability against humidity ingress, UV and temperature variations.
- Development of contact materials and technologies to interconnect solar cells inside a module based on metal polymer compounds or other new solutions.

Materials	2010	2020	2020 / 2030	2030 / 2050
Finger width	70 - 120 µm [20]	20 - 38 µm [20], [34]	backside contacts	backside contacts

Table 5. KPIs for metalisation

1.1.2.1.10 Module production cost reduction:

System prices are expected to decline to 1.32 – 1.52 €/Wp by 2020. Related production costs should be reduced to about 1 €/Wp to make this possible. Target module production costs will need to be about 0.50 €/Wp.

- Continuous fully automated production (lay up, tabbing, stringing, lamination, framing J-box application testing).
- Improvement of handling and processing in module preparation with very thin solar cells
- Savings in materials costs of about 50 % is required.
  - Cheaper thinner films
  - If possible, substitution of EVA by cheaper materials with more favourable properties. Encapsulation and backsheet material has to be considered together.
  - Very thin front sheet-glass ($\leq$ 0,4 mm) to reduce the process time and the total weight of the module. The structural strength from backsheet or the substructure.
- Modules to be considered as integral part of the system.
- Continuous and possibly direct conversion of materials to module, minimizing process steps across the whole supply chain.

1.1.2.1.11 Encapsulation materials:

- Chemically stability under environmental conditions.
- Easy and fast to process ◊ module lamination time 1 – 3 min, instead about 30 min.
- High transparency ≥ 95 % including front sheet (see table 4).
- Optimized refractive index, fitted to front sheet and solar cells.

1.1.2.1.12 Back sheet material:

- Chemically stable under environmental conditions.
- Easy and fast to process
- Supports easy recycling.
- Preferably from natural sources.
- Thin glass is one obvious candidate
- Integrated structural support function and interconnection of solar cells
- Easily adoptable to support structure of the PV generator.

1.1.2.1.13 Front sheet materials:

- Very thin front glass to improve transmission and reduce weight.
- Durable flexible (fluoro)polymer sheets with high light transmission, controlled humidity ingress (barrier layers) and UV stability at low cost.

1.1.2.1.14 ARC material:

- Durability
- Touch tolerant to different materials, no staining
- Scratch & weather resistance

1.1.2.1.14 Interconnector materials:

- Soft material to avoid stress in contacts.
- Substitute of ribbon interconnectors by new materials, especially for back contact cells.
- Low resistivity to avoid big cross sections that would avoid thermal expansion issues.
- Back sheet with integrated structured conductive interconnection layer.
- Defined contact formation within module lay-up, integrated in lamination process.
- Interconnection of very thin solar cells with high efficiencies, i.e. high currents.
- Low resistivity interconnection of modules with large dimensions and high power, e.g. 1 kW modules [26].

Materials	2010	2020	2020 / 2030	2030 / 2050
modules				
encapsulants	EVA, PVB, Ionomers, transmission including frontsheet 88 - 93,9 %	chemically inert polymers, no development of any chemical under operations conditions that could react with solar cell materials, transmission > 95 %, AR coating on frontsheet easy recycling	chemically inert polymers, no development of any chemical under operations conditions that could react with solar cell materials, transmission > 95 %, AR coating on frontsheet easy recycling	chemically inert polymers, no development of any chemical under operations conditions that could react with solar cell materials, transmission > 95 %, AR coating on frontsheet easy recycling
backsheet	PET- PVF laminate, some water vapor ingress, relatively impermeable for acidic acid, no integrated cell interconnection	Inert polymer, intergrated cell interconnection, integrated support structure, for mechanical stability, low heat capacity for fast lamination	strong support structur, integrated wiring, from natural sources, sandwich laminate, easy to recycle	mechanically and electrically integrated part of the system, represents the interface to the system.
frontsheet	low iron patterned tempered glass, 3,2 mm - 6 mm, a small percentage (5 - 10 %) AR coated	better transmission with thin front glass 2 mm thickness, AR coating, scratch resistant, weather proof	better transmission with ultra thin front glass < 0,5 mm thickness, AR coating	better transmission with ultra thin front glass < 0,5 mm thickness, AR coating
interconnectors	H-pattern cells connected withCu-ribbons with Sn/Pb coating, 120 - 180 µm thick, 1,5 - 2,4 mm wide,	integrated wiring of back contact cells, e.g. MWT cells with metalized polymer backsheet, new solder contacts and process	interconnection by conductive layer in supporting backsheet with separate electrical interface	cells are devices put on a rigit circuit board forming an interface to the system
reliabilty assessment	lifetime 20 years	lifetime > 25 years	lifetime > 30 years	lifetime > 35 years or easy and cheap to exchange

Table 5. KPIs for encapsulants, backsheets, front sheets, interconnecotors, reliability

1.1.2.2 CdTe modules

CdTe manufacturing can be divided into two broad categories:

a) High temperature (550C) – CSS, CSVT and variations
b) Lower temperature (<400C) – HVE, Sputtering, Electro deposition, MOCVD …..

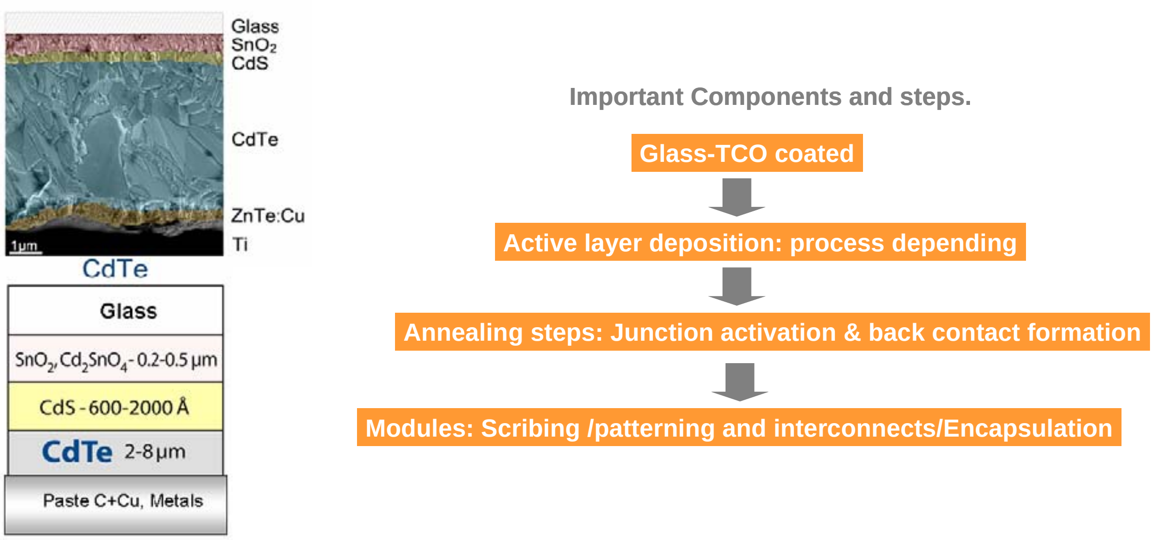


Figure 11. CdTe cell configuration and manufacturing value chain (J.Hererro-Rueda)

Typically the higher deposition temperatures have higher efficiencies, but limit the choice of substrates to use. Various TCOs have been proposed for CdTe however the most prevalent today is $F{:}SnO_2$ (FTO). ITO and AZO have been tried. Cd_2SnO_4 is also a candidate, but obtaining Cd containing sputtering targets is problematic for EHS reasons.

Key challenges for CdTe modules

The key is for cost reduction through manufacturing productivity, materials usage and technology (increased module efficiency) improvements.

In the medium term it will be desirable to have tandem junction cell structures combining CIGS and OPV cells.

Materials costs

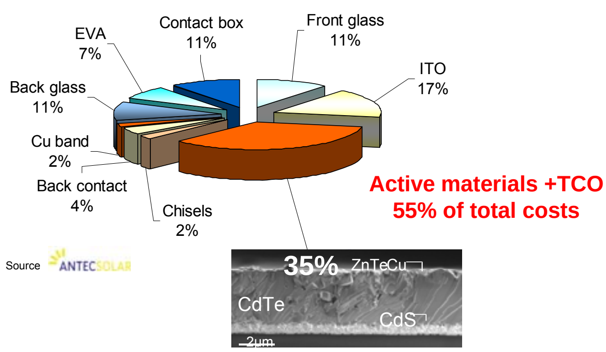


Figure 12. Materials cost breakdown for CdTe modules

1.1.2.2.1 Active layers

The active materials and TCO layers represent 55% of the bill of materials. It will be necessary to reduce the amount of materials used (thinner layers – 1 μm) and increase the efficiency of the device (possibly through graded materials).

1.1.2.2.2 Glass

Front glass represents 11% of costs. There are two types of front glass currently available

a) Borosilicate
   - Higher temperature
   - Higher transmission
   - Higher cost

b) Soda Lime
   - Lower temperature thermo-physical properties (however adequate for all current PV technology processes)
   - Possible source of impurities (Na migration in the long term to absorber and TCO layers – applicable to CdTe and other TFPVs)
   - Adequate optical properties for current applications: long term effects (Note that low iron glass has similar properties to borosilicate)

Borosilicate glass is typically used in the lab environment due to its intrinsic attributes, but in commercial production more than 99% of the glass used will be soda lime glass. So although soda lime glass meets present PV technology requirements there is a case to be made for the future for improved glass properties and controlling the cost.

1.1.2.2.3 CdTe / CdS layers

A better understanding is required of

- nucleation & grain growth kinetics
- interface and diffusion properties
- role of impurities: define optimum material (low cost but high performance)
- band-gap engineering for advanced devices

Ideally this should be achieved with low temperature deposition and industrially compatible activation process (dry, fast, control, ambient, etc.)

1.1.2.2.4 Back contact

- Dry (vacuum) in-line processing: No chemical etching
- Alternative materials and processes for higher efficiency and longer stability

KPIs - CdTe

		2012	2015	2020	2030-2050
Industrial manufactured module efficiency	%		13	15	18
Industrial manufacturing cost	Euros/Wp		< 1	0,5	0,3
CdTe layer thickness	μm	1,8	1,5	1,0 graded absorbers and minimisation of Cd / Hg	
CdS layer thickness	μm	0,1	0,1	0,1	0,1
Al layer thickness	μm	0,3	Alternative back contact		
Deposition temperatures	°C	450	400	=/< 350 Non vacuum printable deposition processes	

Table 6. KPIs for CdTe

1.1.2.3 Thin Film Si PV

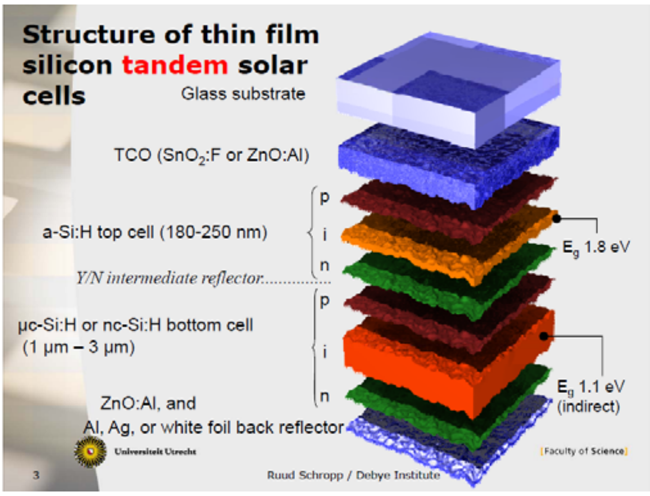


Figure 13. Cell structure for tandem junction TFSi cell

TFSi grew rapidly during the polysilicon shortage and thanks to the availability of turn key production lines from Oerlikon, AMAT and ULVAC.

At present single junction, tandem and multi junction cell structures are vying with each other on cost Vs efficiency for having the most attractive value proposition among the TFSi technologies. Current stabilized total area production module efficiencies are in the range of 6.0 – 9.5 %.

The efficiency gap between lab and fab has been reduced from 30% to about 15% thanks to larger sized modules, advanced monolithic interconnection and improved uniformity.

In principle there are no materials availability issues.

The key challenges for TFSi are:
As for other PV technologies the key challenges for TFSi are cost reduction and performance improvement. Materials represents 40-60% of present TFSi module manufacturing costs, these can be reduced by:

1.1.2.3.1 Productivity and throughput

- Increased deposition rate without loss of quality.
- Alternatives to plasma based deposition
- Development of continuous roll to roll (R2R) processes on flexible substrates
- Lower cost packaging solutions

1.1.2.3.2 Environmental aspects

There is a need for environmentally friendly exhaust gas abatement.

The reactor etch cleaning gases have a greenhouse effect, so requires replacements of SF_6 and NF_3 by F_2 which will at the same time reduce costs.

1.1.2.3.3 Better materials usage required to reduce costs for:

- Source gases (SiH_4) – improving utilization and cycling of feed gases
- Sputter targets – this can include new reactors / rotary targets and development of alternative techniques for contact and electro-optical layers
- Gases (DEZ)
- Reduction of Ag and/or In usage

1.1.2.3.4 Glass substrates

TCO (today SnO2:F) coated glass would seem to be a bottleneck, but this is mainly due to investment in suitable plants by glass makers. The difficulty for the glass maker is to achieve critical mass in terms of manufacturing volumes; for which a large PV market is required.

1.1.2.3.5 Transparent conducting layers

New transparent conducting materials will need to be investigated. These will need to be high transmission, low sheet resistivity, and light trapping; fast and cost effective “on line” production at glass companies, also including advanced antireflection coatings.

1.1.2.3.6 Encapsulants

The cost of encapsulants needs to be reduced whilst maintaining the performance.
Easy and fast lamination process (materials and equipment).

1.1.2.3.7 The efficiency improvements can be addressed by

- Development of higher efficiency devices (single and multi junction) with long term target of up to 40% efficiency
- Enhanced quality nanocrystalline and amorphous silicon and alloys.

- Doped layers with less parasitic absorption.
- Enhanced light trapping techniques
- Reduction of the light-induced defect creation.
- Doped layers with less parasitic absorption.
- Advanced light trapping techniques including TCO and alternatives
- Novel contacting and interconnection methods
- Novel concepts such as QDs, up- / down–converters, plasmonics, photonics and nano 3-D geometries

KPIs - TFSi

		2020	2030	2050
Prod'n module efficiency (rigid)	%	12	15-20	30-40
Prod'n module efficiency (flex)	%	11		
Best stable cell efficiency	%	> 17	> 20	
Best stable module efficiency	%	> 15	> 20	
Module cost (rigid)	Euros/Wp	< 0,65	0,3	0,3
Module cost (flex)	Euros/Wp	< 0.5		
Life time	Years	35	40	=/>40
Energy Pay Back Time	Years	0,5	0,3	0,3

Table 7. KPIs for TFSi

1.1.2.4 CIS/CIGS

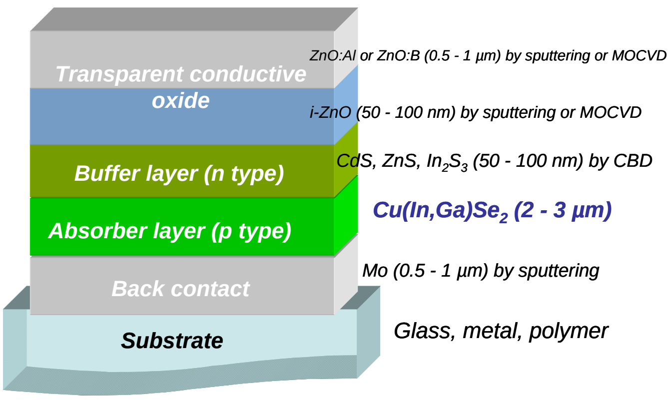


Figure 14. Cell structure CIGS cell (B.Fillon)

CIGS PV technology has shown the highest performance levels both in the lab (17,6% on flexible polyimide and 20,3% on glass) and in production (11-12%) with capability demonstration of 13,8 % on 1 m^2 areas. However CIGS is the least mature of the three TFPV technologies and the gap between best cell results and regular production is also the highest.

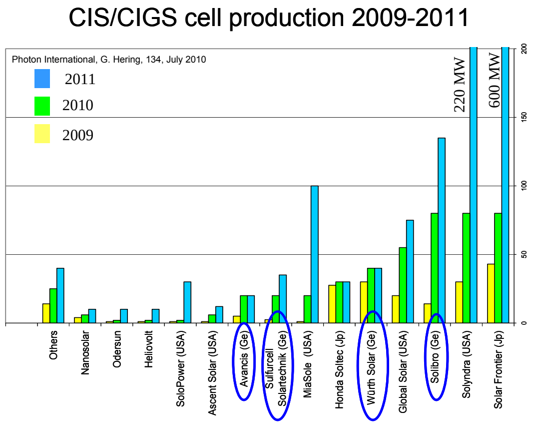


Figure 15. Production figures for CIGS

This is in part due to the complexity of the ternary / quaternary material systems employed and still requires considerable work to optimise the manufacturing processes or for their simplification.

It is interesting and of great concern to note that as with CdTe modules, much of the technology has been developed in Europe, whereas the larger industrial players are in fact likely to be in Japan or the USA in the immediate future.

Referring to figure 15, the world wide production for CIGS is likely to pass from circa 150 MWp production in 2009 to 1.5 GWp by the end of 2011.

Although not an immediate threat, there are concerns about the future ready availability of indium and gallium.

The unique character for CIGS is the deposition and activation of the active absorber layer. There are two techniques for deposition in regular production today; co-evaporation and sputtering – refer to figure 16. Similar efficiencies are obtained in production with both techniques. However these vacuum based techniques are handicapped by high equipment investment costs and slow throughput. Currently Manz Automation and Centrotherm offer turn key CIGS lines with guaranteed efficiency of 12%.

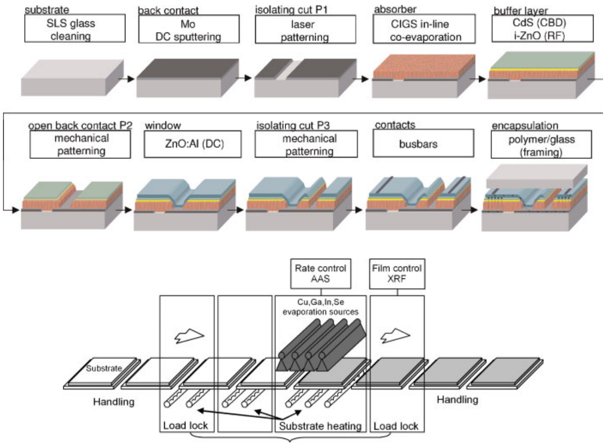


Figure 16. Production layout for co-evaporation CIGS (Source Wuerth Solar)

A new class of non vacuum techniques is in its early days of development. These comprise wet solution processing for deposition and take the form of electro deposition, spray or printing. These are designed to replace the complex vacuum based deposition techniques.

It is anticipated that such techniques will reduce capital investment costs and enhance productivity. They may even enable more homogeneous active layers and contribute to obtaining efficiencies closer to best lab results.

The figure 17 summarises the current state of the art for CIS/CIGS cells and modules.

DEPOSITION METHOD FOR CIGS LAYER	EFFICIENCY		
	Best laboratory cell (~ 1 cm^2)	**Best pilot line module (30x30 cm^2)**	**Commercial module (~ 1 m^2) [9]**
Co-evaporation	**19% - 20%** *ZSW [1], HZB (DE) [2]* *NREL (US) [3]*	**14%** *ZSW (DE) [6]*	**8% - 12%** *Würth Solar, Q-Cells, Solarion (DE)* *Global Solar, Ascent Solar (US)*
Sputtering of precursors + selenization/sulfurization	-	**15% - 16%** *Solar Frontier (JP) [7]* *Avancis (DE) [8]*	**7% - 12%** *Solar Frontier, Honda Soltec (JP)* *Avancis, Sulfurcell, Bosch Solar (DE)* *Sunshine PV (TW)*
Wet coating of precursors + selenization/sulfurization	**14% - 15%** *ISET [4], Nanosolar (US) [5]*	-	**8% - 11%** *Nanosolar (US)*

[1] ZSW press release (2010).
[2] W. Mannstadt *et al.*, 25th EUPVSEC, 3516 (2010).
[3] I. Repins *et al.*, Prog. Photovolt. Res. Appl. **16**, 235 (2008).
[4] ISET, Competitiveness of ink-based thin-film photovoltaics (2010).
[5] J. K. J. van Duren *et al.*, Mater. Res. Soc. Symp. Proc. 1012-Y05-03 (2007); Nanosolar, Ultra-low-cost solar electricity cells (2009).
[6] M. Powalla *et al.*, Thin Solid Films **517**, 2111 (2009).
[7] H. Sugimoto *et al.*, 25th EUPVSEC, 3529 (2010).
[8] T. Dalibor *et al.*, 25th EUPVSEC, 2854 (2010).
[9] Manufacturer websites

Figure 17. Key players and performance for CIS / CIGS

Key challenges for CIS/CIGS:
Improving CIGS performance and lowering costs is of top priority. These objectives are related to an intrinsic combination of suitable material design together with the functional layer manufacturing process steps.

1.1.2.4.1 Higher efficiency

- Better understanding is required of:
  - native defects in active absorber layers
  - the electronic band structure of active layers and interfaces
  - ways to control the nucleation and growth morphology
- The control of the stoichiometry of the CIGS layer laterally over large surfaces needs to be improved
- Better grading control vertically through the active layer of relative copper and gallium concentration is required
- Extrinsic doping of CIGS materials

1.1.2.4.2 Layer interface (buffer/absorber)

- A better understanding is required of the interface zone
- the role of deposition parameters for layer and interface quality
- reliable interface control at nanoscale

1.1.2.4.3 Reduction of material thickness (CIGS<1µm)

- Current thickness is typically 2 – 3 µm for the vacuum based processes. The challenge will be to reduce thickness to less than 1µm and maintain continuous layer integrity with no pin holes / shunts
- Towards thinner and flexible substrate

1.1.2.4.4 Better control of active layer for the wet process at low temperature (<200°C), high transparency (for TCOs), wet deposition process

Such processes should be developed for CIGS, CZTS (refer to “New Materials” later in text) and TCO layers.

Moving to a wet solution based process brings with it a new set of requirements:

- deposition process control (equipment design)
- ink formulation (suitable for high throughput deposition with no performance damaging residuals and no toxicity issues)
- rapid thermal processing (full control of the re-crystallisation step at high throughput).

1.1.2.4.5 Alternative cell structures

As with other PV technologies, new multi junction cell structures allowing a more complete absorption of the solar spectrum will be beneficial.

1.1.2.4.6 Develop back contacts with high adhesion and reflection on flexible substrates.

1.1.2.4.7 Development of alternative absorber layer (eg: Cu_2ZnSnS_4 (CZTS)), buffer layer, TCO layer with vacuum and non vacuum technologies.

Such new materials systems will be necessary to meet the future materials availability challenges (indium, gallium) that will face CIGS.

1.1.2.4.8 Environment / Better LCA

- Eliminating CdS buffer layers whilst maintaining efficiency
- Use of environmentally friendly solvents.
- Recycling of production scraps, elimination of hazardous materials.

KPIs - CIGS

		2020	2030	2050
Module efficiency	%	18%	> 18%	> 25%
Module cost (assumes low cost substitute material system)	Euros/ Wp	< 0,8	< 0,4	< 0,2

Table 8. KPIs for CIGS

1.1.2.5 HCPV

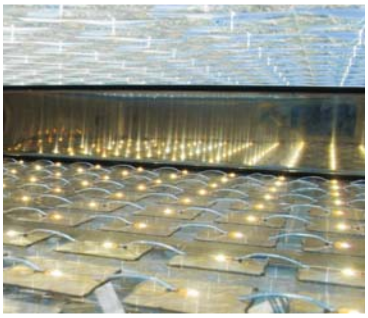


Figure 18. Internal view of HCPV module (Concentrix)

The systems in question are high concentrator PV systems meaning concentrations of more than 400 suns.
Today system efficiencies are about 25% with the potential to reach 35% within 5 years.
HCPV is a very attractive solution for areas of high levels of direct sunlight such as desert areas. Due to its complex nature, it is most unlikely to be adopted for residential rooftop applications.
It is a relatively recent technology; however the high efficiency III-V cells that are used are a direct descendent from space applications with proven reliability. HCPV is in the process of gaining credibility and “bankability”.

As with all other PV technologies, the key is to reduce cost and raise efficiency to make an attractive value proposition for large scale project investors.

Key Challenges for HCPV

1.1.2.5.1 Reduce production costs / raise efficiency
1.1.2.5.2 Develop cheaper Ge substrates through larger ingot / wafer size
1.1.2.5.3 Develop cheaper cell substrate materials e.g. silicon
1.1.2.5.4 Demonstrate reliability for over 40 years
1.1.2.5.5 Increase level of standardisation and modularity
1.1.2.5.6 Development of new multi-junction solar cell processes based on lift-off and wafer bonding in order to reduce cost and increase efficiency
1.1.2.5.7 Development of new optical concentrator materials in order to increase reliability, efficiency and to reduce cost
1.1.2.5.8 Development of new long life optical glues for cell encapsulation and mounting of secondary optical concentrators
1.1.2.5.9 Development of durable functional coatings for the module cover and concentrator optics in order to reduce reflection losses and surface soiling losses
1.1.2.5.10 Development of low cost tracker designs

KPIs - HCPV

		2020	2030	2050
Cell efficiency	%	50		60
Module efficiency	%	42		55
System efficiency	%	39		52
Ge substrate wafer diameter	inch	8 (180 µm thick)		
Cell cost	Euros/Wp	< 0,2		< 0,15
Module cost	Euros/Wp	< 0,6		< 0,35
System cost	Euros/Wp	< 0,9		< 0,6
Life time (all system components)	Years	40		40

Table 9. KPIs for HCPV

1.1.2.5 OPV

OPV cells are still mainly in development with relatively few industrial – commercial applications today. For the sake of this exercise we will group both pure organic and DSSC cells together.

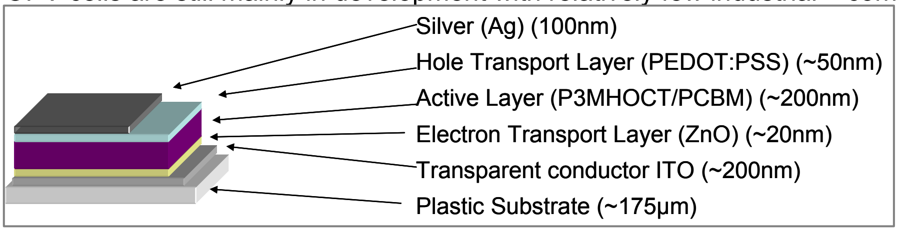


Figure 19. Cell structure for OPV (B.Fillon)

For OPV technologies, in general, two deposition processes are used: evaporation of the material and wet processing (using a solution of the material). The gap in cell performance between these two processes is closing and the most recent reports on small molecule and polymer solar cells have presented very encouraging performance and lifetime data with cell efficiency above 8%.

OPV modules do suffer from two major handicaps which are their low efficiencies (around 8% today) and their short life time (around 3 years due to the instability of the compounds used).

On the other hand they have two very interesting potential advantages which are:

- with the exception of the silver used today in the top contact electrode, they have no intrinsic limitations for materials availability, since these are synthesised organic compounds.
- due to the type of materials used they can be readily processed with low cost deposition processes and so have great potential for low cost production.

OPV technology provides a wide range of active material and electrode combinations for construction of cells/modules and hence provides many options for improving performance.

In general, the main objective should be to find organic materials with high efficiency, stability, with low cost and industrial capability for manufacturing. An intensive study of the material properties should enable cell efficiencies well above 15% and a cost below 0.7 €/Wp.

Key Challenges for OPV

1.1.2.5.1 To produce ultra thin multilayer film at high throughput and high resolution and registration (nanoscale).
1.1.2.5.2 To produce at low temperature a multilayer structure with a sharp interface between layers.
1.1.2.5.3 To produce ultra thin film with patterning.
1.1.2.5.4 Understanding the role of deposition parameters for layer and interface quality.
1.1.2.5.5 Produce alternative cell structures, interconnection
I1.1.2.5.6 mprovement of cell efficiency through specific production of surface texturing.
1.1.2.5.7 On line post laser patterning with high resolution, speed and low cost.
1.1.2.5.8 To develop on line quality control methods
1.1.2.5.9 To develop R2R process compatible packaging methods.
1.1.2.5.10 Improve band gap width through new organic material or tandem architecture.
1.1.2.5.11 Produce and control high purity organic material and understanding the impact of impurities.
1.1.2.5.12 Print and stabilise the nano-morphology of the active layer
1.1.2.5.13 Develop transparent high moisture and oxygen barrier layer.
1.1.2.5.14 Better understanding of the degradation mechanism leading to the device failure
1.1.2.5.15 Better understanding of the influence of spectral dependence on solar cell performance and stability is required
1.1.2.5.16 Investigate and improve cost effective flexible and thinner substrate
1.1.2.5.17 Development of alternative TCO layer with vacuum and non vacuum technologies
1.1.2.5.18 Control of composition and features of particles for development of ink for non vacuum technologies

KPIs - OPV

		2020	2030	2050
Industrial module efficiency	%	>10	16	18
Module cost	Euros/Wp	0,6	0,5	< 0,3
Life time	years	10	> 20	> 25

Table 10. KPIs for OPV

1.1.2.6 Glass

Glass used in PV has a significant influence on the performance of the device and cannot be ignored in the bill of materials.

For TFPV – CdTe, a-Si, OPV, DSSC: the front cover glass is 3,2mm clear and low iron float glass typically coated with a TCO whose sheet resistance and topology is adapted according to type of TFPV. The back cover is clear float glass.
For TFPV – CIGS: the front plate is low iron and the back plate is coated with Mo plus sometimes a Na^+ blocker.
The TCO coating may be applied directly on the float glass line or off-line.
For c-Si rolled, surface textured, toughened, low iron glass is used.
CPV cells require back surface mirrored, low iron, shaped glass.

Glass key challenges
For the glass industry, the PV segment has only just recently started to represent a significant market. It can be said that the industry is now starting to organise itself to reply to the PV demand. C-Si requires 66,700 tonnes of 4.0 mm glass per GWp of 15% efficient modules. For TFPV it requires 160,000 tonnes of glass per GWp. A typical single float glass furnace produces 500 – 800 tonnes / day of glass sufficient for up to 1.5 GWp TFPV, whereas the total market for TFPV today is about 3 GWp spread around the world. Since changing from one glass type to another in a float line requires a lengthy and costly preparation, it is not easy for the glass industry to manage. Higher volumes of PV will help rationalise production, but it will remain a logistics challenge for the glass industry to manage.

1.1.2.6.1 Low iron glass

For TFPV modules the front cover glass represents 15-20% of the cost of the module. The cost of glass is expected to fall with economies of scale. However whereas there is no expected shortage for clear glass, the current projected increase in demand for PV may create some supply chain issues for both rolled and float line low iron glass. Low iron glass production requires significant modifications to a float line. One solution would be a cluster of PV module manufacturers in the vicinity of a glass production line that would justify a dedicated low iron line. This is not always the case today.

A second issue with low iron glass is that the ideal situation is the use of particular grades of silica with low impurities. Increased PV volumes will require enlarging the present supply of such feed raw materials. It will possibly be interesting to develop new processes for more economical low iron glass production through process conditions or for example acid leaching techniques etc.

1.1.2.6.2 Glass weight / strength

Making thinner glass has some benefits:

- Better light transmission, which may help relax specifications on low iron glass
- Less mass to heat and so lower energy costs
- Less weight to transport – lower costs / less energy
- Lower weight modules meaning lighter and cheaper support structures / lower installation costs

Increasing the strength of glass will have benefits, but this must be done without penalising the cost or transparency. Some module concepts (e.g. BIPV) will benefit from high strength tempered glass where the glass is an integral structural element.

Thermal tempering is well understood and done correctly no optical distortion will be noticed. It remains very challenging for glass thicknesses of less than 2mm. Any thermal glass tempering will have to survive any subsequent thermal process steps in the PV cell and vice versa.

Chemical tempering techniques are well understood for thin glass and avoid optical distortion, however it is slow, introduces extra cost and the compression depth is shallow. It is therefore useful to consider developing novel methods and new glass compositions to address these issues.

Novel glass compositions may also allow better matching of thermal expansion with cell / modules structures and reduce thermally induced stresses during manufacture.

Redesigning module construction to lower the stress on the glass, may also help to allow thinner glass without strength increase.

		2020	2030	2050
Glass thickness (implementation)	mm	1,0	0,5-1,0	< 0,5

Table 11. KPIs for Glass

1.1.2.7 TCO coatings

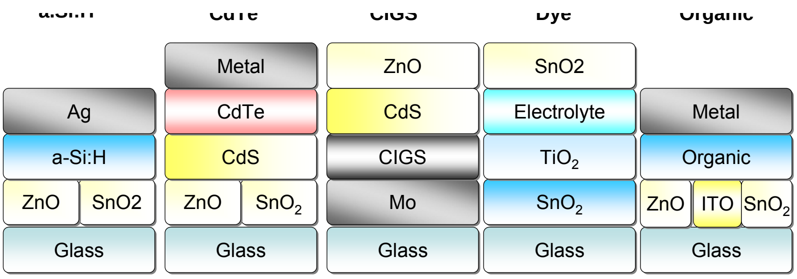


Figure 20. Comparative cell structures for TFPV and TCO

Transparent conducting layers are required by all TFPV devices. They are today exclusively metal oxides based on In, Zn or Sn.

The TCOs currently in use typically have visible light optical transmittance of > 80% and resistivities in the range of 10 – 3 Ω.cm

TCOs are deposited on- and off-line by the glass maker or by the PV device manufacturer.

For ITO films,

- DC sputtering using ceramic targets is an established technology
- Low resistivity of ρ< 150 μΩ.cm for TS> 200 °C.
- Poor stability in reducing ambient, TS> 200 °C.
- High costs for In and powder metallurgy.

For SnOx films,

- SnO_2: F deposited by CVD is the only TCO that can be deposited in-line on float glass (It can also be deposited off-line also by CVD).

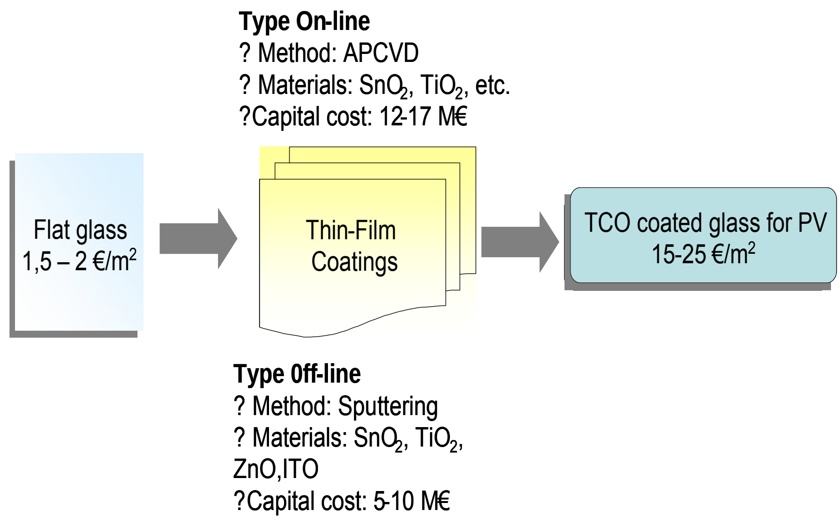
- SnO_2:F is the cheapest TCO
- SnO_2:F has better chemical and high temperature stability than either ITO or AZO.
- Slightly higher absorption than ITO or ZnO
- Limited to float glass as substrate.

For ZnO:X

- RF and DC sputtering using ceramic and metallic targets.
- Acceptable resistivity and transmittance (vs. ITO films)
- Stable in reducing ambient.
- Poor stability against moisture
- Degradation at process temperature > 350º.
- Cost effective for PV applications

Key Challenges for TCO

There are several challenges for TCO into the future.



1.M.J. Gray, K. Strobl, Photovoltaics World pp 26-29. November/December 2010.

Figure 21. Key challenges for TCOs

The first one is to be able to reduce the cost without sacrificing performance.

A second one will be to improve performance.

A third challenge is to improve the material's effective life time and resistance to environmental factors.

A fourth challenge for a highly developed PV market will be the availability of indium for ITO TCOs.

A number of strategies will be necessary to address these challenges.

1.1.2.7.1 A better understanding of the TCO / semi conductor interfaces is necessary.

1.1.2.7.2 Holistic integrated approach to surface texturing of the external TCO layers as well as the interfaces could be beneficial to improve light management in the absorber layers thus allowing thinner absorber layers.

1.1.2.7.3 Engineered multi functional transparent conducting layers that will also improve light capture

1.1.2.7.4 A reliable control of thickness at nano scale

1.1.2.7.5 Elimination of shunt defects

1.1.2.7.6 Faster lower cost TCO manufacturing processes will need to be developed e.g. rotary sputter magnetron technology that will increase materials usage rates significantly.

1.1.2.7.7 Integration of in-line rapid thermal processing for high temperature annealing of TCO leading to improved sheet resistances

1.1.2.7.8 Optimisation of metal grid pattern / TCO structure for flexible devices and c-Si HIT cells.

1.1.2.7.9 Alternative to TCO materials that do not have supply constraints and offer the potential of lower costs e.g. CNT, graphene.....

KPIs for TCOs

		2015	2020	2030	2050
Resistivity	Ω/□	8-20	5-10	< 5	<< 5
Transmittance	% (λ = 400-1100nm)	80-90	90	90	> 90
Figure of Merit* $\Phi_{TC} = T^{10}/R_{sq}$ (T at 500 nm)	$10^{-3}\ \Omega^{-1}$ (T at 500 nm)	20-3	70-7	>70	>> 70

*G. Haake, J. Appl. Phys. 47(9), 4086, 1976

Table 12. KPIs for TCO

Note that the cost of supplying the TCO for PV is considered today to be an important and sensitive issue. The challenge will be to reduce today's manufacturing cost, although this will also be greatly influenced by economies of scale and supply logistics.

1.1.2.8 Anti reflective coatings

The key challenges relate to cost, performance, robustness and soiling / staining.

1.1.2.9 Anti-soiling coatings

PV output is a function of light input. Ensuring clean transparent surfaces is key to consistent performance particularly in areas where dust and pollution are a problem. The challenge is to understand the soiling mechanism and develop suitable counter measures that provide reliable, cost effective and wear resistant anti soiling coatings

1.1.2.10 Inverters

Solar inverters are power electronic systems. They convert the DC power from the photovoltaic generator into AC power that can be fed into the electric power grid.
Based on the power rating, the market of solar inverters consists of basically three types of products:

- Module oriented inverters in the power range of a few 100 Wp
- String oriented inverters in the power range of 1...20 kWp
- Inverters for big photovoltaic systems with a power range of 100...2,000 kWp

The biggest portion of the market in terms of cumulated power and quantity are the string-oriented solar inverters. These consist of stand-alone units normally wall-mounted with high enclosure (IP65) that can be used both out-door and in-door. Internally these solar inverters consist of a software-controlled electronic power conversion system based on power electronics (power switches and diodes) combined with the necessary electrical peripherals (esp. inductors and capacitors).

Key Challenges for inverters

1.1.2.10.1 A solar inverter accounts for approx. 10...20% of the value of a total photovoltaic system. From the market it is expected that the specific costs of solar inverters are reduced continuously over time. The industry expects prices to go down by 50% by 2020. Therefore cost reduction is the biggest challenge for solar inverters for the next 10 years.

1.1.2.10.2 Other challenges include improved reliability and additional software functionality for electric grid integration.`

Most materials used in solar inverters are identical to other power electronic systems of similar power ratings (esp. industrial frequency inverters for drives, power supply systems). Traditionally, solar inverters have used components that have been developed for these markets. In addition many of the components in power electronic systems are identical to components found in electronic systems in general. Solar inverters can therefore source many of its materials and component requirements from these applications.

However, from a materials perspective, power electronics and the magnetic components are specific for solar inverters.

Power electronics in solar inverters are currently based on silicon power transistors and silicon or SiC power diodes. Silicon power transistors (both IGBTs and MOSFETs) have limitations in

switching frequency (which in turn determines the size of the magnetic components) and power losses (which is responsible for the efficiency of the power conversion). Therefore there has been a search for other materials for building power transistors for a long time.
Today silicon carbide (SiC) seems to be at a maturity level that can expect industrial usage in the next 5 years. Galium nitride (GaN) promises even higher switching frequencies, but commercially available technology seems still to be 10 years away from industrial use. Both materials need intensive research in terms of material cost, reliability, process technology.

The magnetics in solar inverters are specific due to their size and quantity. There is no other market that needs inductors with similar ratings in such large quantities. The materials and the production methods are currrently adopted from applications with lower volume production. New materials systems that can be used in magnetics with high power ratings, usable at higher frequencies (50…1.000 kHz) and being suitable for automated, low cost, high volume component production (for example injection moulding) would result in significant cost reductions.

KPIs for Inverters

	Date of implementation	2015	2025
Power electronics - Impact (Vs 2011) on total inverter cost	%	-30=>40%	-50=>60%
Power electronics - Material choice	-	SiC	GaN
Power electronics - Switching frequency	kHz	50	100=>200
Power electronics - Power losses	%	1,5%	<1,0%
Magnetics – materials choice	-	Amorphous composites	TBD (Nano composites
Magnetics – Frequency	kHz	50	100=>200
Magnetics – Cost reduction impact	%	-50=>60	-70=>80

Table 13. KPIs for Inverters

1.1.2.11 Non Vacuum Deposition

It has been mentioned for several of the technologies above that cheaper deposition processes would be beneficial to address the cost of especially TFPV. Non vacuum deposition techniques such as printing, spraying, electro plating are all candidates to provide such solutions.

At present there are a number of research and industrial organisations who have been working on this topic in the lab / small pilot scale and some IP/patents have been filed and granted. There have been a number of statements and press releases about the capabilities by some industrial companies (NanoSolar, ISET in the USA). However so far there is no industrially capable process operating.

This represents a high potential for European companies and research organisations who already have considerable expertise in for example TFPV - CIGS (refer to section above on CIGS).

Key challenges for non Vacuum Deposition

1.1.2.11.1 Non vacuum deposition is operating typically in a less well controlled chemical environment. One has to build semi conductors and electro optic functional layers from wet solutions that may need to contain a number of additives necessary for the deposition process, but increase the complexity of achieving a “pure” functional layer. The key will be to ensure controlled physical and chemical homogeneity as well as a reliable control of thickness at the nano scale.

KPIs for non Vacuum Deposition

The following targets should be applicable at an industrial scale between 2015 and 2020.

- Equivalent performance
- Chemical homogeneity and also a reliable thickness control at nanoscale.
- Increase in materials usage to >95%
- Reduce capital cost for layer deposition by >80%
- Module manufacturing cost 0.5-1 Euro/Wp

1.1.2.12 New Materials Systems

A number of programmes have been ongoing for several years in developing new alternative inorganic materials systems that will be future relays; building on current CdTe and CIGS PV technologies. The focus is on using materials with no limitations in terms of resource availability. (Both indium and tellurium are of concern in this respect for massive PV development).

There are several categories of materials being investigated today – FeS_2, SnS_2, Cu_2ZnSnS_4, $Cu_2ZnSn(S,Se)_4$, $Cu_2ZnSnSe_4$, Graphene nanolayers, $MoSe_2$ nano layers......
Figure 22 refers to the CZTS Kesterite system which is perhaps the one that is being the most researched at present.

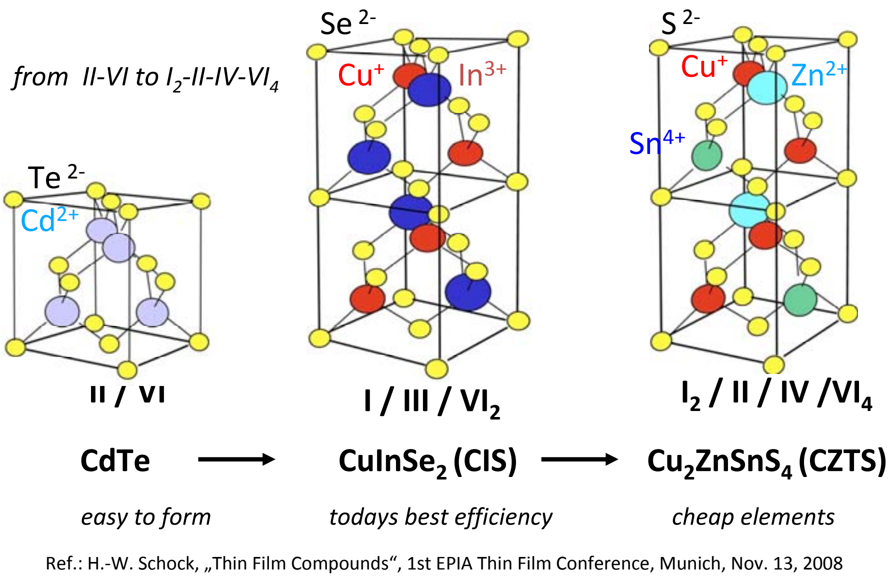


Figure 22. Comparison of CdTe, CIS & CZTS Kesterite material systems

Figure 23 illustrates the remarkable progress in just the last two years for CZTS systems.

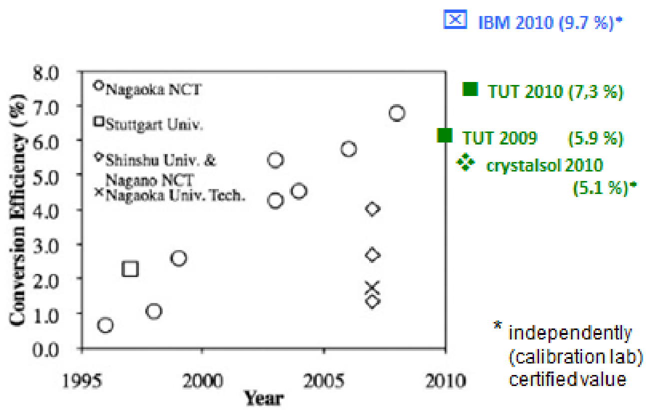


Figure 23 Evolution of lab based conversion efficiency for CZTS cells (source E.Mellikov)

Such materials systems lend themselves to band gap engineering thus enabling optimal potential efficiency within the Shockley – Queisser limits.

An interesting additional benefit of CZTS systems is the very low PV temperature coefficient of -0.16 %/ºC.

Several approaches are being investigated for production of such systems including vacuum based, non vacuum solution based and novel architectures such as composite single crystal particulate membranes as illustrated in Figure 24

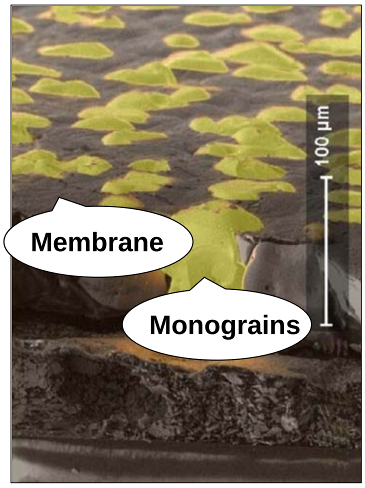


Figure 24. Schematic of novel mono-grain CZTS cell structure (Crystalsol)

Key challenges for New materials Systems

The new materials systems have been investigated for the last 5 – 10 years. They hold great promise for the future and provided they have the right combination of performance and cost could, together with c-Si, be a dominant PV technology in the decades to come (the same can be argued for OPV). However many questions still remain to be answered before a commercially viable system is fully developed.

In the short term until 2020:

1.1.2.12.1 Understanding of processes of formation of CZTS materials with tailored elemental, phase and defect composition.
1.1.2.12.2 Development of processes for high speed deposition of homogenous CZTS layers.
1.1.2.12.3 Understanding of chemistry of doping of CZTS materials.
1.1.2.12.4 Reducing of the use of Cd-containing materials.
1.1.2.12.5 Reliable control of interfaces at the nano scale

In the medium term till 2025 and beyond:

1.1.2.12.6 Understanding of formation of new perspective materials (FeS2, SnS2, …..) with tailored elemental, and defect composition.
1.1.2.12.7 Understanding the electronic band structure of active layers and interfaces.
1.1.2.12.8 Understanding of role of deposition parameters in material formation processes.
1.1.2.12.9 Full replacement of Cd-containing materials. New recycling processes for the main SC materials.
1.1.2.12.10 Full recovery of wastes
1.1.2.12.11 Multi-junction solar cells .

KPIs for New Materials systems

Please refer to table 16 for detailed description.

1.1.2.13 Novel PV Technologies

"Novel PV technologies" are defined as:

- Targeting very high efficiencies that defy the Shockley – Queisser limits.
- Lack convincing proof of concept today
- Being intimately linked with materials development

(Note that this differentiates them from "emerging technologies" which can be considered to have already reliable proof of concept e.g. OPV, DSSC….).

There are two approaches possible; either adapting the active layers to the sun's spectrum or adapting the sun's spectrum to existing devices:

1. Material development for novel active layers tailoring the active material to the solar spectrum
    - From 3-D to 0-D materials
    - Either aimed at:
        - Combining improved long-wavelength absorption with high voltage of host semiconductor with larger band gap (quantum wells) – InGaN, InGaAs, Metallic Intermediate Band (MIB)
        - Increasing band gap by quantum confinement effects (quantum dots, quantum wires)
        - Hot carrier effects – multiple exciton generation

2. Material development for peripheral layers and structures tailoring the solar spectrum to the active material
    - Up-converting materials
    - Down-converting materials
    - Photonic structures such as plasmonics
    - Aimed at higher injection levels

The advantage of the second of these approaches is that it can be applied to enhance existing PV technologies and leverages other work already performed in other fields of electro optics such phosphor development. Consequently the time to implement is quite likely to be shorter and have a wider impact. Novel active layers on the other hand are more specific.

1.1.2.12.1 Key Challenges for Novel PV Technologies

This area is cutting edge science for PV and the overall challenges are important. Particularly in the case of #2 the difficulties are about integrating known phenomena into a PV device. `

Careful choices will be needed with respect to which materials systems will be selected. Novel active layers will probably rely on indium, gallium, selenium and tellurium. The Up and Down converters will require rare earths such as Yb^{3+}, Er^{3+}, Ho^{3+} and Tm^{3+} any of which may face supply restrictions.

KPIs for Novel PV Technologies

Between 2020 and 2030, the following targets should be ready for implementation:

Boosting structures at the periphery of devices:

- Cost of applied layer < 0,05Euros/Wp
- More than 10% of the existing non-spectrum conversion baseline efficiency improvement (relative)

Novel Active Layers:

- Device efficiency >30% (absolute)
- Module cost < 0.5 Euros/Wp

1.2 Material Supply Status and Challenges

Materials Availability / Recycling

The range of materials that may be considered as critical with respect to PV are as follows:

PV Technology		Critical materials
Crystalline silicon		Silver (Ag)
Thin Film	a-Si / micro cryst.	Germanium (Ge) *
	CdTe	Tellurium (Te)
	CIGS	Indium (In) *, Gallium (Ga) *, Selenium (Se)
Concentrator PV		Germanium (Ge) *

Table 14 – Critical materials for PV
** Identified by EU as being "Critical Mineral Raw Materials"* (6)

Most of these elements are by-products associated with commodity metals such as Copper, Lead and Zinc.

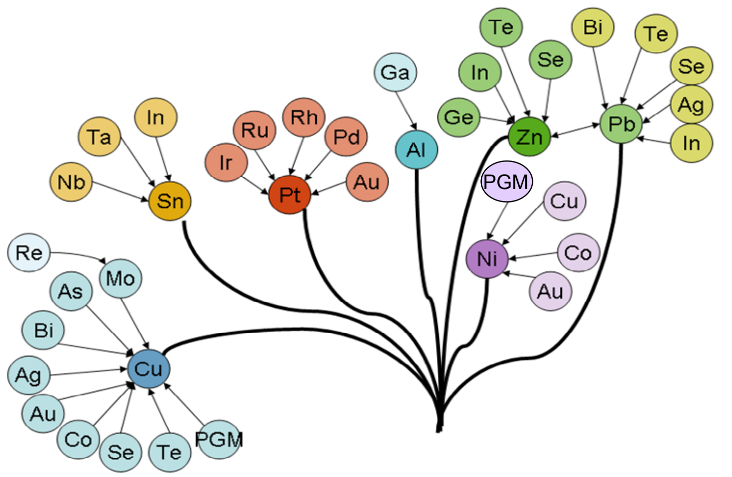


Figure 25. Materials "tree" Sources of precious and minor metals (Umicore) *metals*

Consequently, primary feed of the critical minor metals is dependent on the extraction levels of the major metals and the subsequent recovery rates at the extraction and refining steps.

This situation is further complicated by the fact that the concentrations of each of the minor metals varies from one deposit to another. There is a lack of publicly available reliable data about such reserves and its interpretation. Consequently estimates about future availability are very diverse due to the different assumptions possible for the economic modelling.

A typical flow sheet for the materials is shown schematically in figure 26.

Ores are concentrated at the mine to facilitate transport and extraction of the major metal; this is the first potential loss of minor metals. If the ore concentrate contains high value by-product precious metals (Au, Pt…), then the residues from the major metal recovery may be transferred to a refining step. At this stage the other less valuable minor metals may also be recovered. Although the current trading prices of the minor metals fluctuate they are far from the threshold to ensure optimal recovery when not associated with higher value by products.

As it is though, the metals value of the minor metals in the total cost of thin film PV modules is important if not the principal material cost item. Increased efficiencies and reduced layer thickness will contribute to the further reduction in material costs. This will give thin film PV producers extra margin for manoeuvre to absorb higher metal prices, however it is unlikely that they will be able to absorb precious metal level pricing to ensure higher recovery rates.

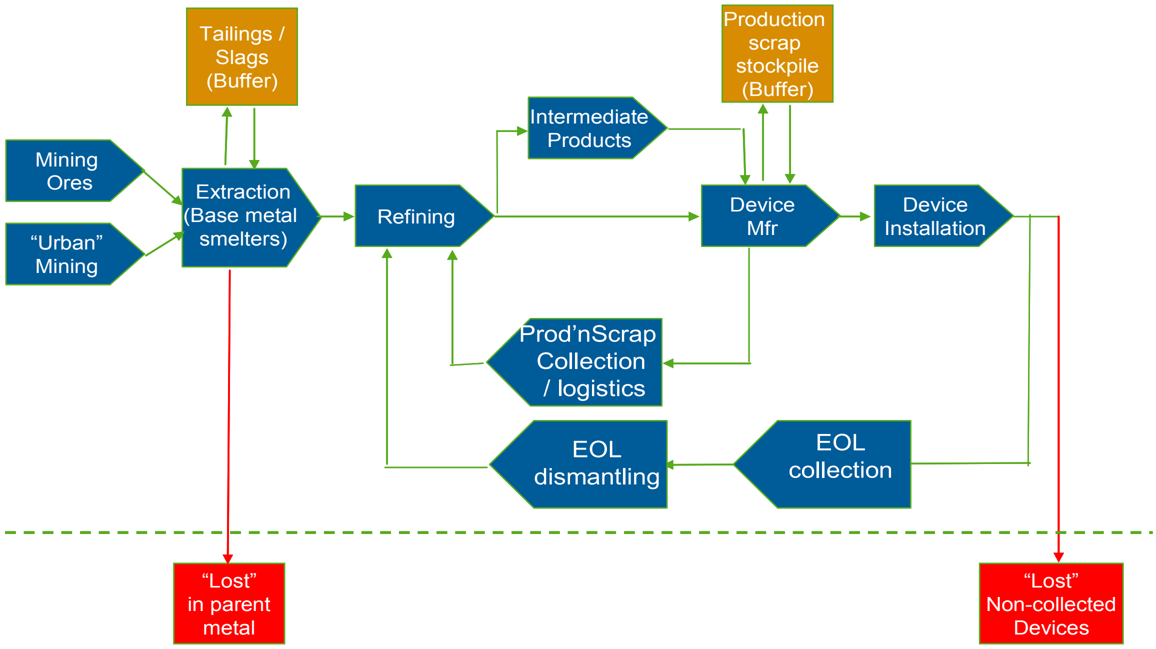


Figure 26 Typical materials flow sheet (Umicore)

A second source of metals is secondary recycling of production waste. Both CdTe and CIGS rely currently on vacuum based deposition processes during manufacture where only 30 – 40% of the materials finish up deposited on the module. The remainder is production scrap in the form of spent targets and reactor chamber wall and shield deposits. The quality of this scrap is quite high and with the right process, the key materials can be effectively recovered with recovery rates of the order of 80%. Umicore has in place an industrial process that can recover effectively the various elements in CIGS production scrap.

Finally, the third source for metals is end-of-life modules which will constitute a major source of fresh material as from 2030 when the presently installed modules are starting to be replaced. It is not felt that there is any real need for new research into developing new technologies. Sunicon (8) (for crystalline silicon) and First Solar (9) (for CdTe) both have processes that are in at least the pilot stage. The production scrap recovery processes mentioned above can be adapted similarly for CIGS.

1.2.1 Looking at the key critical PV metals individually:

1.2.1.1 Silver

Feltrin & Freundlich estimated that the current top silver electrode technology will ultimately place a limit on c-Si PV at about 100 GWp production. To alleviate this potential shortage new thinner electrodes and/or substitutes for the silver itself will need to be developed.

1.2.1.2 Tellurium

Tellurium is a by product of copper production.

Andersson suggests that in fact a mere 8% of the Te contained in copper ores is actually recovered. It is clear that the mining operation in a trade off situation will always privilege the recovery rate of the major metal over the minor metal.

Fthenakis argues that it should be possible to recover 1,450 Tonnes/ year of tellurium from copper electrolytic refinery slimes by 2020, which would allow approximately 20 GWp of CdTe production (It will require in 2020 about 50 tonnes of Te for 1 GWp of CdTe module due to expected reduction in the active layer thickness and increased efficiencies). However he assumes 80% recovery of the Te from the slimes whereas today it is only 30%. Technically this may be possible but it also has to be economically viable in the context of the prevailing copper prices. Over the last 10 years Te prices have increased by a factor 10, but there has not been a significant increase in tellurium recovery rates. In addition there is a tendency for the copper industry to replace electrolytic refining by solvent extraction techniques where it becomes more complex to recover the by-products.

If the 30% recovery rate for Te were to be maintained with no substitution taking place, the total production of Te by 2020 would in fact be 725 tonnes. Non PV applications for Te (metallurgy, chemicals & pharma, electronics) will require 465 tonnes. Therefore in this scenario, Cd Te production would be limited to about 5 GWp.

However by increasing the recovery rate of current slimes production or accessing other “waste” streams at the phase of extraction, it should be feasible to meet the extra demand for PV.

1.2.1.3 Indium

Indium is currently sourced principally from Zinc ores. In 2010 about 80% of the total 1,150 tonnes production of indium was consumed in flat panel displays in the form of ITO.
Virgin Indium production has increased by a factor of 3 over the past 15 years (primary Indium supply estimated at 550 – 570 tonnes in 2009) because base metal smelters have improved the extraction process and were able as well to treat lower grades of Indium in the concentrates. In the past, the revenues that smelters could generate from Indium recovery were not sufficient to change concentrate suppliers habits or pay more freight expenses to source indium-containing concentrates from further away. Today, smelters have a more proactive approach mainly due to the increased demand and pricing for Indium. Output has also increased as result of higher recovery yields. Indeed, in the past less than 20% of Indium content in concentrates was extracted to yield Indium but higher prices of Indium made it economically viable for smelters to invest to increase yields and capacities.

According to Indium Corporation however, still only about 30% of the 1,500 tonnes of Indium mined worldwide every year is currently transformed into refined Indium metal for 2 reasons:

- 30% of Indium-containing base metal concentrates do not reach smelters active with recovering Indium (about 500 tonnes are thus lost)
- 70% of Indium-containing concentrates that do reach smelters active with recovering Indium are only extracted at a final average rate of about 50% - The remaining 50% not immediately transformed into Indium metal remains associated with other elements and impurities as a residue that is accumulated (tailings/slag) and can be further treated for Indium recovery later (potential of 500 tonnes/year).

Large amount of tailings and slags were accumulated over the years at smelters. These tailings / slags are more difficult and expensive to treat but they can be if prices go sufficiently high to provide profits. Indium Corporation has identified that the total residues reserve worldwide amounts to over 15,000 tonnes of Indium. About 500 tonnes could be recovered yearly from tailings/slags accumulated in the past.

Without any change in the present recovery rates of primary indium or increase in recycling and no substitution, the total supply of indium available in 2020 would amount to 1,920 tonnes. Non PV applications will be approximately 1,500 tonnes, thus leaving enough indium available for about 8 GWp of CIGS even when integrating the anticipated developments in higher efficiencies and thinner films.

1.2.1.4 Gallium

Gallium is a by product of aluminium production and is considered as one of the critical metals by the EU.
Gross consumption in 2009 has been estimated at 119 tonnes rising to a possible production of 360 tonnes in 2020. CIGS modules will require about 12 tonnes of Ga per GWp. Demand from non PV applications in 2020 may amount to about 200 tonnes leaving enough for 13 GWp.

It must be noted though that if all the bauxite were treated to recover Ga an estimated total annual production of 4 000 tonnes/year could be made available. So there is no intrinsic physical shortage of Ga as such. However since it is present on average at about 50 ppm in bauxite, there is limited economic incentive to recover it at present pricing levels.

1.2.1.5 Selenium

Selenium is also a by product of copper production and faces the same challenges as tellurium. Its recovery rate is about 65%. Its major applications are in glass, pigments and metallurgy, consuming together 75% of total production.

Production and consumption of selenium in 2009 was about 2,835 tonnes and without substitution, non PV applications’ consumption can be extrapolated to grow to 4,800 tonnes in 2020. This should be compared with an extrapolated production potential of selenium of about 4,600 tonnes.

Increasing selenium prices will tend to push the recovery rates of selenium up slightly, but probably not by enough to meet demand with a strong CIGS growth. However, both the metallurgy and glass industries are very price sensitive and substitutes do exist for selenium. An increase in selenium pricing will most likely cause a switch away from selenium by the metallurgy and glass sectors. A 10% substitution for example would lead to enough selenium for 10 GWp of CIGS.

1.2.1.6 Germanium

Current germanium production is about 120 tonens and is mainly sourced from zinc production and coal in China and Canada and limited sources in Europe. China is the largest producer today. Included in the 120 tonnes is 25% recycled Ge.
There is reserve production capacity from the coal source which can be rapidly brought on and off stream as demand varies. It should be noted that significant reserves of germanium are to be found in coal. In China for example a report in 2007 confirmed that China's Ge production capacity alone to be 105 Tonnes of which 75 tonnes from coal origin and total reserves of Ge of 3,000 tonnes. Similarly in Russia, there are studies showing that similar sources of germanium exist.

30 Tonnes of Ge is in fact used in the manufacture of PET bottles. There would be options of substitution in this particular application to free up some of the Ge.

According to Fthenakis the resource constraints of Ge could limit production of TF Si to 3 – 11 GWp.
In the case of CPV, 1GWp of PV cells requires about 10.5 tonnes of Ge.

A more thorough analysis of Germanium production and reserves is required to assess the absolute resource constrained limitation on PV, however it is felt that either TF Si or CPV can be readily supported up to 10 GWp.

1.2.1.7 Rare Earths

Rare earths are not so much used today in PV. Some of the novel PV technologies envisaged involving up and down converters may rely on the rare earth elements such as Yb^{3+}, Er^{3+}, Ho^{3+} and Tm^{3+}.

Country	Mine Production (metric tons)	% of total	Reserves (million metric tons)	% of total	Reserve Base[a] (million metric tons)	% of total
United States	none		13.0	13	14.0	9.3
China	120,000	97	36.0	36	89.0	59.3
Russia			19.0	19	21.0	14
(and other former Soviet Union countries)						
Australia			5.4	5	5.8	3.9
India	2,700	2	3.1	3	1.3	1
Brazil	650		small			
Malaysia	380		small			
Other	270		22.0	22	23	12.5
Total	124,000		99.0		154	

Source: U.S. Department of the Interior, Mineral Commodity Summaries, USGS, 2010.

a. Reserve Base is defined by the USGS to include reserves (both economic and marginally economic) plus some subeconomic resources (i.e., those that may have potential for becoming economic reserves).

Table 15 Rare Earth reserves - US Geological Services

As shown in Table 15, a very large proportion of known reserves of rare earths today is located in China with the now well known risks for reliability of supply.

A recently published useful study by Oeko Institute (Study on Rare Earths and Their Recycling – January 2011) suggests that demand for paseodymium, dysprosium, terbium, lanthanum, yttrium and europium may exceed supply in the coming years. New mines in addition to the ones presently planned will be required by 2014.

With respect to recycling, there is as yet no established process for recovery / recycling of rare earths from end of life electric motors and generators. This is an area that is being addressed in Germany with a feasibility study due to start in April 2011 by a newly formed consortium coordinated by Siemens and supported by the BMBF.

PV is not the only technology that has an interest in rare earths and will be dependent on a strategic pan European approach that will ensure ready access to such elements. Increasing demand will push prices up, which is unwelcome for manufacturers, but will create an incentive to better manage the materials cycle and encourage recycling.

1.2.2 Conclusions and needs for materials availability

The challenges facing the PV materials sector are common. The PV device that faces the least challenge for materials availability is c-Si and TFSi. However even here, research will need to be done to find ways of reducing / replacing silver in the top contacts for c-Si. Nevertheless, these two PV technologies alone will not necessarily meet all the future operational requirements of all PV applications. It is therefore essential to continue to support other PV technologies that offer the potential of higher efficiency and lower cost manufacturing and resolve the materials availability issues accordingly.

Taking the World average annual PV production scenarios in Table 2, we see that by 2030 the average annual PV production could range from 60 to 110 GWp/year.
In the case of the Low Scenario, there will probably not be any issues with respect to materials availability assuming that there is a balanced portfolio of PV technologies. In the case of the High Scenario, it is unlikely that any single PV technology could be supplied with enough materials especially in a “business-as-usual” scenario with respect to materials recovery.

It is believed that there are reasonably large additional amounts of material to recover from both ongoing primary production and historical tailing deposits provided the trading price of the metal is high enough and that the recovery process is cost effective. There is a lack of available consolidated data to accurately assess the full potential of such sources. A case can be made for further research into assessing the size of these deposits and developing more cost effective recovery processes.

Recycling of production waste is currently taking place with proprietary developed processes. The quality of this waste stream is sufficiently high to ensure that it is self driven. Current know how in chemistry within major chemical corporations is largely sufficient to ensure the effective recovery of materials from production scrap. Several organisations are already serving this particular market with proprietary processes; Umicore (CIGS scrap), First Solar (CdTe) and NEO Materials (CIGS) are just three companies that have developed such processes. In general it is felt that there is little need for funded research into improving these processes. They are already cost effective and the specialised companies already operating here will optimise their processes to maximize the recovery of the metals at the lowest cost.

End-of-life modules will constitute a major source of fresh material as from 2030 when the presently installed modules are starting to be massively replaced. It is not felt that there is any real need for new research into developing new technologies. Sunicon (for crystalline silicon) and First Solar (for CdTe) both have processes that are in at least the pilot stage. The production scrap recovery processes mentioned above can be adapted similarly for CIGS.

Nevertheless there are three main hurdles for effective recycling with high recovery of all metals for end of life devices:

a) The key materials in all the PV technologies are present in relatively low concentrations. Their intrinsic value is low in absolute terms even if their strategic value to society is high. It is highly unlikely that any collection and environmentally sound recycling process will ever be cost effective based on pure recovered metals value. Some form of voluntary or legislative economic mechanism that reflects the strategic value of the contained trace minor metals will need to be established, whereby a fair price is paid to remunerate a recycling *service*.
b) Careful consideration will be required for the recycling target levels. In view of the low concentrations of such strategically valuable materials, a simple weight-based specification for recovery will not in any way ensure conservation of these materials.
c) Low market volumes today means that it is not viable based on the value of metals recovery alone on a European scale to build and operate an environmentally sustainable industrial plant for PV end of life modules. Some form of private public partnership should probably be established to ensure the viable operation of a sufficiently large demonstration plant that will handle the industry’s needs over the next 10 – 15 years and be ready for up-scaling when large volumes of End of Life PV Modules appear on the market.

1.2.3 Overall to alleviate the materials availability situation a number of priority actions need to be envisaged:

- A thorough inventory study of the potential of the mining industry to furnish greater volumes of minor metals. The conclusions will need to be drawn taking into account the competition for such scarce materials between different applications.
- Develop more cost effective processes to enable increased recovery of minor metals at primary extraction and refining, ideally making it economically viable to recover them without the presence of precious metals and a maximum price increase of the minor metals of 5 – 10 times compared with current pricing.
- Develop industrial processes capable of recovering rare earths from end of life goods such as electric motors and generators.
- Increase the recycling rates of production scrap (this is an industry related logistics issue and does not need further research into new processes)

- In general for all PV technologies research is required to reduce layer / wafer thickness and increase device efficiency.
- Develop cheaper non-vacuum deposition materials/processes with materials yields greater than 90% for the various layers in PV devices and so reduce the production waste. (note this cannot be done at the expense of device performance).
- Develop substitute materials for ITO layers in PV and flat panel displays. Performance of such layers will be dictated by the device characteristics.
- New top electrode systems for c-Si devices consuming less or no silver will need to be developed with no sacrifice in performance and hopefully a reduction in cost.
- Develop substitute material systems for thin film (e.g. Kesterite CZTS systems)
- Investigate feasibility of sea bed mining of ferromanganese nodules (e.g. 9 million tonnes of Te may exist [(20)]) as well as the environmental impact of such techniques.
- Proper policy with effective set of guidelines and drivers to ensure that minor metals are correctly recovered (e.g. Ensure that the indium employed in flat panel displays is effectively recovered at end of life).

1.3 On-going Research and Actors in the Field of Material Research for Energy Technology Applications and Challenges

Since PV is heavily reliant on intrinsically combined materials research and device manufacturing process steps, the number of research projects in materials in Europe and world wide is enormous and very difficult to document thoroughly. Although far from a complete list, some of the key organisations involved in PV research are described below. It should be noted that this is not a complete inventory of neither research groups nor industrial organisations involved in PV research.

1.3.1 c-Si

1.3.1.1 Silicon

The Siemens C Process dominates the technology. Research is done in-house at the big players like Wacker, Hemlock, DCC. They all have plans to expand their capacities. Alternative developments have been investigated in the nineties funded by JPL, USA.

1.3.1.2 Crystallisation and Wafering

Since the 1990s, research has been ongoing to improve crystal quality. Germany has done a lot of research for the improvement of the multi-crystalline silicon.

- The last finished project was “SolarFocus” concentrating on UMG-silicon aspects. In 2011 a new project focussing on multi-crystalline silicon crystals prepared by pure feedstock will start. The target is the avoidance of structural defects and impurities based on solar grade semiconductor silicon.

- Fundamental research into wafering was accomplished at the TU Bergakademie Freiberg, Prof. Dr. Moeller. The focus is on basic understanding of slicing mechanisms and the investigations of the operation parameters to improve the productivity of the process.

- The consortium “Solarvalley Mitteldeutschland” manages projects targeting cost reductions in the value chain from silicon to high performance modules. Thin wafer preparation is one of the challenges within these projects.

- The EC supported “Crystal Clear” project involved the relevant PV industry of Europe and many research Institutes and Universities (Fig. 27). The project had a wide scope with the target of module production costs at about 1 €/Wp.

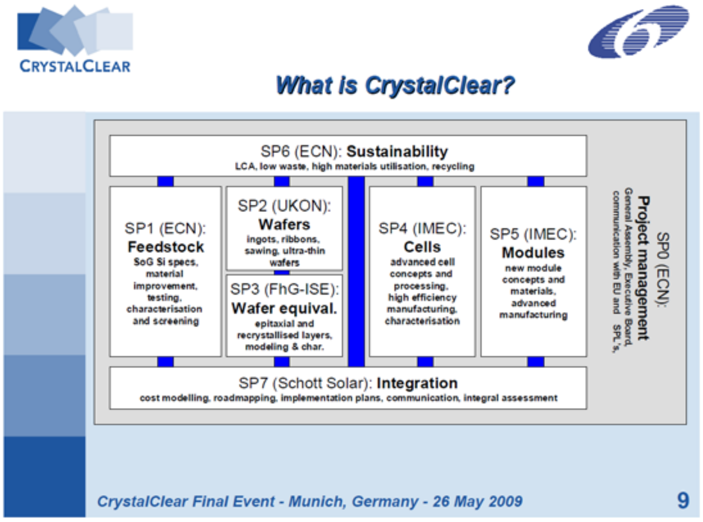


Figure 27. Scope of Crystal Clear (FP6)

The challenge beyond “Crystal Clear” with a cost target of 1 €/Wp on **module level**, is to reduce costs on the **system level to below 1 €/Wp**.

Other EU supported c-Si projects are:

- Hetero-junction Solar Cells based on a-Si c-Si
  (Project HETSI, Start and end dates: 01/2008 – 01/2011)

- Ultra thin solar cells for module assembly – tough and efficient
  (Project ULTIMATE, Start and end dates: 01/10/2008 – 30/09/2011)

- Modelling of interfaces for high performance solar cell materials
  (Project HIPERSOL, Start and end dates: 01/12/2009 to 30/11/2012)

1.3.2 CdTe

Nowadays there are no ongoing joint research Projects at EU scale. Groups with relevant RTD actions are:

Industry:

- First Solar (USA-DE) – major player
- Plus several smaller players World wide

R&D:

- ETZH-EMPA (CH)
- Technical University of Darmstadt (DE)
- University of Durham (UK)….

1.3.3 TFSi

Current main TF-Si PV projects in the EU:

Silicon-Light: Silicon thin film solar cells on foil (ECN, EPFL, U. Ljubljana, U. Copenhagen, U. Valencia, JiaoTong Univ. Shanghai, Umicore, Nanoptics, VHF Technologies).
ThinSi: Powder to substrate concept (SINTEF, Elkem Solar AS, ENEA, Fraunhofer Institute for Solar Energy Systems, Innovative Materials processing Technologies Ltd., IMEC, Isofoton S.A., NT-MDT Europe BV, Oxford Instruments Plasma Technology Ltd., PyroGenesis S.A., University of Nottingham)
HELATHIS: Optical light confinement in large area tandem solar cells (T-Solar, AGC Solar, FZ Juelich, Utrecht U., U. Barcelona)
PEPPER: Lower environmental impact modules (Oerlikon, EPFL, U. Northumbria, U. Patras, Bosch, Heliosphera, Linde)
PV-GUM: Flexible thin film Si cells for roofing (Imperbel B.V.,)

1.3.4 CIGS

FP7 programme in CIGS

- HIPO CIGS – start 01/01/10
  Main objective: Develop innovative flexible substrate materials and deposition processes for the R2R-deposition of highly efficient CIGS solar modules with potential for low production costs < 0.6 €/Wp

- NOVA CIGS – start 01/01/10
  Main objective: Develop an ink based non-vacuum simple and safe deposition process of the CI(G)S absorber layer for highly efficient low cost solar cells (module cost of below 0,8 €/Wp)

- ALPINE – start 01/09/10
  Main objective: Improve, in terms of precision and speed, of the existing scribing technology in PV modules through the usage of high quality beam fiber lasers.

DEPOSITION METHOD FOR CIGS LAYER	EFFICIENCY		
	Best laboratory cell (~ 1 cm²)	Best pilot line module (30x30 cm²)	Commercial module (~ 1 m²) [9]
Co-evaporation	**19% - 20%** *ZSW [1], HZB (DE) [2]* *NREL (US) [3]*	**14%** *ZSW (DE) [6]*	**8% - 12%** *Würth Solar, Q-Cells, Solarion (DE)* *Global Solar, Ascent Solar (US)*
Sputtering of precursors + selenization/sulfurization	-	**15% - 16%** *Solar Frontier (JP) [7]* *Avancis (DE) [8]*	**7% - 12%** *Solar Frontier, Honda Soltec (JP)* *Avancis, Sulfurcell, Bosch Solar (DE)* *Sunshine PV (TW)*
Wet coating of precursors + selenization/sulfurization	**14% - 15%** *ISET [4], Nanosolar (US) [5]*	-	**8% - 11%** *Nanosolar (US)*

Table 16 Major research centres and organisations involved in CIGS

1.3.5 HCPV

HCPV multi-junction solar cell research centers which are also performing testing on the materials for HCPV modules are NREL (US), Fraunhofer ISE (Germany) and Universidad Politécnica de Madrid UPM (Spain). Module component and module testing is also done at Instituto de Sistemas Fotovoltaicos de Concentración ISFOC (Spain).

The difficulty is that the material development for CPV module materials is segmented and dispersed. E.g., there is no consistent work on the UV stability of the different optical concentrator types. The mentioned institutions cover only a small part of the required material development.

1.3.6 OPV / DSSC

Five FP7 EC projects focus on OPV solar cells are running. Three are focused on DSSC system for OPV solar cells, since 2008 one project has been launched every year on this topic on this topic in order to develop new concept cells and nanostructures component. The two projects have been launched one on printed OPV to develop ITO free cell and the other on the up and down-conversion shifting concept.
Major industrial and R&D players In Europe:

- Industry: KONARKA (USA/FR); SOLARMER (USA), HELIATEK (Ge), ARMOR (FR), SOLARONIC (CH), G24i (UK), 3G Solar (Is)
- R&D: ECN (NL), RISO DTU (DN), IMEC (B), ISE (G), IAPP (G), CEA(FR), EPFL(CH), Uppsala University (SW) , Linz University (A)

1.3.7 Glass

There is very little (published) research on development of the properties of low-iron glass.

There is some European work investigating glass strength: a (not-exhaustive) list might include Dr Russell Hand (Sheffield University), Dr Tanguy Rouxel (Rennes University), Dr Heiko Hessenkemper (TU Bergakademie Freiburg), Dr Lothar Wondracek (Erlangen), and Elizabeth Bouchard (CEA Saclay) These efforts are not part of some coordinated research program, but depend on the interests of the individual researchers. In the US, by contrast, there is a concerted program to improve the strength of glass – organised by the Glass Manufacturing Industry Council, entitled “The Usable Glass Strength research coalition”.

There is significant effort on coatings – especially in the area of transparent conducting coatings and (for Si-based thin film systems) novel light-scattering technologies. All the major glass companies have patent activity in the area of TCOs. And these are areas of extensive academic research. Some of the main groups involved include TCO - Miro Zeman (Delft), Christophe Ballif (Neuchatel), and plasmonics - Darren Bagnall (Southampton).

1.3.8 New materials systems

At the moment PV cells developed in IBM lab based on Kesterite CZTS materials have the best performance close to 10% (fig. 2).

Despite the level of effort in CZTS materials and solar cells production, there remains a large discrepancy in efficiencies even between the laboratory-scale CZTS solar cells developed in different laboratories. In part, this is due by the lack of a good comprehensive scientific base for the formation CZTS materials in different technological processes. The most common CZTS thin film production routes are by vacuum technologies followed by sulphurisation (selenisation) however wet solution chemical technologies are gaining a lot of attention. In soft chemical processes the research outside Europe has been more successful and has resulted in highest parameters of CZTS solar cell structures [xx]. Some interesting work has been done at TUT and Crystalsol OÜ where single crystal mono-grain layer structures are created to form the active layer with a number of potential benefits

The last year the first workshop of major industrial and R/D organizations from Europe and US interested in CZTS materials and SC technologies on their base was organized by Uppsala University and Tallinn University of Technology. All the participants pointed out the necessity of collaboration and to act together in possible activities in Europe in this field and declared that there is need for EC financed projects in the field.

Major R&D and industrial players in Europe:
R&D: Helmholz Centre (DE), Uppsala University (SW), TUT (Estonia), IREC (Spain), University of Luxembourg (Luxembourg), University of Bath (UK), Northumbria University (UK), CEA Litten.
Several other material systems have been studied with the aim of replace existing indium based CIGS materials. The more studied are binary materials as SnS_2, ternary materials as $CuGaS_2$, $CuAlSe_2$ and $CuAlS_2$, $AgInS_2$, quaternary materials $Cu_2ZnGeSe_2$ and $Cu_2ZnGeSe_2$, Cu2SnSe3 but the results till have been not very encouraging.
Industry: Crystalsol OÜ (Estonia), Solibro Research (SW)

1.3.9 Novel PV Technologies

There is a multitude of research centres working on different aspects of NPVT. However to name but a few of the leading centres:

- III-V Quantum wells: Imperial College, London, ...
- III-V Quantum dots: University Glasgow, ...
- InGaN-cells: University of Texas, ...
- Si-nanowires: imec, ...
- Si-quantum dots: University of New-south Wales (UNSW) , INES (Strasbourg, ...)
- Metallic Intermediate Band cells: Polytechnical University of Madrid, ...
- Up- and downconversion: UNSW, ISE, ...

With some specific EU projects examples:

- All-inorganic nano-rod based thin-film solarcells on glass
  (Project: ROD-SOL, Start and end dates: 01/01/2009 – 31/12/2011)

- Semiconductor Nanomaterial for Advanced Photovoltaic Solar cells Using New concept of nanocrystal and conductive host
  (Project: SNAPSUN, Start and end dates: 01/06/2010 – 31/05/2013)

- Silicon nanodots for solar cell tandem
  (Project: NASCEnT, Start and end dates: 1/09/2010 – 31/08/ 2013)

- Architectures, Materials, and One-dimensional Nanowires for Photovoltaics - Research and Applications
  (Project: AMON-RA, Start and end dates: 01/10/2008 – 30/09/2012)

- Intermediate band materials and solar cells for photovoltaics with high efficiency and reduced cost
  (Project: IBPOWER, Start and end dates: 01/02/2008 – 31/01/ 2012)

- Nanomaterials for harvesting sub-band-gap photons via upconversion to increase solar cell efficiencies
  (Project: NanoSpec, Start and end dates: 1/06/2010-31/05/2013)

1.4 Materials Specification Targets for Market Implementation in 2020/2030 and in 2050

1.5 Synergies with other Technologies

Sections 1.4 and 1.5 are summarised in Tables 16 &17.

1.6 Needs and Recommendation of Activities addressing 2020 and 2050 Market Implementation

There are a number of reports issued by PV associations and the PV Technology platform which make well measured recommendations regarding fostering and building a thriving PV industry and market, which in turn will benefit the materials sector.

It is not the purpose of this report to re-iterate these messages. However materials research can be seen as a key enabler to ensure high performance, long life PV systems at the right cost. It is therefore essential to support such research programmes.

Since the European industry relies on exports as well as imports, it is considered counter productive to instigate measures that can be likened to protectionism.

More specifically with respect to research into PV in Europe there are a number of key messages to adopt:

1.6.1 It is not sufficient to fund pre-commercial R&D in a region and assume market forces will automatically develop an added value market for the benefit of the tax payers. Any research programme has to be closely coordinated with an effective industrial policy that will “accompany” the inventions right the way through to their commercial stage (lab to fab). This implies that research programmes must be developed hand in hand between independent research organisations, industry and governments at regional, national and EU level.

It is of course illusory to expect that 100% of the added value will remain in the original area of support for development and in some cases this would even be counter productive in meeting the performance targets as defined. In terms of defining the added value, one should consider in the short term the complete value chain from intellectual property (IP), materials, devices, modules, BOS equipment and installation. This should also be a dynamic picture over time e.g. as module costs come down, the relative weight of transport costs increases and so limit the geographic radius of commercial viability for future manufacturing the glass and auto industries may well provide interesting comparisons. In the longer term, the life cycle analysis (LCA) will be useful to evaluate the net impact of having available state of the art PV technology generating electricity.

It is clearly the challenge for any industrial policy to avoid long-lasting distortion of free markets while at the same time ensuring that the results of R&D-efforts strengthen the economic fabric of a region. Such a balanced industrial policy should result in a level-playing field where the European industry can take its fair share of the R&D-results performed and obtained within Europe for the different PV-technologies.

1.6.2 With respect to its role, the EC is doing the right thing by pushing to develop targeted road maps that represent the voice of both industry and research communities. The EC’s task and responsibility must be to ensure that MSs adopt the roadmaps and commit to support the research priorities so defined. The EC’s funding role should continue as “seed money” to prime the pump and to ensure that there is real pan-European coordination and beneficial international cooperation. The MS’s / regional funding bodies can and should commit to supporting specific programmes that are validated by the road maps. Ways must be found to overcome the political and regional barriers of “localised” funding without restricting such funding commitments.

<u>One vehicle that may be considered as appropriate to achieve such a goal would be to create a European scale PPP specifically on materials for PV technology that would include both industry and research centres.</u>

1.6.3 Currently, research into PV related activities is spread across a large number of independently operated institutions both large and small acting on regional or national agendas with up until now little effective coordination at a pan EU level concerning the strategic development of the PV industry.

Some of the larger organisations have each developed their own specialty fields and by and large stay off each others' turf. The larger number of smaller typically university based research groups have some difficulty in demonstrating critical mass due their size and funding resources and are often perceived as operating independently. However, some of the most creative thinking is performed at these latter institutes and so greater effort should be made on all sides to vitalise and better accommodate the potential contributions of all research centres to achieve optimal complementarity.

Flanders is a good example whereby the region has used the SEII for inspiration of its own PV development goals encompassing all of its research centres large and small. This being said, if several MSs or regions were to do the same, some form of coordination will be essential to ensure that the ensemble of selected topics remain balanced across Europe and in accordance with a European road map. The fear is that following this route too closely will transform the European research agenda into the arithmetic sum of each regions desiderata.

In all of the above mentioned reflections, care has to be taken that the move towards sufficiently large entities mobilizing sufficient critical mass still leaves room for diversity and avoids R&D-monopolization.

Present national and regional funding schemes represent 80–90% of funding available for PV research. In order to reach maximal effectiveness for the funds spent by the Member States it would be good to see a gradual increase of cross-border R&D-funding in case where clear win-win situations are identified. A great deal of benefit could be had for the sector as a whole by finding ways to pry open such national barriers; to ensure a true sharing and optimal use of both physical and intellectual resources.

A further extension to this would be to join forces with leading international research centres in the USA, Japan, Korea, Taiwan……

1.6.4 There is at present a multitude of advocacy platforms springing up e.g. EU PV Tech Platform, EERA, SEMI, German PV consortium, SOFIA etc….. Each of these groups are working with the best of intentions and up until now there has been reasonably good convergence. However at best this represents a duplication of effort and sub critical representation at worst it will lead to diverging viewpoints, confusion in communication and dilution of the expressed needs.

A better solution would be to have a single robust fully representative organisation that functions according to a well defined mandate. It would be desirable that there is a source of EU funding that would help it get established and provide it with credibility. This could well be achieved by further reinforcing the role of the PV Technology platform and making it even more attractive for all stakeholders.

1.6.5 EU PV Test Centre
The recent launch of the European Infrastructure Project (SoPhia) could be the first step in the vision of an EU PV Test Centre. SoPhia is coordinating a group of European centres of excellence in PV research with a focus on characterisation, modelling and accelerated ageing. Its goals are to:

- develop a coordinated approach to using the partners' expertise and infrastructures more effectively, adding value to research projects and investments at all levels and promoting European leadership in this sector.
- facilitate a wider sharing of knowledge, tools and techniques across fields and between academia and industry all over Europe.
- accelerate pre-normative research and promote the rapid transfer of research results into industrial standards for emerging PV technologies.

This is an important initiative and every effort should be made to ensure that the industry becomes fully involved and a strategy should be in place so that the results and recommendations that ensue are universally accepted as a set of standards for PV.

It should be noted that SoPhia's role is at present constrained by being limited to simple coordination. It is however a very important first step in demonstrating the benefits of openly cooperating and sharing resources on a pan-European level.

1.6.6 Standardisation of PV products

PV products have evolved empirically leading to a situation of a very heterogeneous range. There would be significant cost reduction potential to have standardisation in for example:

- Module dimensions
- III-V cells
- Standardised tests as outlined in section 5

1.6.7 EU wide building codes for PV / BIPV

- Structural
- Thermal properties
- Weather tightness
- Fire safety
- etc

1.6.8 Module design

- Develop multi functionality of BIPV products
- PV modules with integrated support structure for free field sites
- Intelligent modules containing inverters, data interfaces and safety devices

1.6.9 HCPV – support required to demonstrate bankability of large CPV power plants and ensure that there are adequate means in place to transport energy from southern EU / N. Africa to middle and northern Europe.

1.6.10 Underpinning the overall aim to develop a sustainable source of energy, major research orientations should be validated thorough life cycle analysis based on the IEA and EPIA task 12 guidelines contained in the report IEA-PVPS T12-01:2009.

1.7 Annex: PV Expert's papers

Accessible at www.XXXXXXXXXXX.org.

European Commission

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Author(s): Peter Rigby, (Rapporteur), Bertrand Fillon, Andreas Gombert, José Herrero Rueda, Edwin Kiel, Enn Mellikov, Jef Poortmans, Ruud Schropp, Ingo A. Schwirtlich, Paul Warren, *JRC Coordination:* A. Jäger-Waldau and E. Tzimas

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Abstract
This scientific assessment serves as the basis for a materials research roadmap for solar photovoltaic technology, itself an integral element of an overall "Materials Roadmap Enabling Low Carbon Technologies", a Commission Staff Working Document published in December 2011. The Materials Roadmap aims at contributing to strategic decisions on materials research funding at European and Member State levels and is aligned with the priorities of the Strategic Energy Technology Plan (SET-Plan). It is intended to serve as a guide for developing specific research and development activities in the field of materials for energy applications over the next 10 years.

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