A Strategic Research Agenda for Photovoltaic:

Solar Energy Technology

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١ Executive summary

The direct conversion of sunlight into electricity is a very elegant process to generate environmentallyfriendly, renewable energy. This branch of science is known as “photovoltaics” or “PV”. PV technology is modular, operates silently and is therefore suited to a broad range of applications and can contribute substantially to our future energy needs.

Although reliable PV systems are commercially available and widely deployed, further development of PV technology is crucial to enable PV to become a major source of electricity. The current price of PV systems is low enough for PV electricity to compete with the price of peak power in grid-connected applications and with alternatives like diesel generators in stand-alone applications, but cannot yet rival consumer or wholesale electricity prices. A drastic further reduction of turn-key system prices is therefore needed and fortunately possible. This was emphasised in the document A Vision for Photovoltaic Technology, published by the Photovoltaic Technology Research Advisory Council (PV TRAC) in ٢٠٠٥ [PVT ٢٠٠٥] and referred to frequently in this report. Further development is also required to enable the European PV industry to maintain and strengthen its position on the global market, which is highly competitive and characterised by rapid innovation.

Research and Development - “R&D” - is crucial for the advancement of PV. Performing joint research addressing well-chosen issues can play an important role in achieving the critical mass and effectiveness required to meet the sector’s ambitions for technology implementation and industry competitiveness. This led the PV Technology Platform to produce a Strategic Research Agenda (SRA) to realise the “Vision” referred to above. The SRA may be used as input for defining the EU’s Seventh Framework Programme for Research (the main source of funding for collaborative research between European countries), but also to facilitate a further coordination of research programmes in and between Member States.

**The table below summarises the key targets contained in the SRA.
The figures are rounded and indicative.**

	1980	Today	2015	2030	Long term potential
Typical turn-key system price (2006 €/W_p, excl. VAT)	>30	5	2.5	1	0.5
Typical electricity generation costs southern Europe (2006 €/kWh)	>2	0.30	0.15 (competitive with retail electricity)	0.06 (competitive with wholesale electricity)	0.03
Typical commercial flat-plate module efficiencies	up to 8%	up to 15%	up to 20%	up to 25%	up to 40%
Typical commercial concentrator module efficiencies	(~10%)	up to 25%	up to 30%	up to 40%	up to 60%
Typical system energy pay-back time southern Europe (years)	>10	2	1	0.5	0.25

Current turn-key system prices may vary from ~٤ to ~٨ €/Wp, depending on system type (roof-top retro-fit, building-integrated, ground-based,...), size, country, and other factors.

The figure of ٥ €/Wp, however, is considered representative. Similarly, prices in ٢٠١٥ may range between ~٢ and ~٤ €/Wp. All prices are expressed as constant ٢٠٠٧ values.

The conversion from turn-key system price to generation costs requires several assumptions. This report assumes:

- An average performance ratio of ٧٥%, i.e. a system yield of ٧٥٠ kWh/kWp/yr at an insolation level of ١٠٠٠ kWh/m٢/yr. In southern Europe, where insolation is typically ١٧٠٠ kWh/m٢/yr, a performance ratio of ٧٥% translates into ١٢٧٥ kWh/kWp/yr n ١% of the system's price will be spent each year on operation & maintenance n the system's economic value depreciates to zero after ٢٥ years n a ٤% discount rate

The overall aim of short-term research is for the price of PV electricity to be comparable to the retail price of electricity for small consumers in southern Europe by ٢٠١٥. Continued price reduction after ٢٠١٥ implies that this situation will apply to most of Europe by ٢٠٢٠. This state, where prices are comparable, is known as 'grid parity'. Larger systems and ground-based PV power plants that are not connected directly to end-consumers will generally need to produce electricity at lower prices before they can be said to have reached 'grid parity'.

To reach these targets, the SRA details the R&D issues related to:

- PV cells and modules: - materials - conversion principles and devices - processing and assembly (incl. equipment) n Balance of System (BoS): - system components and installation - materials installation - operation and maintenance n concentrator systems n environmental quality n applicability n socio-economic aspects of PV.

A range of technologies can be found in commercial production and in the laboratory. No clear technological "winners" or "losers" can yet be identified, as evinced by the investments being made worldwide in production capacity based around many different technologies, and in the numerous concepts developed in laboratories that have large commercial potential. Therefore it is important to support the development of a broad portfolio of options and technologies rather than a limited set. The development of PV is best served by testing the different options and selecting on the basis of the following criteria:

- The extent to which the proposed research is expected to contribute to reaching the overall targets set.

- The quality of the research proposal and the strength of the consortium or research group(s) involved.

Concerning "cells and modules", a distinction is made between existing technologies (wafer-based crystalline silicon, thin-film silicon, thin-film CIGSS and thin-film CdTe) and 'emerging' and 'novel' technologies (advanced versions of existing technologies, organic-based PV, intermediate band semiconductors, hot-carrier devices, spectrum converters, etc.).

It is noted that in addition to the cost of PV electricity generation the value of the electricity generated is important. The latter may be enhanced, for instance, by matching PV supply and electricity demand patterns through storage.

The main R&D topics per technology area that are addressed to realize the Vision are summarized below. The detailed descriptions can be found in subsequent chapters.

١.١ Cells and modules

١.١.١ Topics common to all technologies

n Efficiency, energy yield, stability and lifetime Since research is primarily aimed at reducing the cost of PV electricity it is important not to focus solely on initial capital investments (€/Wp), but also on the energy yield (kWh/Wp) over the economic or technical lifetime.

High productivity manufacturing, including in-process monitoring & control Throughput and yield are important parameters in low-cost manufacturing and essential to achieve the cost targets.

E environmental sustainability The energy and materials requirements in manufacturing as well as the possibilities for recycling are important for the overall environmental quality of the product.

Applicability Achieving a degree of standardization and harmonization in the physical and electrical characteristics of PV modules is important for bringing down the costs of installing PV. Ease of installation as well as the aesthetic quality of modules (and systems) are important if they are to be used on a large scale in the built environment.

١.١.٢ Wafer-based crystalline silicon technology

Reduced specific consumption (g/Wp) of silicon and materials in the final module

New and improved silicon feedstock and wafer (or wafer equivalent) manufacturing technologies, with careful consideration of cost and quality aspects

Devices (cells and modules) with increased efficiency

New and improved materials for all parts of the value chain, including encapsulation

High-throughput, high-yield, integrated industrial processing

Safe, low-environmental-impact processing

Novel and integrated (cells/modules) device concepts for the longer term

١.١.٣ Existing thin-film technologies

١.١.٣.١ Common aspects

Reliable, cost-effective production equipment for all technologies

Low cost packaging solutions both for rigid and flexible modules

Low cost transparent conductive oxides

Reliability of products: advanced module testing, and improved module performance assessment

Handling of scrap modules, including re-use of materials

Developing replacements for scarce substances such as indium

١.١.٣.٢ Thin-film silicon (TFSi)

Processes and equipment for low-cost large area plasma deposition of micro/Nano crystalline silicon solar cells.

The interplay between the effects of plasma, devices and up scaling should be fully mastered

Specific high-quality low cost transparent conductive oxides suitable for large, high performance modules (greater than ١٢% efficiency)Demonstration of higher efficiency TFSi devices (meaning greater than ١٥% at laboratory-scale), improved understanding of interface and material properties, of light trapping, and of the theoretical performance limits of TFSi based materials and devices

١.١.٣.٣ Copper-indium/gallium-dieseline/disulphide (CIGSS)

Improvement of throughput and yield in the whole production chain and standardization of equipment

Modules with efficiencies greater than ١٥%, developed through a deeper understanding of device physics and the successful demonstration of devices with efficiencies greater than ٢٠% at laboratory-scale

Alternative or modified material combinations, of process alternatives like roll-to-roll coating and of combined or non-vacuum deposition methods

Highly reliable and low cost packaging to reduce material costs

١.١.٣.٤ Cadmium telluride (CdTe)

Alternative activation/annealing and back contacts for simpler, quicker and greater yield and throughput

New device concepts for thinner CdTe layers

Enhanced fundamental knowledge of materials and interfaces for advanced devices with high efficiencies (up to ٢٠% at laboratory scale)

١.١.٤ Emerging and novel technologies

١.١.٤.١ Emerging technologies

Improvement of cell and module efficiencies and stability to the level needed for first commercial application

Encapsulation materials and processes specific to this family of cell technologies

Product concepts and first generation manufacturing technologies

١.١.٤.٢ Novel technologies

Demonstration of new conversion principles and basic operation of new device concepts

Processing, characterization and modelling of (especially) nanostructured materials and devices; understanding of the morphological and opt-electrical properties (including development of theoretical and experimental tools).

Experimental demonstration of the (potential) effectiveness of add-on efficiency boosters (spectrum converters.

١.١.٥ Concentrator technologies

١.١.٥.١ Materials and components:

١. Optical systems - Find reliable, long-term, stable and low-cost solutions for flat and concave mirrors, lenses and Fresnel lenses and their combination with secondary concentrators ٢. Module assembly - Materials and mounting techniques for the assembly of concentrator cells and optical elements into highly precise modules that are stable over the long-term using low-cost, fully automated methods ٣. Tracking - Find constructions which are optimized with respect to size, load-capacity, stability, and stiffness and material consumption.

١.١.٥.٢ Devices and efficiency

Develop materials and production technologies for concentrator solar cells with very high efficiencies, i.e. Si cells with efficiencies greater than ٢٦ % and multi-junction III-V-compound cells with efficiencies greater than ٣٥ % in industrial production and ٤٥ % in the laboratory. Find the optimum concentration factor for each technology.

١.١.٥.٣ Manufacturing and installation

Find optimized design, production and test methods for the integration of all system components; methods for installation, outdoor testing and cost evaluation of concentrator PV systems.

١.٢ Balance-of-System ('BoS') components and PV systems

It is important to understand better the effect of BoS components on turn-key system costs and prices. BoS costs vary according to system type and - at least at present - the country where the system is installed, which impact on whether the cost targets for BoS may be deemed to have been reached or not. This report recommends that a study of BoS aspects be undertaken to quantify in detail the cost reduction potential of PV technology beyond ٢٠٣٠ (see Table I). BoS and system-level research should aim to:

Increase inverter lifetime and reliability

Harmonies the dimensions and lifetimes of components

Increase modularity in order to decrease site-specific costs at installation and replacement costs over the system's lifetime

Assess and optimize the added value of PV systems for different system configurations

Produce workable concepts for maintaining the stability of electrical grids at high PV penetrations

Devise system components that enhance multifunctionality and/or minimize losses n Develop components and system concepts for island PV and PV-hybrid systems

BoS research should include research into new storage technologies for small and large applications and the management and control systems required for their efficient and reliable operation.

١.٣ Standards, quality assurance, safety and environmental aspects

n Identification of performance, energy rating and safety standards for PV modules, PV building elements and PV inverters and AC modules

Common rules for grid-connection across Europe

Quality assurance guidelines for the entire value chain

A cost-effective and workable infrastructure for the reuse and recycling of PV components, especially thin-film modules and BoS components

Analysis of lifetime costs especially of thin-film and concentrator PV and BoS components over the short term and for emerging cell/module technology over the longer term

١.٤ Socio-economic aspects and enabling research

Identifying and quantifying the non-technical (i.e. societal, economic and environmental) costs and benefits of PV

Addressing regulatory requirements and barriers to the use of PV on a large scale

Establishing the skills base that will be required by PV and associated industries in the period to ٢٠٣٠ and developing a plan for its provision

Developing schemes for improved awareness in the general public and targeted commercial sectors

The countries associated to FP٧ should use this SRA as a reference when developing or fine-tuning their national R&D programme(s). By interpreting the research priorities described here in their own national contexts (national R&D strengths, presence of industry), they can align their publicly-funded R&D with the SRA's recommendations, to the benefit of PV in Europe.

PV solar energy is a technology that can be used in many different products, ranging from very small stand-alone systems for rural use, to building-integrated grid-connected systems, and large power plants. PV will make a very large contribution to the global energy system in the long term and will be a key component of our future, green energy supply system. The rapid growth of the PV sector offers economic opportunities for Europe that must be seized now unless they are to be ceded to other regions of the world. The coming years will be decisive for the future role of the European PV industry.

٢ Introduction

٢.١ What is photovoltaic solar energy (PV)?

The direct conversion of sunlight into electricity is a very elegant process to generate environmentallyfriendly, renewable energy. This branch of science is known as "photovoltaics" or "PV".

PV technology is modular, operates silently and is therefore suited to a broad range of applications and can contribute substantially to our future energy needs. Although the basic principles of PV were discovered in the ١٩th century, it was not before the ١٩٥٠s and ١٩٦٠s that solar cells found practical use as electricity generators, a development that came about through early silicon semiconductor technology for electronic applications.

Today, a range of PV technologies are available on the market and under development in laboratories.

Complete PV systems consist of two elements: “modules” (also referred to as “panels”), which contain solar cells, and the “Balance-of-System” (“BoS”). The BoS mainly comprises electronic components, cabling, support structures and, if applicable, electricity storage or optics & sun trackers.

BoS costs also include the labor costs of installation.

٢.٢ Why a Strategic Research Agenda (SRA)?

Although reliable PV systems are commercially available and widely deployed, further development of PV technology is crucial to enabling PV to become a major source of electricity. The current price of PV systems is low enough for PV electricity to compete with the price of peak power in grid-connected applications and with alternatives like diesel generators in stand-alone applications, but cannot yet rival consumer or wholesale electricity prices. A major further reduction of turn-key system prices is therefore needed and fortunately possible. This was emphasised in the document A Vision for Photovoltaic Technology, published by the Photovoltaic Technology Research Advisory Council (PV TRAC) in ٢٠٠٥ and referred to frequently in this report [PVT ٢٠٠٥]. Further development is also required to enable the European PV industry to maintain and strengthen its position on the global market, which is highly competitive and characterised by rapid innovation.

Research and Development - “R&D” - is crucial for the advancement of PV. Performing joint research addressing well-chosen issues can play an important role in achieving the critical mass and effectiveness required to meet the sector’s ambitions for technology implementation and industry competitiveness. Therefore the PV Technology Platform has decided to produce a Strategic Research Agenda (SRA) to realise the Vision document referred to above. The SRA may be used as input for the definition of the ٧th Framework Programme of the EU (the main source of funding for EU joint research), but also to facilitate a further coordination of research programmes in and between Member States.

٢.٣ PV historic development, state-of-the-art and potential

PV modules and other system components have undergone an impressive transformation, becoming cheaper, greener and better performing.

This is evinced by the module and BoS price reductions shown in so-called “learning curves” (see A Vision for Photovoltaic Technology, mentioned above), by the increase of power conversion efficiencies and energy yields, by enhanced system availabilities, by drastically shortened “energy pay-back times” (the period needed for a system to amortise the energy required for its manufacture), and by a variety of other indicators. Nevertheless, PV technology has by no means demonstrated its full potential. Table I gives an indication of where PV was ٢٥ years ago, where it stands today and what it could realistically achieve over the next ٢٥-٥٠ years. The figures in the column “long term potential” are more uncertain than the others.

Table 1. Expected development of PV technology over the coming decades - figures are rounded and indicative, and should be interpreted with reference to the provisos listed below.

	1980	Today	2015/2020	2030	Long term potential
Typical turn-key system price (2007 €/W_p, excl. VAT)	>30	5	2.5/2.0	1	0.5
Typical electricity generation costs southern Europe (2007 €/kWh)	>2	0.30	0.15/0.12 (competitive with retail electricity)	0.06 (competitive with wholesale electricity)	0.03
Typical commercial flat-plate module efficiencies (see below)	up to 8%	up to 15%	up to 20%	up to 25%	up to 40%
Typical commercial concentrator module efficiencies (see below)	(~10%)	up to 25%	up to 30%	up to 40%	up to 60%
Typical system energy pay-back time southern Europe (years)	>10	2	1	0.5	0.25

"Flat plate" refers to standard modules for use under natural sunlight, "concentrator" refers to systems that concentrate sunlight (and, by necessity, track the sun across the sky).

Current turn-key system prices may vary from ~٤ to ~٨ €/Wp, depending on system type (roof-top add-on, building-integrated, ground-based,), size, country, and other factors. The figure of ٥ €/Wp, however, is considered representative. Similarly, prices in ٢٠١٥ may range between ~٢ and ~٤ €/Wp. All prices are expressed as constant ٢٠٠٧ values.

The conversion from turn-key system price to generation costs requires several assumptions. This report assumes:

An average performance ratio of ٧٥%, i.e. a system yield of ٧٥٠ kWh/kWp/yr at an insolation level of ١٠٠٠ kWh/m٢/yr. In southern Europe, where insolation is typically ١٧٠٠ kWh/m٢/yr, a performance ratio of ٧٥% translates into ١٢٧٥ kWh/kWp/yr

١% of the system’s price will be spent each year on operation & maintenance n that the system’s economic value depreciates to zero after ٢٥ years

A ٤% discount rate

٢.٤ The value of PV for Europe and the world

٢.٤.١ Energy and climate

The solar energy resource is larger than all other renewable energy resources [UND ٢٠٠٠] [WBG ٢٠٠٣]. In one ambitious scenario, PV covers ٢٠% of global electricity consumption by ٢٠٤٠. Already in ٢٠٢٠ PV may contribute to the reduction of CO٢-emissions by the equivalent of ٧٥ average-sized coal-fired power plants or ٤٥ million cars [EPI ٢٠٠٤]. Since PV is deployable within Europe, it can play an important role in improving the security of Europe's energy supply. Moreover, PV is very well suited to providing access to energy in rural areas, thus enabling improved healthcare and education and providing economic opportunities. It may bring electricity to hundreds of millions people in developing countries by ٢٠٢٠ to ٢٠٣٠.

٢.٤.٢ PV and the Lisbon Agenda

In ٢٠٠٠ the European Council adopted the "Lisbon strategy", the aim of which is, by ٢٠١٠, to make the EU "the most dynamic and competitive knowledge-based economy in the world, capable of sustainable economic growth with more and better jobs and greater social cohesion, and respect for the environment".

The European photovoltaic industry and research community's knowledge, diversity, creativity and enthusiasm are key factors in the creation of a competitive advantage. At the European Summit in Barcelona in ٢٠٠٢, European Heads of State and Government set themselves the goal of increasing Europe's overall level of investment in research to ٣% of GDP by ٢٠١٠, two thirds of which were to come from the private sector. The highly innovative and competitive PV sector in Europe contributes towards these goals. It is clear that it can only maintain and strengthen its position on the world market if continuous, substantial R&D investments are made.

٢.٤.٣ Economy and jobs

The global PV sector has grown by an average of ٢٥% per year over the past two decades and by almost ٥٠% per year over the past five years. This has happened because several countries have put in place successful market development policies. In Europe, these countries are Germany, Spain, Portugal, France, Italy, Greece and Belgium - perhaps soon to be joined by many more. Outside Europe, Japan, Korea and the USA provide good examples of well-developed or emerging markets.

A report from ٢٠٠٤ forecast that the photovoltaics sector stands a realistic chance of expanding from € ٥.٨ billion in ٢٠٠٤ to € ٢٥ billion in ٢٠١٠ with ٥.٣ GWp in annual sales [SPS ٢٠٠٤]. Within the last ٨ years, employment in the photovoltaics sector in Germany rose from approximately ١,٥٠٠ to ٣٠,٠٠٠. By ٢٠٠٥, ٦,٣٠٠ jobs had been created in Spain, bringing the European total to approximately ٤٠,٠٠٠ (data from German industry associations and IEA [BSW ٢٠٠٦], [IEA ٢٠٠٥]). The sector needs a diverse and qualified workforce ranging from technicians close to the customers who install and maintain the PV systems to expert semiconductor specialists working in high-tech solar cell factories. The photovoltaic industry has the potential to create more than ٢٠٠,٠٠٠ jobs in the European Union by ٢٠٢٠ and ten times this number worldwide. Although the labour intensity will decrease with decreasing system prices, the rapid market growth will guarantee a strong increase in the number of jobs in Europe.

٢.٤.٣.١ International competition

Europe’s photovoltaic industry competes with companies from Asia, the USA and other parts of the world. Two of these countries have instituted programmes to support their domestic PV industry - Japan and China. The effectiveness of the programme sponsored by Japan’s Ministry of Economy, Trade and Industry, METI, is already apparent. Due to long term planning, support schemes, investment security, and a substantial domestic market, the Japanese PV industry has around ٥٠% of the world market share in PV products.

China is the second country with an industrial strategy geared towards building up a highly competitive PV industry. China wants to cover the whole value chain from silicon feedstock to complete systems. The fruits of this relatively new strategy are already visible. Chinese cell and module manufacturers are rapidly establishing a significant share of the world market and their production capacity increases are unrivalled.

If Europe does not react to this challenge, there is the danger that PV production will move to China, in common with many other manufacturing technologies. So far, Europe still has a competitive edge due to the excellent knowledge base of its researchers and engineers. However, without steady and reliable R&D funding and support from the public purse, this advantage could be eroded in a short time. More support for innovation and clearer long-term strategies are needed for the European PV industry to continue to invest in Europe and to ensure that European companies increase their market shares and become world leaders.

٢.٤.٣.٢ PV for development and poverty reduction

The Plan of Implementation of the United Nations' World Summit for Sustainable Development, which took place in Johannesburg in August ٢٠٠٢ contains the commitment from the UN's Member States to "improve access to reliable, affordable, economically viable, socially acceptable and environmentally sound energy services and resources, taking into account national specificities and circumstances, through various means, such as enhanced rural electrification and decentralised energy systems, increased use of renewables, cleaner liquid and gaseous fuels and enhanced energy efficiency" [WSS ٢٠٠٢]. At the same time, the European Union announced a $٧٠٠ million partnership initiative on (renewable) energy and the United States announced that it would invest up to $٤٣ million in ٢٠٠٣.

The International Conference for Renewable Energies followed up the UN's conference in June ٢٠٠٤. It yielded the International Action Programme, which includes some ٢٠٠ specific actions and voluntary commitments for developing renewable energy, pledged by a large number of governments, international organisations and stakeholders from civil society, the private sector and other stakeholder groups. Photovoltaic off-grid systems are the preferred option for rural electrification in developing countries, where they are crucial in providing energy for light, drinking water, refrigeration and communication. More than ١ billion people in the world do not have access to electricity.

PV is a cost-effective way of meeting the rapidly expanding electricity demand of developing countries, while minimising the environmental impact of this demand. Delivering affordable modern energy services for health, education and social and economic development is central to international aid objectives.

As a clean, free-fuel (except for sunlight) energy source, PV has the potential to create economic and political stability, with clear implications for improved international security. It should also be emphasised that robust demand from less developed countries could make an important contribution to reducing the costs of PV technology through economies of scale from increased cell and module production. The goal for European industry is to capture a ٤٠% market share of the annual market for rural use by ٢٠١٠ and to keep this level thereafter.

٢.٥ Targets and drivers for PV development

٢.٥.١ What are the PV implementation targets?

In ١٩٩٧, the European Commission envisaged ٣ GWp PV being installed across Europe by ٢٠١٠ [COM ١٩٩٧]. It is now clear that as a result of successful market incentives in Germany and other countries the capacity by that date will probably be more than ٥ GWp. For the longer term, [PVT ٢٠٠٥] offers an “ambitious, though realistic” target for ٢٠٠ GWp installed in the EU by ٢٠٣٠ (of an estimated ١٠٠٠ GWp worldwide). In relation to the new EU renewable energy targets and the increased overall sense of urgency it has been stated recently, though, that the rapid development of the PV industry may give a considerable upward potential for the ٢٠٠ GWp figure if adequate policy measures are implemented and R&D support is strengthened.

Japan aims at ٥ GWp by ٢٠١٠, and has developed roadmaps for ٥٠-٢٠٠ GWp of PV capacity by ٢٠٣٠ [NED ٢٠٠٤]. The Korean government has set a target of ١.٣ GWp by ٢٠١٢.

Few other countries have specific targets for PV implementation. Usually PV is an unspecified part of the (renewable) energy portfolio.

٢.٥.٢ Conditions for PV to meet the targets

Very large-scale deployment of PV is only feasible if PV electricity generation costs are drastically reduced. However, because of the modular nature of PV, the possibility to generate at the point-of-use, and the specific generation profile (overlap with peak electricity demand), PV can make use of ”lead markets” on its way to eventually becoming as cheap as wholesale electricity. In particular PV may compete with peak power prices and consumer prices in the short and medium term. The corresponding PV system price targets are therefore very important for the rapid deployment of PV. Ambitious targets are also crucial for the global competitive position of the European PV industry sector.

The evolution of turn-key PV system prices outlined in A Vision for Photovoltaic Technology (Figure ١) provides an excellent starting point to define underlying cost targets to be addressed in this SRA. It is noted that research and technology transfer to industry directly influences manufacturing and installation costs (as well as some other parameters), but not directly turn-key prices. The latter are also determined by market forces. Cost reduction targets are nevertheless essential to enable price reduction.

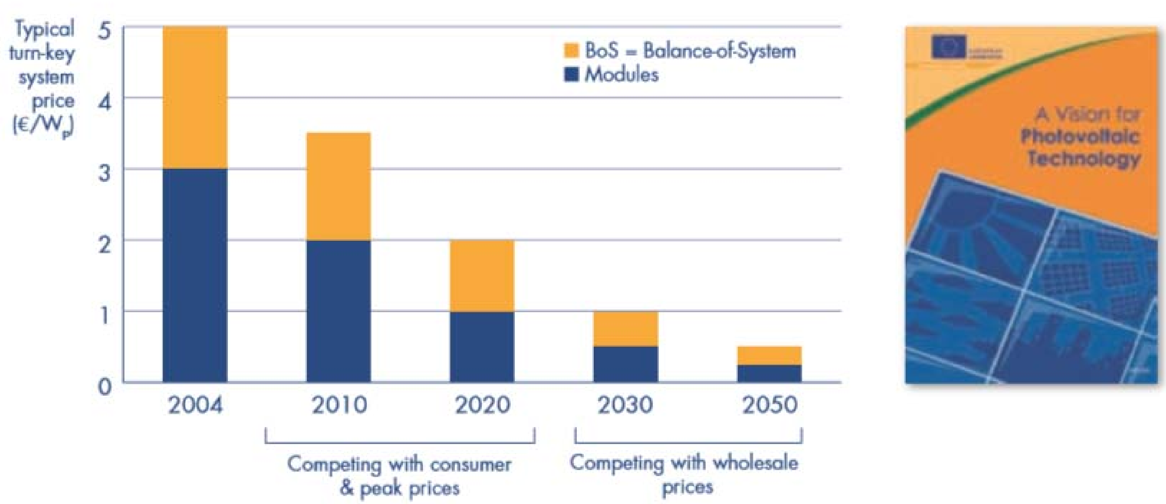


Figure 1. Possible evolution of turn-key PV system prices (adapted from A Vision for Photovoltaic Technology)

The SRA refers to time-scales using the following definitions:

٢٠٠٨ ~ ٢٠١٣: short term

٢٠١٣ ~ ٢٠٢٠: medium term

٢٠٢٠ ~ ٢٠٣٠ and beyond: long term

The year ٢٠١٣ has been chosen because it coincides with the end of the European Commission's current programme for funding research, 'FP٧'. The start of 'short term' does not coincide with the start of FP٧ (٢٠٠٧) because no significant results are expected from FP٧ in its first year. The convention used in this report is to refer research priorities to the time horizons in which they are first expected to be used in commercial product, not to the year by which widespread use is expected.

A technology is said to meet a cost target if pilot-scale production at that cost has been achieved. This implies the technology will one or two years later be ready for commercial production at that cost.

٢.٥.٣ Drivers and enablers for PV development

Generally, the cost and performance of PV technology is the focus of research effort, but the importance of other drivers should be emphasised.

First of all R&D also needs to address the value of PV electricity. For example, if electricity from PV could be supplied at times when electricity demand is greatest rather than merely when sunlight is most available, its value would be higher. This may imply a need for low-cost, small storage systems. Note that PV supply and electricity demand also match to a certain extent without storage, especially in the case of peak demand due to air conditioning and cooling.

Secondly, the lifetime of system components must be considered. High technical lifetimes not only help to reach cost targets, it also increase the overall energy produced and eases the integration of PV in buildings.

Thirdly, it is essential that energy and materials consumption in manufacturing and installation be addressed. Further shortening of the energy pay-back time of systems will add to the advantages of PV as an energy source and, in the longer term, its ability to avoid carbon dioxide emissions. Avoiding the use of scarce or hazardous materials, or if that is not possible, closing material-use cycles, is an important topic with great R&D challenges.

Finally, the ability to combine PV components and systems and integrate them with building components may be significantly improved. This requires standardisation and harmonisation, but also flexibility in system design, and should be accomplished without additional engineering (costs).

In addition to the technical issues described above, the document addresses socio-economic aspects related to the large-scale implementation of PV.

In summary, this SRA identifies and addresses the following drivers for PV development:

Electricity generation costs and value

- turn-key investment costs (price):
  - modules
  - BoS
  - system engineering
- operation & maintenance costs (& planned replacement if applicable) / technical lifetime
- value:
  - e.g. possibilities for supply-on-demand or at peak prices
- energy yield
- (factors out of scope of this SRA: interest rate, economic lifetime,…)

Environmental quality

- energy pay-back time:
  - modules
  - BoS
- substitution of hazardous materials
- options for recycling

Integration

- method and ease of mounting, cabling, etc. (also for maintenance and repair)
- flexibility / modularity
- aesthetics and appearance
- lifetime

Socio-economic aspects

- public and political awareness
- user acceptance
- training and education
- financing

۳ Governing principles of the SRA

Short-term research should be fully dedicated to the competitiveness of the EU industry. The coming decade is expected to be decisive for the future prospects of the EU PV industry. The global PV sector will grow to maturity and achieve multi-billion dollar turn-overs. Competition will be fierce. Rapid innovation and high production volumes are crucial to establish leadership.

No exclusivity

PV comes and will come in different formats. The SRA does not exclude technologies but sets overall targets that each PV format must reach and describes the research priorities for each format in order for it to succeed in meeting the targets.

There is a need for public money to fund short-, medium- and long-term research into all parts of the value chain(s), as well as research into socio-economic issues. Since drastic cost reductions are needed for all elements of the PV system, research should address all parts of the value chain, from raw materials up to the complete system, and even beyond. In addition, public funding agencies should make a strategic top-down decision on how to allocate funding between short-, medium- and long-term research. Industry will push for short-term research to be the main beneficiary of funding and as the PV industry grows, this pressure may become stronger. Governments must, however, look ahead to the medium and long term and set aside fixed budgets for research applicable to these time-frames. This report recommends that the combined research spending of the public and private sector should be distributed between topics with commercial relevance in the short, medium and long term in the typical ratio ٦:٣:١ in the near term, moving to the ratio ١٠:٥:١ as private sector funding increases. See Chapter ٥ for details.

Based on a detailed analysis of cost reduction potentials, the working group decided that the same cost targets shall be used for all flat-plate PV module technologies considered: ٠.٨-١.٠ €/Wp for technology ready by ٢٠١٣ and implemented in large-scale production in ٢٠١٥, ٠.٦٠-٠.٧٥ €/Wp in ٢٠٢٠, and ٠.٣-٠.٤ €/Wp in ٢٠٣٠. The targets are expressed as a range in order to reflect the efficiencies of different types of module. To meet the overall, cross-technology cost targets, lower efficiency modules need to be cheaper than higher efficiency modules, due to the area-related component of the BoS costs. These targets should not be interpreted as predictions. It is possible that some technologies will even exceed them. The efficiency targets quoted later in the SRA for each technology and are to be considered as performance targets that should be met in order to meet the cost target. System costs and prices, it should be noted, are dependent on the specific application that the system is put to. Therefore the costs and prices mentioned in the SRA are only approximate.

The Balance-of-System (BoS) costs are strongly dependent on, among other factors, the type of system (e.g. roof-top, building-integrated, ground-based), the efficiency of the modules used, and the country where it is sited. This makes it difficult to formulate general targets. Indicative targets for the BoS costs for roof-top systems are: ٠.٩-١.١ €/Wp in ٢٠١٣, ٠.٧٥-٠.٩ €/Wp in ٢٠٢٠, and under ٠.٥ €/Wp in ٢٠٣٠. The ranges in system cost targets mainly correspond to the range in module efficiencies mentioned in the previous paragraph, reflecting the fact that part of the BoS cost is system area-related and thus affected by module efficiency (a given system power requires a smaller area when using higher efficiency modules).

Possible differences in BoS cost structure and figures between EU Member States are not taken into account here.

For concentrator systems target costs it is not meaningful to distinguish between modules and BoS. Therefore indicative targets for the turn-key cost (not price) of full systems have been identified: ١.٢-١.٩ €/Wp in ٢٠١٣, ٠.٨-١.٢ €/Wp in ٢٠٢٠ and ٠.٥-٠.٨ €/Wp in ٢٠٣٠. Considerable uncertainty exists for these numbers because, with little industrial production at present, extrapolation from what does exist carries high uncertainty. Furthermore, no clear definition so far exists of the watt peak (Wp) power rating of concentrator technology, because, unlike other technologies, they function only under direct sunlight. Some attempts to define a Wp rating have, however, been made and are the basis for the cost targets above.

term)

٤.١ Cell & module technologies

PV modules are the basic building blocks of flat-plate PV systems. Modules consist of solar cells, fabricated on wafers or from thin active layers on an inert, low cost substrate. For the end-user, the nature of the cell technology used is seldom their main concern. The parameters they find more important are the price per watt-peak of module, the energy yield per watt-peak under field conditions, the module's efficiency, its size and weight, flexibility or rigidity, and appearance. Customers will also be interested in the retailer's provisions for taking back and recycling the modules at the end of their lives. On the other hand, for the R&D community, sound understanding of different cell and module technologies is crucial in defining the work to achieve cost reduction, performance enhancement and an improved environmental profile. Different technologies require their own research and development activities. The categories of technology chosen for the SRA are:

١. Wafer-based crystalline silicon;

٢. Existing thin-film technologies;

٣. Emerging and novel technologies (including "boosters" to technologies in the first and second category)

The R&D issues surrounding concentrator systems need to be addressed in a different, more integrated manner, so they are covered in a separate subchapter, ٤.٢. Research conducted under the "Emerging and novel technologies" category is also relevant for concentrator systems.

In the following paragraphs the R&D needs of the four technology categories are analysed in detail. The technology categories have a number of R&D issues in common, which are briefly summarised here:

٤.١.١ Efficiency, energy yield, stability and lifetime

Research aims to optimise combinations of these parameters rather that one parameter at the expense of another. This implies careful analysis of the costs and benefits of individual technological improvements. Since research is primarily aimed at reducing the cost of electricity generation, it is important not to focus only on initial costs (€/Wp), but also on the system's energy yield (kWh/Wp) over its economic or technical lifetime.

٤.١.٢ High productivity manufacturing, including in-process monitoring & control

Throughput and yield are important parameters in low-cost manufacturing and are essential to achieving the cost targets. In-process monitoring and control are crucial tools for increasing product quality and yield.

٤.١.٣ Environmental sustainability

The energy and material requirement of manufacturing as well as recyclability are important parameters in the overall environmental quality of the product. Shortening still further the energy pay-back time of.

modules (table ١), designing products in a way that makes them readily recyclable and, where practical, avoiding of the use of hazardous materials are the most important issues to be addressed here.

٤.١.٤ Integration

As discussed in more detail in the chapter on BoS, standardisation and harmonisation of specifications will help bring down the costs of PV. Efforts to standardise module specifications should also be made and may make installation easier. Finally, the appearance of modules (and systems) will grow in importance as they become a more common sight in the built environment.

٤.٢ Wafer-based crystalline silicon

٤.٢.١ Introduction

Wafer-based crystalline silicon has dominated the photovoltaic industry since the dawn of the solar PV era. It is widely available, has a convincing track-record in reliability and its physical characteristsics are well understood, in part thanks to its use in the half-century-old microelectronics industry. A learning curve for the progress in silicon wafer-based technology can be drawn that spans three decades. It shows that the price of the technology has decreased by ٢٠% for each doubling of cumulative installed capacity. Two driving forces are behind this process: market size and technology improvement. Such progress was not made by chance but is the combined result of market-stimulation measures and research, development and demonstration activities with both private and public support.

The total PV market has increased by an order of magnitude in the last decade, growing by almost ٥٠% per year in the last five years, with crystalline silicon accounting for more than ٩٠% of the total volume.

Crystalline silicon modules are manufactured in six-steps: (i) silicon -production, (ii) -purification, (iii) -crystal growth, (iv) wafer slicing, (v) cell fabrication and (vi) module assembly. Although considerable progress has already been made in each step, they may all be significantly further improved.

For example, wafers have decreased in thickness from ٤٠٠ µm in ١٩٩٠ to ٢٠٠ µm in ٢٠٠٦ and have increased in area from ١٠٠ cm٢ to ٢٤٠ cm٢; modules have increased in efficiency from about ١٠% in ١٩٩٠ to typically ١٣ % today, with the best performers above ١٧%; and manufacturing facilities have increased from the annual outputs of typically ١-٥ MWp in ١٩٩٠ to hundreds of MWp for today’s largest factories. Plans for GWp-scale factories have been announced.

Three main routes to cost saving have been followed in recent years and need to be followed further and faster: reduction in material consumption, increase in device efficiency and advanced, high-throughput manufacturing. Other important measures that should receive attention include reducing embedded energy content (and hence the energy pay-back-time), the environmental friendliness of PV systems over their life cycle, the definition of accepted standards for crystalline silicon products and advanced manufacturing practices such as process automation and advanced process control.

Crystalline silicon is a technology with the ability to continue to reduce its cost at its historic rate. Direct production costs for crystalline silicon modules are expected to be around ١ €/Wp in ٢٠١٣, under ٠.٧٥ €/Wp in ٢٠٢٠ and lower in the long term. This will happen if R&D effort is directed towards the issues of greatest strategic concern.

٤.٢.٢ Materials and components

Purified silicon (polysilicon) is the basic ingredient of crystalline silicon modules. It is melted and solidified using a variety of techniques to produce ingots or ribbons with different degrees of crystal perfection. The ingots are shaped into bricks and sliced into thin wafers by wire-sawing, or by laser if the aim is to use the wafers to make ribbons. Wafers and ribbons are processed into solar cells and interconnected in weather-proof packages designed to last for at least ٢٥ years. The processes in the manufacturing chain have improved significantly during recent years but can improve yet further. For the past few years the availability of polysilicon feedstock has been a critical issue for the rapidly growing PV industry. The tight supply has caused very high polysilicon spot market prices and has limited production expansion for part of the industry. On the other hand, it has triggered rapid innovation in wafer production and cell manufacturing, as evinced by the lower silicon consumption per Wp of module power produced. Silicon usage is currently ١٠ g/Wp, whereas it was typically ١٣ g/Wp just a few years ago.

The development of new, lower cost and less energy-intensive techniques for silicon feedstock preparation is underway. This feedstock is expected to come at prices in the range ١٠-٢٠ €/kg (now ٣٠-٥٠ €/kg) and will thus be a key enabler for future PV growth and cost reduction. As well as having to contend with high feedstock prices, cell manufacturers are faced with the problem that they lose ٥٠% or more of the polysilicon starting material during the manufacturing process, even after recycling. To improve casting and wafering, it is necessary to reduce waste during polysilicon crystallisation, recycle saw dust and other silicon off-cuts, and improve material handling in the production process through automation. It should be possible to reach polysilicon consumption below ٢ g/Wp in the long term. The targets for the short and medium term are achievable even at moderate to high feedstock prices. For wafer equivalent technologies, the challenge is to develop high-throughput low-cost silicon film deposition techniques with suitable low-cost substrates.

Module assembly is also material-intensive. The assembly must protect the cells from the outdoor environment for a minimum, typically, of ٢٥ years while allowing the cell to function as efficiently as possible. The current standard design, using rigid glass-polymer encapsulation in an aluminium frame, fulfils these basic requirements, but represents about ٣٠% of the overall module cost, contains a lot of embedded energy (increasing the energy pay-back time of the module) and is a challenge to manufacture on automated lines even at current wafer thicknesses.

New cheaper, more flexible, highly durable encapsulation materials with improved optical properties are expected to be developed. They may also be better suited for high-throughput manufacturing than the materials currently used.

New materials and techniques for connections between cells need to be developed to improve the automated assembly of very thin wafers. Metal contact cell geometries may depart significantly from the traditionally H shaped front-rear structure. The use of back-contacted cells may favour automation and simplify processes by reducing the complexity of cell interconnection. Simpler schemes for electrical interconnection, due in part to improved cell design and to newly developed metallisation techniques, may eliminate discrete soldering steps because the interconnection scheme could be embedded in encapsulation sheets.

Future, very large-scale manufacturing may require alternatives to be found for scarce chemical elements currently used in module manufacture, such as silver, which is consumed at an average of ٨٠-٩٠ mg/Wp, or some ١٣٠ tonnes/year.

Table 2. Research priorities for wafer silicon materials - time horizons for first expected application of research results in (pilot) manufacturing and products

Materials	2008 - 2013	2013 - 2020	2020 - 2030 and beyond
Industry manufacturing aspects	■ **Polysilicon targets** Consumption 5 g/W_p Cost 15-25 €/kg (dependent on quality) Wafer thickness <150 µm ■ **Critical issues** Si availability	■ **Polysilicon targets** Consumption <3 g/W_p Cost 13-20 €/kg (dependent on quality) Wafer thickness <120 µm	■ **Polysilicon targets** Consumption <2 g/W_p Cost < 10-15 €/kg (dependent on quality) Wafer thickness <100 µm
Applied/advanced technology aspects	■ New Si feedstock ■ Improved crystal growth ■ Reusable crucibles which introduce only small amounts of impurities into the silicon ■ Low kerf loss sawing ■ Fracture mechanics of thin wafers ■ Metal pastes suited for thin wafers ■ Low-cost encapsulants ■ New frames and supporting structures ■ Recycling ■ Low impact manufacturing ■ Safe processes	■ New Si feedstock ■ Low defect (high electronic quality) silicon wafers ■ Improved wafering ■ Wafer equivalents ■ Improved encapsulants ■ Avoidance of hazardous materials ■ Safe processes ■ Conductive adhesives or other solder free solutions for module interconnection	■ New Si feedstock ■ Low defect (high electronic quality) silicon wafers ■ Improved wafering ■ Wafer equivalents ■ New encapsulants ■ Safe processes
Basic research and fundamentals	■ Defect characterisation and control in silicon	■ Defect control in silicon ■ New feedstock	■ Wafer equivalent technologies

٤.٢.٣ Performance and devices

Cell and module efficiency directly impact on the overall €/Wp cost (and price) of a PV module and have historically been a focus for technological development. Increasing the efficiency of the solar cells and the power density of the modules, together with the reduction of the specific consumption of silicon, are the main paths to cost reduction. An increase of ١% in efficiency alone is able to reduce the costs per Wp by ٥-٧%.

Small cells with efficiency values up to ٢٤.٧% have been produced in expensive clean room facilities with vacuum technologies used for the deposition of metal contacts.

Only three of these high efficiency cell processes have so far been demonstrated at production scale, in non-clean-room manufacturing environments. All three use monocrystalline silicon, whilst the majority of commercial cells use a low-cost screen-printing process on multicrystalline silicon wafers.

Commercial module efficiency values (defining efficiency on the basis of the total outer dimensions) are in the range ١٢-١٤% for screen-printed cells and ١٥-١٧.٥% for the best performing cells. Device designs capable of achieving module efficiencies of over ١٨% for multicrystalline silicon, and over ٢٠% for monocrystalline silicon are expected to be achieved at production scale in the short to medium term. Promising candidates for such developments are heterojunction cells of crystalline silicon wafers with doped amorphous silicon layers and all-back-contacted cells on both mono- and multicrystalline substrates.

In the long term silicon technology is expected to continue to play an important role in the PV sector. However, there is uncertainty regarding the precise module efficiency, silicon consumption, cell and module architecture and nature of the cell raw materials after ٢٠٢٠, when the market size is expected to be around several tens of GWp/year. It is likely that silicon technology will by this time incorporate technologies covered under the heading "Emerging and novel PV technologies" that are currently only at very early stages of development. Also, the separate steps for cell fabrication and module assembly may become one single integrated production step with thinner wafers or wafer-equivalent approaches. In the long term, it is expected that module efficiency will exceed the current laboratory record. This may only be possible by incorporating technologies at the periphery of the device such as up- or downconverters. For this reason, basic and applied research on advanced concepts and materials should be included in crystalline silicon research programmes.

Table 3. Research priorities for wafer silicon cells & modules - time horizons for first expected application of research results in (pilot) manufacturing and products

Cells & Modules	2008 - 2013	2013 - 2020	2020 - 2030 and beyond
Industry manufacturing aspects	■ Module efficiency >17% ■ mono & multi/ribbon >15% ■ In-line high-yield processing ■ Standardisation ■ Safe processing and products	■ Module efficiency >20% ■ mono & multi/ribbon >18% ■ High speed processes ■ Frameless structure ■ Safe processing and products	■ Module efficiency > 25% ■ Energy pay-back time < 6 months ■ Safe processing and products
Applied/ advanced technology aspects	■ Back-contact cell structures ■ New technologies for electrical contacts ■ Heterojunctions for emitters and passivation ■ Contact/surface passivation ■ Roll-to-roll/ automatic module manufacturing ■ Low cost framing/ mounting	■ Lifetimes > 35 years ■ Metal contacts (processes, schemes and materials) ■ mproved device structures and interconnection schemes for modules ■ Metal contacts (processes, schemes and materials)	■ Improved device structures integrating cells/modules
Basic research and fundamentals	■ Epitaxial Si films on low cost wafers ■ Low recombination contacts ■ New device structures ■ New passivation techniques	■ Epitaxial Si films on low cost wafers ■ Recrystallised Si on ceramics ■ Low recombination contacts ■ New device structures	■ New device structures including up/down converters and other novel concepts

٤.٢.٤ Manufacturing and installation

Material consumption must be reduced to avoid scarcity, reduce costs and reduce the energy pay-back time and other environmental impacts associated with PV module production.

Investment costs for manufacturing plant represent an inevitable part of the cost breakdown of crystalline modules but should reduce with manufacturing equipment standardisation. It is expected that specific plant investment costs will reduce from ١ €/Wp or more in current factories to less than ٠.٥ €/Wp in the long term.

The size of factories is also important for reducing costs sufficiently to meet to the overall targets. It is expected that the current plant capacity of typically ١٠٠ MWp/year plant will grow to ٥٠٠-١٠٠٠ MWp/year in the short term and probably an order of magnitude higher in the long term. It is likely that in each parallel production line in these plants multiple processes will be performed concurrently. Batch processes will tend to disappear. Module assembly, for instance, will likely become an automated sequence in which sheets of encapsulating materials will be applied on reels and spools. Reaching such production scale will require great effort.

The SRA emphasises cost reduction but attention should also be given to product and process safety and the environmental impact of PV. In order that the large-scale use and production of PV finds popular support, safety must be designed into future products. Materials, manufacturing and installation must be safe and environmentally friendly. Recycling chemicals and system components may result in cost savings and play an important role in increasing the public’s acceptance of PV.

٤.٢.٥ Summary

In conclusion, research into crystalline silicon photovoltaic technology will primarily have to address the following subjects:

Reducing the specific consumption of silicon and materials in the final module

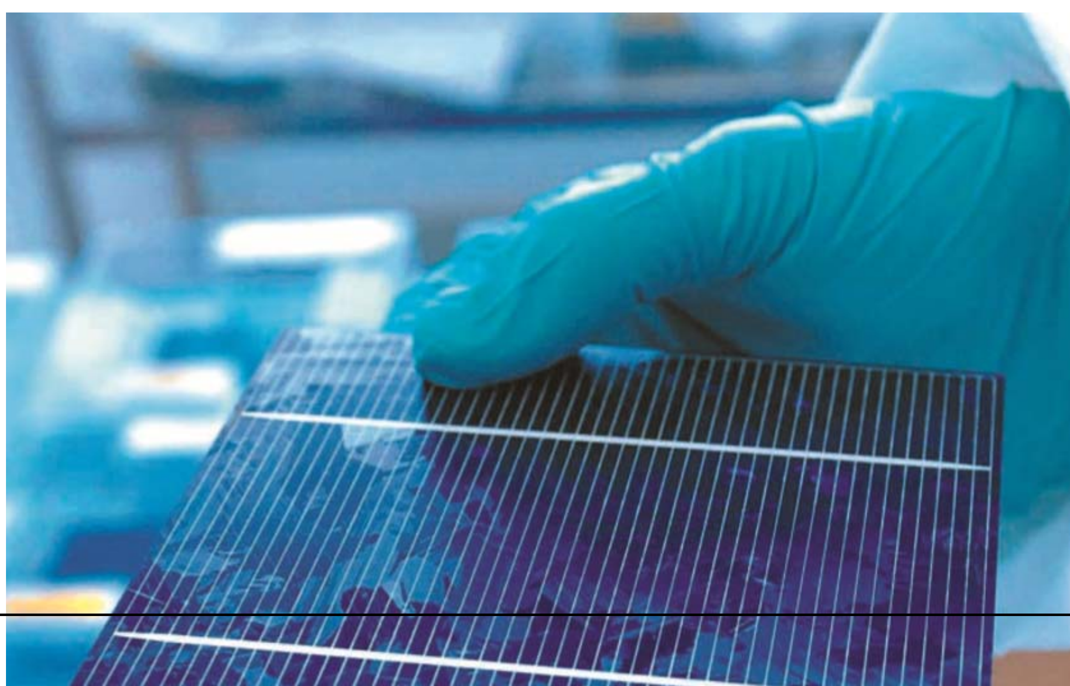
New and improved silicon feedstock and wafer (or wafer equivalent) manufacturing technologies, that are cost-effective and of high quality

Increasing the efficiency of cells and modules and, in the longer-term, using new and integrated concepts

New and improved materials for all parts of the manufacturing chain, including encapsulation

High-throughput, high-yield, integrated industrial processing

Finding safe processing techniques with lower environmental impac



٤.٣ Existing thin-film technologies

٤.٣.١ Introduction

Thin-film solar cells are deposited directly on large area substrates, such as glass panels (square metre-sized and bigger) or foils (several hundred meters long). Thin-film PV has an inherent low-cost potential because its manufacture requires only a small amount of active (high cost) materials and is suited to fully integrated processing and high throughputs. There are three major inorganic thin-film technologies, all of which have been have been manufactured at pilot scale (١-٢ MWp) and are being or have been transferred to high volume production (١٠ MWp to over ٥٠ MWp). The three technologies are amorphous/microcrystalline silicon (TFSi - ١٣% efficiency), and the polycrystalline semiconductors CdTe (١٦.٥% efficiency) and CIGSS (an abbreviation of Cu(In,Ga)(S,Se)٢ - ١٩.٥% efficiency). They share a number of common features. Each technology requires only small amounts of semiconductor material: the film thickness is typically ١/١٠٠٠ mm (١ µm). They have all shown long-term stability under outdoor conditions. They require minimal energy inputs: the energy pay-back time of thin-film modules is already around ١.٥ years in central Europe and ١ year in southern Europe and could reach ٣ months in the future.

At present, the market share of thin-film PV within total PV production is below ١٠%, but might grow to ٢٠% by ٢٠١٠ and beyond ٣٠% in the long term. The availability of large-area deposition equipment and process technology, as well as the experience available from within the architectural glass industry and the flat panel display industry, offer significant opportunities for high-volume and low-cost manufacturing. The monolithic series interconnection of cells to produce modules simplifies assembly in comparison with wafer-based technologies. Flexible lightweight modules can also be produced using thin polymer or metal substrates and roll-coating techniques.

Thin-film technology thus has a great potential for cost reduction.

The challenges facing thin films are to be found mainly in the realm of up-scaling production capacity. The global production capacity of thin films is expected to reach ١ GWp/year in ٢٠١٠ and ٢ GWp/ year in ٢٠١٢. It is being installed mainly in Japan, the USA and Europe. Europe already has excellent thin-film R&D infrastructure and a number of thin-film factories.

Taking account of the increase in production facility sizes, improvements in module efficiency and differences in the calculation methods used by the PV industry, in ٢٠١٠, the total manufacturing costs will most likely be in the range of ١-١.٥ €/Wp. Further cost reduction to below ٠.٧٥ €/Wp in ٢٠٢٠ and ٠.٥ €/Wp by ٢٠٣٠ can be reached. Little difference in cost between the different thin-film technologies is expected in the long term.

In summary, low cost and high-volume production of thin-film PV modules is achievable and should enable costs to reach ٠.٥ €/Wp in the long term if intensive R&D work is carried out.

٤.٣.٢ Common features of all existing thin-film technologies

As thin-film PV modules have broadly similar structures and the key steps in their production steps resemble one another, R&D effort directed at one technology could be applied to another, increasing its usefulness. This section analyses aspects common to the three thin-film technologies, with requirements specific to each one given in later sections.

٤.٣.٢.١ Manufacturing and product issues

Production equipment plays a crucial role in cost reduction. Standard equipment needs to be developed in conjunction with well-defined processes to achieve higher throughputs and yields. Equipment manufacturers will play a vital role in this development and knowledge gained in relevant industries outside PV should be exploited. Deposition equipment from the flat panel display industry is an example. Another is sputtering equipment originally developed for coating glass but which can also be used for the deposition of transparent and metallic contacts on thin-film PV technologies. A final example is the use of roll-to-roll coating equipment, developed for the packaging industry, to manufacture flexible modules on foils. Productivity parameters such as process yield, uptime and throughput have to be improved by optimising existing processes and developing new processes. Quality assurance procedures and in-line monitoring techniques need to be developed further to improve production yield and module efficiency. The integration and automation of production and processing steps into one line should also help reduce production costs.

Standardising substrates for modules and other common elements for the different technologies will help reduce the capital cost of production plant. Jointly pursuing the standardisation of equipment and of building construction elements is necessary and will have positive effects on overall system costs.

Low-cost flexible modules on alternative substrates offer further potential for cost reduction and enable new module designs. The equipment and processes for the manufacture of such thin-film products on polymer and metal films have to be developed and improved to take full advantage of roll-to-roll production technologies and monolithic interconnection.

Low-cost module encapsulation (also known as “packaging”) needs to be developed. Packaging includes the backsheet, bypass diodes, frames and laminating foils. In addition new module concepts are required that for example allow higher system voltages or that better tolerate shading.

Common R&D needs for all thin films are summarised as follows:

Standardised product sizes to make the handling of products easier for vacuum deposition equipment

Standardised deposition techniques employed by the equipment Lower cost transparent electrode materials with better optical and electrical properties, cycle times and yields and finding ways to include them in manufacture

Patterning processes for monolithic integration that reduce electrical and area loss and improve cycle time and yield (e.g. laser scribing)

Polymer or alternative sealing solutions with longer lifetimes that are suitable for higher throughput manufacturing

New and low-cost packaging of the active layers: barrier coatings, polymer foil to reduce material cost and to enhance productivity, in-line processes for packaging

Concepts for easier mounting and interconnection of modules

BIPV module designs that look more attractive and perform optimally; while being adapted to current practice in the construction sector

Quality control methods and inline quality assurance

Supply chain logistics (primarily outside the factory) for large-scale productio

٤.٣.٢.٢ Efficiency and material issues

The fundamental properties of inorganic thin films (with the exception of amorphous Si) are only partially understood. There is less accumulated knowledge of how to process thin films compared with the situation for crystalline Si. Fundamental research is needed to improve device quality and module efficiency and to develop a better understanding of the relationship between the deposition processes and parameters, the electrical and optical properties of the deposited materials, and the device properties that result.

Better fundamental understanding of the electronic properties of the three families of materials and their interfaces is needed

Improvement of the quality and stability of transparent conductive oxide (TCO) layers is required, while at the same time reducing the TCO's cost

More advanced methods for optical confinement are required so that active layers can be thinner and cost less.

Advanced optical and electronic modelling of heterostructures is required and technologies for the implementation of these methods needs further development

High-efficiency concepts using materials with different band gaps for wide spectrum absorption should be developed. Alternative absorber materials should be explored

Novel high-efficiency concepts are required, including, with a view to the long-term, spectrum conversion

٤.٣.٢.٣ Performance

Although thin-film modules have been in use for over ٢٥ years, field experience of today's technology is limited. The material modifications and continuous process optimisations in thin-film module production are changing the characteristics and performance of devices. Although no fundamental problems have so far arisen, there is a need for accelerated ageing tests of new thin-film modules to assess their designs, requiring a better basic understanding of their ageing mechanisms. The development of standard procedures for measuring the performance and energy yield of thin-film modules is also important.

٤.٣.٢.٤ Recycling and energy pay-back time

As with any new product, dedicated recycling processes need to be developed both for production waste and modules that have reached the end of their lives. The processes should minimise the generation of toxic waste and allow high value metals and module elements to be recuperated.

Table 4. Research priorities for thin film PV - common aspects - time horizons for first expected application of research results in (pilot) manufacturing and products

	2008 - 2013	2013 - 2020	2020 - 2030 and beyond
Industry manufacturing aspects	■ Optimisation of production lines with respect to productivity and product quality. ■ Standardisation of equipment.	■ Assessment of advanced materials and processes. ■ Integration of advanced quality control. ■ Piloting roll-to-roll-concepts	■ Proof of concepts for modified/new deposition methods, and combinations of processes and materials.
Applied/advanced technology and installation (incl. O&M) aspects	■ Increase of module efficiency by 3% (absolute). ■ Improvement of deposition and patterning components and concepts. ■ Development of quality control methods.	■ Increase of module efficiency by a further 2% (absolute). ■ Trials of other deposition methods and substrate/sealing concepts. ■ Demonstration of low-material-cost manufacture.	■ Increase of module efficiency by a further 2% (absolute).
Basic research / fundamental science	■ Basic understanding of the physics and chemistry of TF materials.	■ Optical confinement. ■ Development of other concepts for deposition, patterning, sealing. ■ Diversification away from flat glass as a substrate	■ Multi-junctions. ■ Spectrum conversion concepts. ■ Technology merging

٤.٣.٣ Thin-film silicon (TFSi)

TFSi modules are based on amorphous silicon (a-Si) or silicon-germanium (a-SiGe) alloys, microcrystalline Si (µc-Si), and on processes involving the large-scale recrystallisation of Si. Following two decades of slow growth, the TFSi industry is reviving, thanks to new technologies like µc-Si and the development of large-area production. Major companies in the US and Japan are offering high quality products manufactured using equipment and processes that they have developed with substantial government support. The TFSi sector benefits directly from the advances that have been made in the flat panel display sector with plasma enhanced chemical vapour deposition (PECVD), which can be applied to the deposition of a-Si on large areas. Several EU companies have recently announced the start of mass production using such equipment. The presence in Europe of a competent pool of module producers, equipment manufacturers and research institutes creates a favourable environment for the advancement of TFSi.

٤.٣.٣.١ Materials and components

The long-term cost of TFSi modules is determined by the cost of active layer material, the modules' efficiency, the choice of encapsulation and packaging materials and the investment cost of production equipment. To reduce these costs, research should focus on improving the active layer material, especially of technologies based on µc-Si, finding ways to produce such materials at industrial scale, and developing adequate transparent conductive oxides (TCOs) and substrates. The most important aims are listed here:

Lower-cost plasma deposition in the manufacture of high quality micro- or nano-crystalline Si solar cells, for example using higher deposition rates and simplified processes

Specific high-quality TCO or glass/TCO-stacks suitable for high-performance cells, as well as materials suitable for "reversed" configurations in which the active cell layers are deposited on a flexible and/or non-transparent substrate (e.g. for roll-to-roll)

Improved understanding of the properties of materials, for example, the transport of electrons in µc-Si and of interfaces in single- and multi-junction devices: - low recombination loss junctions - the use of optical reflectors between cell stacks

New lower cost materials/components for packaging

New layers and materials, for example µc-SiGe, SiC, nanocrystalline-diamond, layers with quantum dots, spectrum converters

Evaluation of alternative, potentially lower-cost approaches for the deposition of high quality layers (for example without plasma)

٤.٣.٣.٢ Performance and devices

Several possibilities exist for improving the efficiencies of single-junction amorphous silicon modules. For instance, features such as microcrystalline junctions may be added, or the modules may be combined with SiGe alloys. The introduction of these advanced features at low cost and the achievement of higher module efficiencies are key to the long-term success of the technology. A promising concept is the a-Si/µc-Si tandem cell. The best typical stabilised laboratory conversion efficiencies are currently in the range of ٩.٥% (a-Si), ١٢% (tandem a-Si:/µc-Si) and ١٣% (triple junction using SiGe alloys). This translates into commercial module efficiencies of ٦.٥, ٨.٥ and ٧%, respectively but large area module efficiencies up to ١١% have been demonstrated at the prototype scale.

Achieving a laboratory-scale performance from production modules and mastering the production of multi-junction devices are the major challenges facing TFSi

Table 5. Research priorities for thin-film silicon (TFSi) - time horizons for first expected use of research results in (pilot) manufacturing and products

	2008 - 2013	2013 - 2020	2020 - 2030 and beyond
Industry manufacturing aspects	■ PECVD systems to deposit microcrystalline-Si ■ High-rate µc-Si deposition ■ Produce high-quality TCO ■ Low cost packaging solutions/reliability ■ Produce technology (interconnection/ cleaning,...) ■ Roll-to-roll processing **Target : line demonstration** < 0.95 €/W_p for 100 MW_p, η >10% (glass substrate) < 0.75 €/W_p for 50 MW_p, η > 9% (flexible substrate)	■ Demonstrate next generation equipment with lower material use, higher throughput and higher efficiency ■ Simplified production processes ■ Ultra-low cost packaging **Target : concept demonstration** < 0.65 €/W_p for 200 MW_p, η > 12% (rigid) < 0.5 €/W_p for 100 MW_p, η > 11% (flexible)	**Target : concept** < 0.4 €/W_p at 500 MW_p, η >15% (rigid) < 0.3 €/W_p at 500 MW_p, η > 13% (flexible)
Applied/advanced technology aspects	■ Large area plasma processes for amorphous and microcrystalline Si Plasma process control ■ Improved substrates and TCO (light trapping) ■ Advanced embedding materials ■ Alternative techniques for absorber deposition **Target :** Demonstrate modules with η > 12%	■ New deposition reactor concepts ■ Fast high quality TCO/ substrate preparation ■ Introduce fully optimised light trapping schemes on large area ■ Process gas recycling/ full gas use **Target :** concept for modules with η > 15%	■ Test advanced device in pilot-reactors ■ Designs for ultra-high-throughput lines/ reactors ■ Process simplification ■ Fully integrated production line
Basic research/ fundamentals	■ Quantitative understanding of electronic properties of layers and interfaces in devices ■ TCO/semiconductor interfaces ■ Quantitative understanding of light trapping ■ Developments of improved selected cell layers (e.g. µc-SiGe, SiC, nanocrystalline-diamond) **Target :** push up efficiencies and demonstrate stable cells with η > 15%	■ New techniques for very high-rate deposition ■ Incorporate quantum dots or spectrum-converting effects in thin-film Si ■ Combine thin-film Si with other PV technology ■ Understand fundamental limitations of thin-film Si **Target :** concepts for stable cells with η > 17%	■ higher performance materials ■ p-type TCOs ■ Photonic crystals, diffraction effects, effective medium approaches, etc. ■ introduce new materials ■ test new concepts **Target :** to narrow down the range of ideas for cost reduction

Short-term obj

Manufacture c ... at industrial scale

Plasma process control and monitoring

Quantitative understanding of the fundamental limits of µc-Si solar cells incorporated into multi-junction cells

Quantitative understanding of light trapping, and of the fundamental efficiency limits of TFSi-based multi-junction devices (including SiGe alloys)

Demonstration of TFSi cells with stabilised efficiencies above ١٥%, and, at the module scale, over ١٢%

In the long term, higher stablilised cell efficiencies should be demonstrated (above ١٧% by ٢٠٢٠). One possible route to higher efficiencies could involve the incorporation of selected improved layers into devices (e.g. μc-SiGe, SiC, nanocrystalline-diamond, photonic crystals), the use of quantum dots or spectrum-converting effects in thin-film Si, and the combination of thin-film Si with other absorbers (PV technology merging).

٤.٣.٣.٣ Manufacturing and installation

Analyses suggest that within the next two or three years production costs in the range ١.٣-١.٦ €/Wp should be achievable for a-Si modules (efficiencies of ٦.٥ to ٧.٥ %), and for “micromorph” modules (efficiencies ٨ to ٩%) using production equipment that has recently become available. The target for ٢٠١٣ is an efficiency increase to above ١٠%, with production costs below ١ €/Wp on rigid substrates. The corresponding targets for flexible substrates are ٩% and ٠.٧٥ €/Wp respectively. The targets assume production lines of ١٠٠ MWp /year for glass substrates and ٥٠ MWp /year for flexible substrates. To meet these goals, cost-effective deposition of microcrystalline Si on large area (> ١ m٢) must be achieved. The second priority is to ensure the availability of suitable production equipment for high quality large area TCOs or TCO-stacks. Thirdly, to reach efficiencies in the range of those of crystalline Si, improvement across the manufacturing chain is required (achievable through minimising interconnection losses, improving homogeneity and using in-line process control). The value in developing modules on both glass and flexible substrates with reliable, lower cost packaging should be assessed.

Manufacturing and installation-related aims are summarised as follows:

A full understanding of the relationship between plasma processes, reactor geometry and layer / device properties and the effects of upscaling

The design and construction of low-cost equipment able to deposit μc-Si and related layers over a large area at high rates

Large area, high rate fabrication of TCOs with high transparency, and light trapping ability

Interconnection using laser-scribing to minimise area losses, cheaper packaging, better reliability through moisture resistance

Processes and equipment specific to roll-to-roll production

Semi-transparent thin-film silicon modules integrated into buildings
Source : Schott Solar

Amorphous silicon solar cell on plastic roll after monolithic interconnection of the segments
Source : VHF-Technologies

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(CIG

CIGSS technology currently exhibits the highest cell and module efficiencies of all inorganic thin film technologies (cells of ١٩.٥%; commercial modules of ١٢%; prototype modules of ١٣-١٤% for areas of ٠.٣٥٠.٧m٢). There exist however, a number of subjects that must be addressed if costs are to be reduced.

Large-scale manufacturing (mainly in Europe) of the first generation of CIGSS modules has begun, but there remains a need for research into production processes, like absorber deposition equipment and tools for in-line characterization. New non-vacuum techniques for the deposition of device layers (like nanoparticle printing and electro deposition) as well as the use of substrates other than glass (e.g. flexible metal and polymer foils) and low-cost encapsulation (using barrier coatings, transparent polymers) could reduce cost. In parallel, the industry must prepare itself for the production, in the medium to long term, of more efficient second generation CIGSS devices.

A main challenge specifically facing CIGSS thin-film technology is the reduction of the material costs: high cost materials (In, Ga) should be replaced with, for example Al (a challenge that will become more pressing as CIGSS production increases to the very large scale), less material should be wasted during manufacture, active layer thicknesses should be reduced, and tolerance to impurity in the materials should be increased. The replacement of the CdS buffer layer and the optimization of the TCO layers in these devices are key to facilitating reduced cost large-scale manufacture. The development of wide band gap materials for CIGSS-based tandem cells and band gap-engineering of these materials is also required for higher module efficiencies.

٤.٣.٤.١ Materials and components

Fundamental research is needed in the short to medium term to find materials with high stabilised efficiencies that are also low-cost and easy to handle in large-scale manufacturing:

Better understanding of interface and grain boundary chemistry, diffusion behaviour and defect chemistry and the reversible gains through light soaking should enable cell efficiencies well above ٢٠% to be reached

Improved understanding and control of nucleation and growth morphology of thin films on foreign substrates

Reduction of pin-hole and inhomogeneity effects

Better understanding of the influence of the deposition process on film characteristics and device behavior under both accelerated lifetime testing and after long-term outdoor exposure.

Material cost minimization through thinner films, maximizing material yield and optimizing material purity

Screening and synthesis of chalcopyrite's that offer potential for improved efficiency, longer-lasting stability and/or that are cheaper and that contain fewer scarce materials n
New device concepts (spectrum conversion, quantum effects, multi-gap cells)

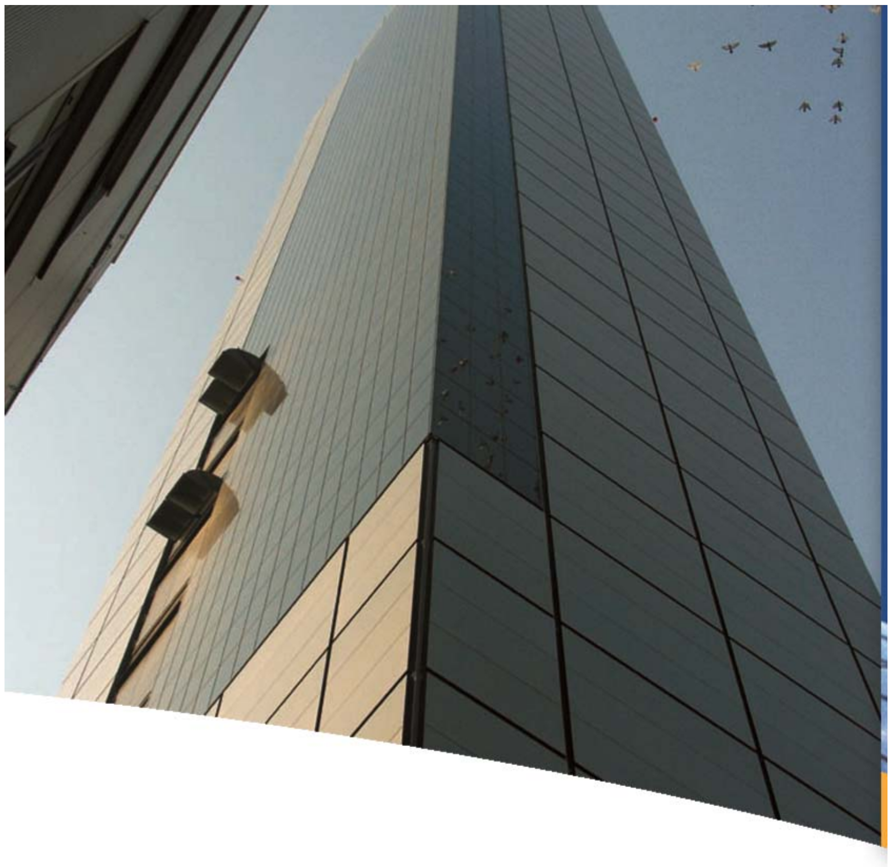
٤.٣.٤.٢ Performance and devices

Intensive R&D is necessary to prepare for future industrial production CIGSS-based modules:

‘Proof of concept’ modules with efficiencies above ١٦% in the medium term

Alternative substrates for glass, such as polymer or metal foils, and design of the whole production chain including sealing of the active films

Testing of new deposition concepts like electrode position, nanoparticle printing, and micro- or macroscopically rough substrates (glass fiber mat)



Roof mounted PV system with CIS modules in buildings under monumental protection (Friedenskirche, Tübingen)

High level of automation in CIS production

Precise quality check by experts in CIS production

Note : CIS = copper-indium-diselenide

Source : Wurth Solar

٤.٣.٤.٣ Mar

Industrial d

The standa n management

Development and qualification of high-throughput processing equipment and high temperature processing (٦٠٠°C) for reduced cycle times

Equipment designed for very large area in-line deposition on glass substrates of up to several square metres and roll-to-roll substrates

Reduction of material usage and cost through the optimisation of deposition equipment and material purity, as well as through the use of thinner films. The tendency for substrates should be towards the use of thinner and more flexible materials

Productivity improvements (production time, process yield, equipment uptime)

Quality control methods and quality management systems

Production modules at costs of much less than ١ €/Wp and module efficiencies well above ١٥%

Recycling techniques for the re-use of material during production and for products at the end of their lives

Development of building-integrated PV, i.e. of modules that may be used in the construction of buildings and as architectural components

Quality control of CIS modules during production
Source: Wurth Solar

Table 6. Research priorities for thin-film CIGSS - time horizons for first expected use of research results in (pilot) manufacturing and products

	2008 - 2013	2013 - 2020	2020 - 2030 and beyond
Industry manufacturing aspects	■ Production equipment for today's CIGSS module processes optimised for production yield, high-throughput, reduced investment cost and material consumption. ■ High-throughput, low cost packaging processes and equipment that prolong module lifetimes ■ Demonstrate equipment for CIGSS modules at 14% efficiency at absorber deposition	■ Production equipment for CIGSS modules at 16 to 17% efficiency ■ Equipment optimised for low energy, low material consumption and alternative buffer layers ■ Recycling processes for modules and waste material from production ■ Demonstrate roll-to-roll processes for module production ■ Demonstrate ultra low cost packaging for rigid and for flexible modules ■ Demonstrate large area	■ Perform studies on the 'industry and manufacturing' aspects of very large production units for CIGSS modules with very high efficiency at very low production costs ■ Transfer of modified interconnect structures and processing ■ Transfer of ultra light and low cost packaging ■ Reoptimise processing to minimise energy needs, material costs, waste

٤.٣.٥ Cadmium telluride (CdTe)

The attractive features of CdTe are its chemical simplicity and stability. Because of its highly ionic nature, the surfaces and grain boundaries tend to passivate and do not contain significant defects. Its ionic nature also means that absorbed photons do not damage its stability. CdTe’s favourable thermo-physical properties, simple phase diagram and chemical robustness make CdTe cells easy and cheap to manufacture, using a variety of deposition methods. The efficiency of CdTe cells depends on how the CdTe layers are grown, the temperature at which the layers are deposited and the substrate on which they are deposited. CdTe layers grown at high temperatures (~٦٠٠ °C) on "alkali-free" glass yield cells of up to ١٦.٥% efficiency, while lower efficiencies are obtained from CdTe grown at low temperature or on other types of substrates. There is a large gap between the theoretically achievable efficiency (>٢٥%) and efficiency reached in practice (١٦.٥%). Intermixing elements at the heterojunctions and using activation/annealing treatments to control the electronic properties of the CdTe layer and solar cells are important for further improving efficiency. It is essential to develop processes that are simple and compatible with high-throughput in-line manufacture.

The "electrical back contact" on CdTe is an important R&D topic since it influences the efficiency and long term stability of CdTe modules. Efficient and stable electrical contact on p-type CdTe is a challenge because of both the high electron affinity and band gap of CdTe. Though several methods have been used to develop efficient quasi-ohmic contacts on p-type CdTe, there is a need to develop processes that further improve efficiency and stability and simplify device production. Alternatives to wet chemical etching processes should be identified.

The most efficient CdTe solar cells on glass and polymers are grown as "superstrates", i.e. the substrate will be facing the sun in the finished product. The properties of TCOs in such configurations and their compatibility with device structure and processing are crucial for high module efficiency and high production yield. The use of thinner CdTe absorber layers will lead to a better utilisation of raw material such as tellurium.

CdTe thin-film modules are already being produced in both Europe and the USA at capacities of roughly ١٠٠-٢٠٠ MWp/year. Asia is expected to follow soon. Module efficiencies of ٩% have been reached and manufacturing costs already seem to be competitive with c-Si. Fast and simple deposition of absorber and contact materials allow for high-throughput production and promise further scope for cost reduction.

CdTe has the potential to reach ١٥% efficiency at a specific cost of ٠.٥ €/Wp in the medium to long term. However, to reach these values the material needs further R&D work to understand better its fundamental physical properties.

In the short term it is necessary to work on improving production technology and on better understanding production parameters and processes. For the medium and long term, advanced low temperature cell production on glass and foil substrates needs to be developed, as well as device configurations employing techniques for enhanced optical confinement (which will allow CdTe layers to become thinner) and modified or multi-absorber cell concepts for higher efficiencies.

Finally, it is important to develop and implement a system for module end-of-life return and to close material-use cycles, especially as production volumes increase.

Table 7. Research priorities for thin-film CdTe - time horizons for first expected use of research results in (pilot) manufacturing and products

	2008 - 2013	2013 - 2020	2020 - 2030 and beyond
Industry manufacturing aspects	**Improved standard cell production technology:** ■ Advanced activation/ annealing suited to in-line production, dry processes, use of alternative chlorine -containing precursors	**Advanced cell production technology:** ■ Devices with thinner films ■ Control of nucleation and film morphology during deposition ■ Simple and robust	**Optimised cell production technology:** ■ Modified device structures (inverted film sequence, p-n cells) ■ Device structures and conversion efficiencies that approach the

٤.٣.٥.١ Materials and components

For further increasing efficiency and stability, intensive fundamental R&D probing of the physics and chemistry of CdTe and the other films that make up CdTe-based solar cells is required. The results will be used to develop lower cost techniques. Some of the key areas for study include:

Fundamental understanding of the physics of CdTe solar cells

Fundamental understanding of interface and interdiffusion processes and of grain boundary effects

Extrinsic doping and simple activation processes

Ohmic contacts and materials with multi-functionality that increase overall performance and reduce production cost

Fundamental knowledge of materials and interfaces for advanced devices with high efficiencies (over ٢٠% at laboratory scale).

Further improvement of single layer or bi-layer TCO materials and processes

New substrate materials and modified processes that allow low temperature deposition and high growth rates (i.e. high-throughput manufacturing)

Materials and processes for multiple band gap approaches.

٤.٣.٥.٢ Performance and devices

The following performance- and device-related topics need to be addressed to reach the targets outlined earlier.

Improvements in activation/annealing and back contact formation

Device structures employing enhanced optical confinements in thinner CdTe layers

High performance (efficiency and stability)

Modified cell structures on glass and foils

Interconnection schemes for reducing interconnect-related losses

٤.٣.٥.٣ Manufacturing and installation

Industrial development is required in the following areas:

Higher productivity and standardised process equipment

Reduction of the quantity and purity of material needed for high efficiency devices

Processes to recycle production waste and CdTe modules that have reached the end of their lives.

٤.٣.٦ Summary for thin films

Thin-film PV has a very high potential for cost reduction if materials and manufacturing can be improved by intensive and effective R&D on the fundamental science and production technology. The main and most important R&D aspects with highest priorities are:

Reliable, cost-effective production equipment

Low cost packaging solutions both for rigid and flexible modules

More reliable modules through better quality assurance procedures (advanced module testing, and improved assessment of module performance)

Recycling of materials and old modules

Alternatives for scarce chemical elements such as indium and gallium

TFSi

Processes and equipment for low-cost, large area plasma deposition of micro/nanocrystalline silicon solar cells. Mastery of the interplay between plasma/devices/upscaling.

Development of high-quality low cost TCOs suitable for large area high performance (>١٢% efficiency) modules

Demonstration of higher efficiency TFSi devices (above ١٥% on laboratory scale), improved understanding of interface and material properties, of light trapping, and of the fundamental limits faced by TFSi-based materials and devices

CIGSS

Improvement of the throughput, yield and degree of standardisation of production equipment

Modules with efficiencies greater than ١٥% (or greater than ٢٠% at laboratory scale) through deeper understanding of the fundamental physics of these devices

Alternative/modified material combinations and alternative approaches to processing like roll-to-roll coating and combined or non-vacuum deposition methods; highly reliable and low cost packaging to reduce material costs.

CdTe

Activation/annealing treatments to control the electronic properties of the CdTe layer

Improved and simplified back-contacting for enhanced yield and throughput n Concepts for high efficiency

New device concepts for thinner CdTe layers

Enhanced fundamental knowledge of materials and interfaces for advanced devices with high efficiencies (up to ٢٠% at laboratory scale).

٤.٤ Emerging and Novel PV-technologies

The PV market is dominated by crystalline Si solar cells, but with a number of thin-film technologies challenging this position. Both crystalline Si solar cells and “traditional” thin-film technologies (a-Si:H and its variations based on protocrystalline or microcrystalline Si as well as polycrystalline compound semiconductors) are developing roadmaps aiming at further cost/Wp reductions. Limiting the PV research to these sets of PV-technologies may be risky for two reasons. First, flat-plate modules are limited to efficiencies not exceeding ٢٥%. Secondly, the European PV industry would miss opportunities afforded by step-changes in technology. These beyond-evolutionary technologies, described below, can either be based on low-cost approaches related to extremely low consumption of (often expensive) materials or approaches that push the efficiencies of solar cell devices beyond the ٢٥% limit achievable with incremental improvements to cells based on traditional designs. In fact, the goal to develop crystalline Si and thin-film solar cell technologies with a cost below ٠.٥ €/Wp relies on disruptive breakthroughs in the field of novel technologies. An open attitude towards developments presently taking place in material and device science (nanomaterial’s, self-assembly, nanotechnology, plastic electronics, and photonics) is needed to detect these opportunities in an early stage.

”Emerging” technologies and “novel” technologies are at different levels of maturity. The label “emerging” applies to technologies for which at least one “proof-of-concept” exists or can be considered as longer - term options that will disrupt the development of the two established solar cell technologies - crystalline Si and thin-film solar cells. The label “novel” applies to developments and ideas that can potentially lead to disruptive technologies, the likely future conversion efficiencies and/or costs of which are difficult to estimate. This chapter discusses the material synthesis, material deposition and efficiency requirements for each category and, where possible, costs.

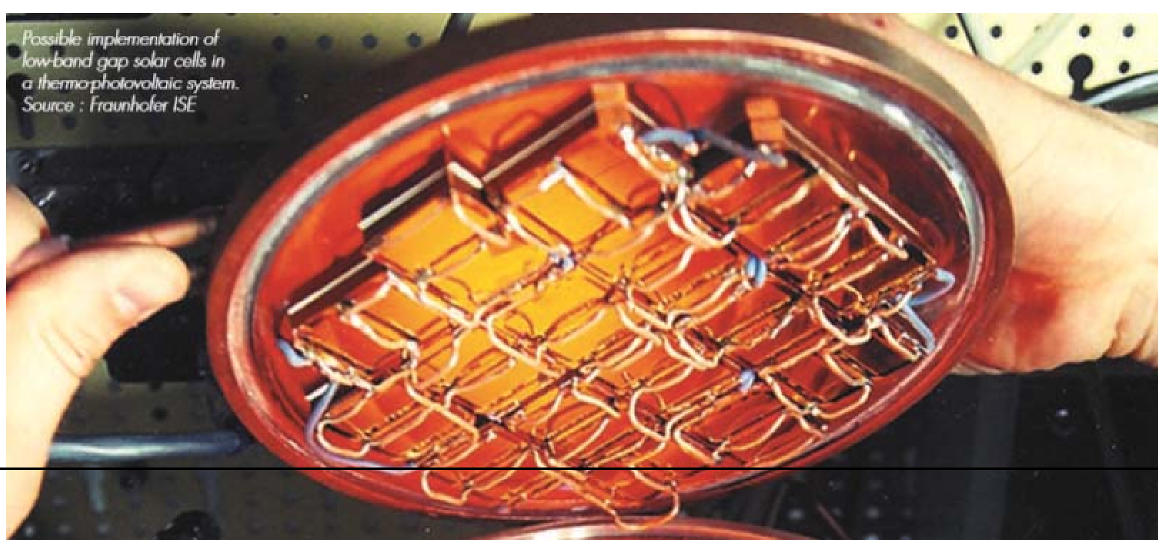
٤.٤.١ Emerging PV technologies

In each of the areas below, Europe has built up a strong R&D position. The first steps towards commercialisation are being taken in some of them. There are three sub-categories within the “Emerging PV technologies” category, all of which essentially aim at very low production costs with efficiencies around ١٥%.

٤.٤.١.١ Advanced inorganic thin-film technologies

Advanced inorganic thin films have their roots in the thin-film technologies covered in the previous chapter, but the concepts discussed here, which relate to substrates, deposition technology and module manufacturing, have the potential to divert TF technology away from the path mapped out in that chapter. An example of such an advanced inorganic thin-film technology is the spheral CIS-approach. In this technology, glass beads (disruptive compared to the present glass substrates) are covered with a thin polycrystalline compound layer (covering the glass bead evenly with a thin layer requires basic adaptations of the deposition technology) and the interconnection process between the spheral cells is fundamentally different from the monolithic module approach typically used.

Another prominent example is the polysilicon thin-film approach where the polycrystalline Si layer is manufactured at temperatures higher than normally used for a-Si:H or microcrystalline Si. This results in a pn-device rather than a pin-device (Image ١). The higher deposition temperature would enable deposition rates to be higher (thereby addressing also one of the issues related to microcrystalline Si solar cells) and increase the quality of active silicon layers. This higher electronic quality should result in laboratory-scale demonstrations of efficiencies around ١٥% in the next ٥ years. However, up scalingof the deposition equipment to deposit polycrystalline Si active layers at temperatures above ٦٠٠oC is still at an early stage and further development of suitable ceramic and high-temperature glass substrates is necessary to exploit the full potential of this technology. Europe has a company involved in bringing the polycrystalline Si solar cell technology into production aided by the intellectual property generated by several leading European R&D groups.


Possible implementation of low-band gap solar cells in a thermo-photovoltaic system. Source : Fraunhofer ISE

of the deposition equipment to deposit polycrystalline Si active layers at temperatures above ٦٠٠oC is still at an early stage and further development of suitable ceramic and high-temperature glass substrates is necessary to exploit the full potential of this technology. Europe has a company involved in bringing the polycrystalline Si solar cell technology into production aided by the intellectual property generated by several leading European R&D groups.

٤.٤.١.٢ Organic solar cells

For all of the approaches in this sub-category, the active layer consists at least partially of an organic dye, small, volatile organic molecules or polymers suitable for liquid processing. Organic solar cells have been the subject of R&D for a long time already because they offer the prospect of very low cost active layer material, low-cost substrates, low energy input and easy upscaling. This last potential advantage offers the possibility of printing active layers, thereby boosting production throughputs typically by a factor ١٠ to ١٠٠ compared to other thin-film technologies. Modules made using such technology could cost less than ٠.٥ €/Wp.

The emergence of organic solar cells has been facilitated by cell concepts that are radically different from the planar hetero- or homojunction solar cells in production today. The basis of these concepts is the existence of nanosized domains resulting in a bulk-distributed interface increasing the exciton dissociation rate and thereby also increasing the collection of photogenerated carriers. Within 'organic solar cells', two technology branches exist. One is the hybrid approach in which organic solar cells retain an inorganic component (e.g. the Graetzel cell, Image ٢). The other is full-organic approaches (e.g. bulk donor-acceptor heterojunction solar cells, Image ٣). The main challenges for both approaches relate to the increase of efficiency, stability improvement and the development of an adapted manufacturing technology. The efficiency of these devices must be raised to ١٠% with a target of ١٥% for laboratory cells by ٢٠١٥, if they are to be deemed to hold potential in the long-term. Only by first reaching such efficiencies on laboratory cells can one hope to develop manufacturing technology for large-area modules with efficiencies over ١٠%. The increase in the performance of organic solar cells requires improved basic understanding of the device physics, the synthesis of novel materials and the development of advanced cell concepts (multi-junction or non-planar approaches). In view of the improvements foreseen for organic materials (both concerning their absorption and transport properties) and cell concepts, there is little doubt that efficiency levels up to ١٥% are indeed feasible. The main challenge is the improvement of stability. The term "stability" is used here to encompass the intrinsic stability of the organic materials used in the active layer, the stability of the cells' nanomorphology and the stability of the contact between metal conductors and organic semiconductors. Work in these three areas and progress in the field of low-cost encapsulation techniques (also needed for organic LEDs and organic electronic circuits), should result in modules with a stability of at least ١٥ years. Europe is well placed to remain at the cutting edge of R&D in and production of organic solar cells in part because of its strong position in related fields like organic electronics.

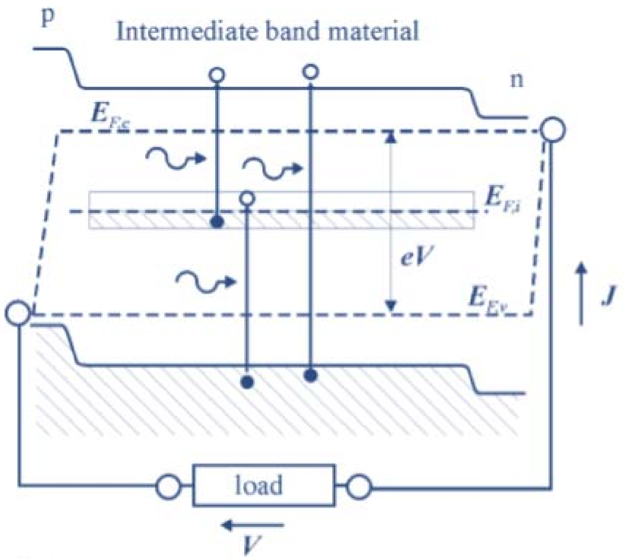
٤.٤.١.٣ Thermophotovoltaics (TPV)

In the long term, this third approach could be used in concentrating solar thermal power applications (CSP). Before that happens, the technology could be used in CHP systems. Within Europe there are several lowband gap cell types being investigated for TPV ranging from germanium-based cells to advanced ternary and quaternary alloys incorporating the elements gallium, antimony, indium, arsenic and aluminium. Although some R&D is still needed on the individual components of a TPV system (cell, monolithic module integration, emitter, filters), the main challenges are to integrated the components in a system, boost reliability and the demonstrate electricity costs less than ٠.١€/kWh and a system efficiency of ١٥% (Image ٤).

Table 8. Research priorities for emerging technologies - time horizons for expected evolution of the technology and for first expected use of research results in (pilot) manufacturing and products, respectively

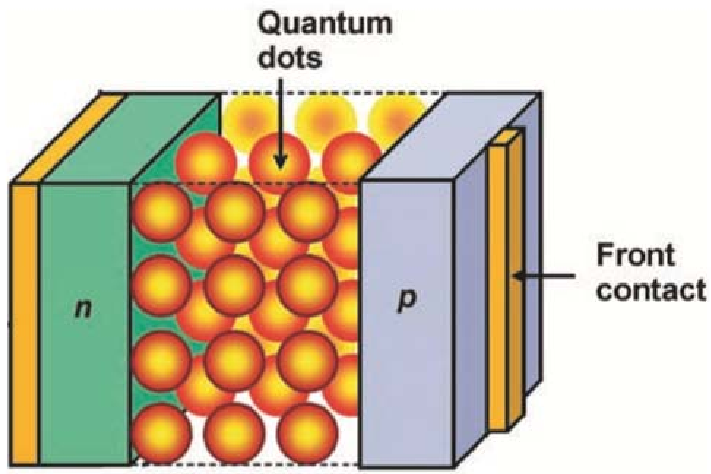
Basic category	Technology	Aspects	2008-2013	2013-2020	2020-2030 and beyond
Advanced inorganic thin-film technologies	Spheral CIS solar cells	Material	Deposition technology	Industrial implementation η > 12 % on industrial level ~0.50.8 €/W_p	Implementation of advanced concepts in solar spectrum tailoring in ultra-thin solar cells to reach < 0.5 €/W_p (see also 3.2.2)
		Device	Parallel interconnection		
		Performance	η = 14%		
		Cost	N.A.		
	Thin-film polycrystalline Si solar cells	Material	Improving poly-Si electronic quality, deposition upscaling	Industrial implementation η = 12 to 14% on industrial level ~0.50.8 €/W_p	
		Performance	η = 14% / monolithic module process		
		Cost	N.A.		
Organic solar cells	Dye solar cells	Material	Improved and stable sensitizers, solid electrolytes, encapsulation to ensure lifetime > 15 years	Industrial implementation η > 10% on industrial level ~0.5-0.6€/W_p	Implementation of advanced concepts of solar spectrum tailoring to reach < 0.5 €/W_p (see also 3.2.2)
		Performance	η = 15%		
		Cost	N.A.		
	Bulk heterojunction	Material	Improved and stable polymers, stabilisation of nanomorphology for 5 years	Low-cost encapsulation materials to guarantee stability > 15 years	
		Device	Printing technology Organic multi-junctions	Organic multi-junctions	
		Performance	η = 15%	η > 10% on industrial level	
		Cost	N.A.	~0.5-0.6€/W_p	
Thermophotovoltaics		Material	Cell/module technology for various active materials	Nanostructured emitters	Novel active layers using nanotechnology
		Performance	Demonstration of reliability	Electrical efficiency > 8%	Electrical efficiency > 8%
		Cost	N.A.	< 20 c€/kWh	< 10 c€/kWh

N.A. = Not Applicable



Band structure of an intermediate band solar cell, showing transitions energy gaps and quasi-Fermi levels Source: Polytechnical University of Madrid

Figure 2



Layer structure of the intermediate band solar cell using quantum dots Source: Polytechnical University of Madrid

Figure 3

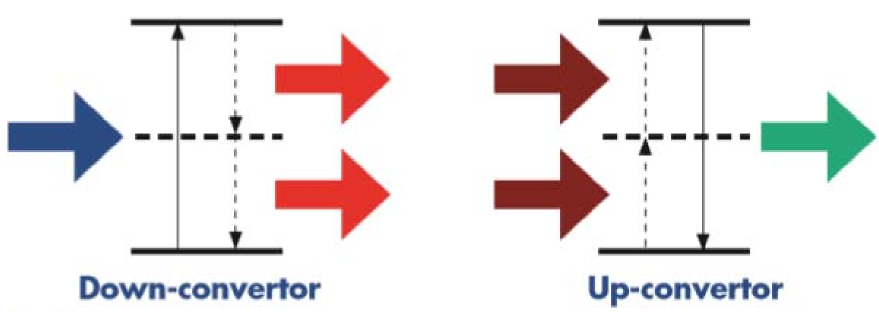


Figure 4

In down-conversion systems a high-energy (e.g. violet) photon is converted to two lower-energy (near infrared) photons allowing more efficient harvesting of the energy of the high-energy photon; in case of the up-convertor two low-energy (e.g. near infrared) photons are converted to a higher energy (yellow~green) photon. Down-conversion systems should be applied at the frontside of the cell, whereas the up-converting systems

٤.٤.٢.٢ Tailoring the solar spectrum to boost existing cell technologies

Tailoring the incoming solar spectrum for maximum conversion to electricity in the active semiconductor layer relies on up- and down-conversion layers and plasmonic effects (Figure ٤). Nanotechnology might again play an important role here. Surface plasmons generated through the interaction between photons and metallic nanoparticles have been proposed as a means to increase the photoconversion efficiency in solar cells by shifting the wavelength of the incoming light towards the wavelengths at which the collection efficiency is maximal or by increasing the absorbance by enhancing the local field intensity. The application of such effects in photovoltaics is definitely still at a very early stage, but the fact that they can be 'bolted-on' to conventional solar cell technologies (crystalline silicon, thin films) may reduce their time-to-market considerably. An improvement of at least ١٠% (relative) of the performance of existing solar cell technologies thanks to up- or down-convertors or the exploitation of plasmonic effects should be demonstrated in the coming decade. With proofs-of-concept available, practical low-cost synthesis routes for these layers and manufacturing processes to introduce these layers into existing solar cell technologies should be developed (expected ٢٠١٥-٢٠٢٥).

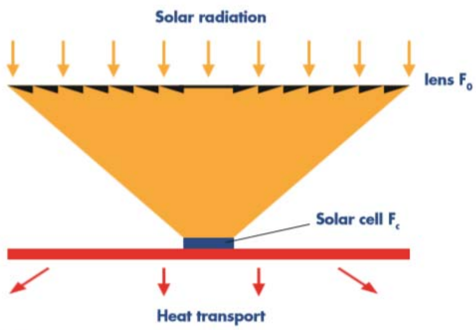


Figure 5

Principle arrangement of a PV concentrator. Here a Fresnel lens is used to concentrate the sunlight onto a small solar cell. The tracking system is not shown.

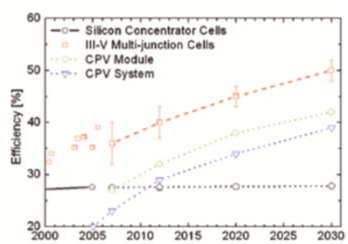


Figure 6

The expected future efficiencies of CPV cells, modules and systems Source: Fraunhofer ISE

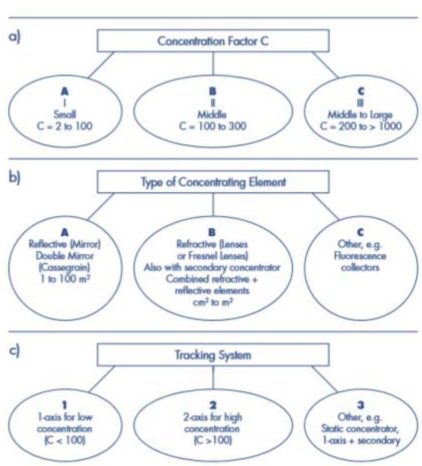


Figure 7

Schematics of CPV systems

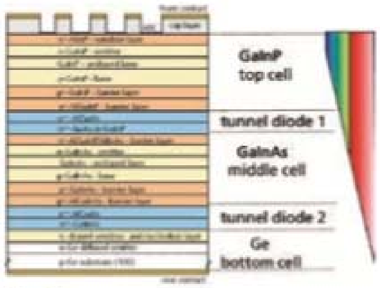
Research in the field of CPV must address the whole system. Only if the interconnections between all the components are considered can the complete system be optimised. This requires strong collaboration between different research groups, making collaborative European projects of particular importance.

Materials research is needed for all the components in CPV systems:

١. High-efficiency silicon cells or III-V- compound multilayer cells should be used in concentrator systems. The environment to create these cells must be ultra-clean. This aspect of the cells' manufacture is described in more detail in the next section ٤.٢.٣.

٢. As shown above, a great variety of optical systems have been introduced and tested, using plane and concave mirrors, lenses and Fresnel lenses and secondary concentrators. The task here is not so much to develop new devices but to combine existing technology in reliable, long-term, stable and low-cost ways. In addition standardised solutions and test procedures are essential. It is not yet clear which concentration range will ultimately be considered optimal but the tendency today is towards systems with concentration factors between ٣٠٠ and ١٠٠٠ (Image ٥). In this range, optical systems must be fairly precise with good surfaces and/or surface coatings. In particular Fresnel lens-type elements must be produced with very sharp ring segment borders in order to exhibit transmittance of over ٩٠ %. Refracting elements must have low absorptance and good anti-reflection coatings. Reflecting elements must have long-lasting coatings able to reflect more than ٩٠ % of incident light. These elements must be produced in a way that minimises material usage and that is automated in order to push costs down. Accelerated ageing tests and long-term real-time outdoor testing are also necessary for the development of optical components.

٣. Module assembly. The optical elements work in a geometry that is fixed with respect to the concentrator solar cells. This mounting must be made in a fully automated process, with high-speed and precise placing of the cells, a task that can be made easier by borrowing from the expertise of microelectronic and opto-electronic device manufacturers. In many cases the cells are mounted on heat dissipating elements. They also must be integrated and interconnected during module assembly. In some cases optical elements and solar cells are enclosed in a weather-proof module box in which they are interconnected in serial or parallel strings. These concentrator modules must be mechanically stable and resistant against humidity, condensation and rainwater ingress over long periods. It is also important to find the module size that maximises long term stability, but minimises fabrication costs and mounting costs. Standardised durability tests need to be developed. Recycling aspects should also be considered and investigated.



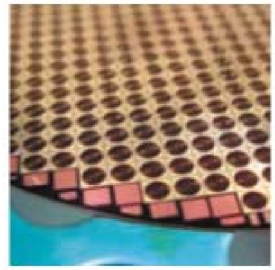
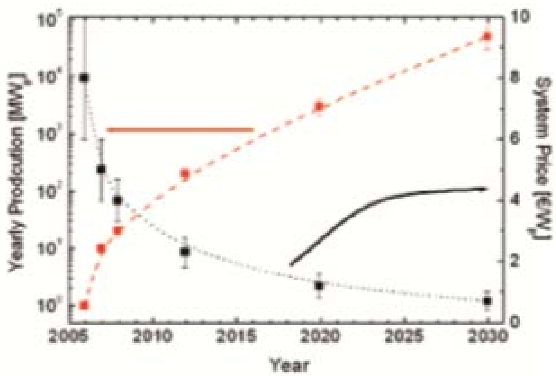


Diagram of a GaInP/ GaInAs/Ge triple solar cell on Ge substrate

Small concentrator solar cells on a 100mm wafer

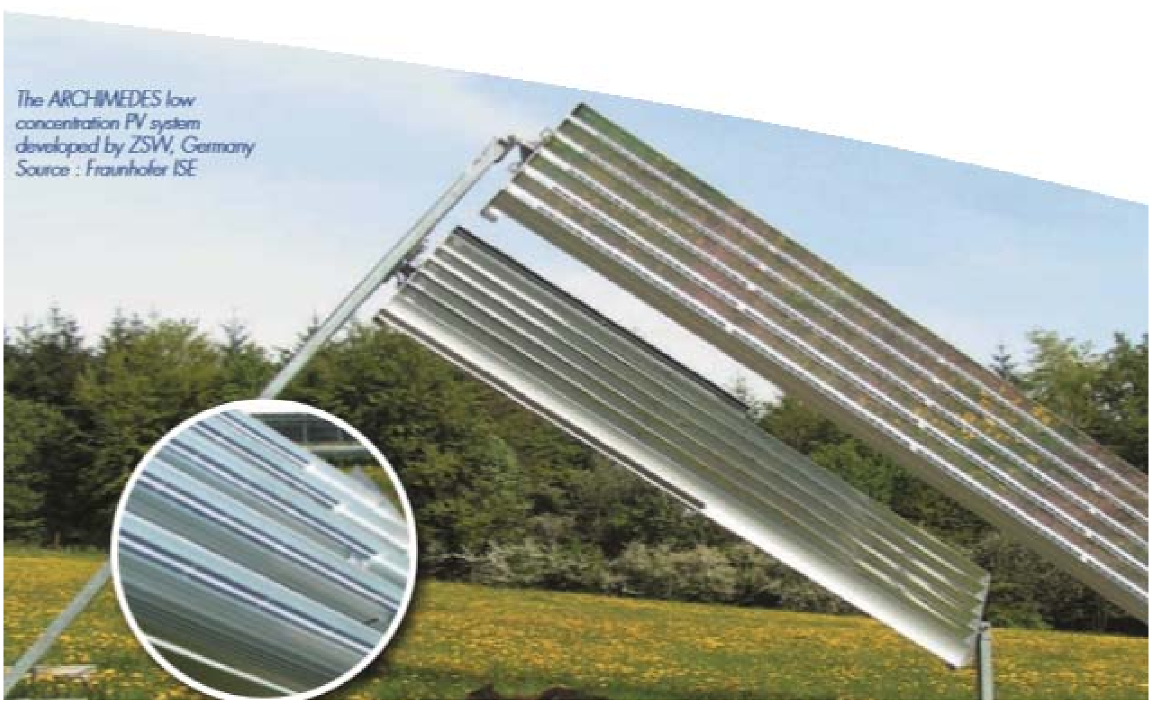
Source : Fraunhofer ISE

Image 7



The expected yearly production of CPV systems (red) and the price of turn-key installed CPV systems in €/W_p (black)
Source : Fraunhofer ISE

Figure 8



The ARCHIMEDES low concentration PV system developed by ZSW, Germany
Source : Fraunhofer ISE

top, building-integrated or ground-based), module efficiency and location. Nevertheless, meeting these targets would imply that the kWh cost of PV-generated electricity will be comparable to the consumer electricity tariff in most European countries by ٢٠١٥ or ٢٠٢٠, depending on the local irradiation, and to a lesser extent on the module’s behaviour under non-standard conditions (at high temperatures, low light intensities, low angles of incidence).

Studies performed in Germany, the Netherlands and the UK have estimated BoS prices to be between ١.٦ - ٢.٥ €/Wp for building-mounted systems on domestic properties, with some evidence that prices could be as low as ١.٢-٢ €/Wp. Still lower prices can be obtained for large ground-based systems. If large amounts of the same component are used in the installation, the unit price of the mounting system can be expected to decrease and installation time can be expected to be less than in the case of same total capacity installed in smaller systems. The economies of scale observed for large PV systems must be applied to small systems by promoting the harmonisation and standardisation of installation approaches.

BoS costs are made up of both power- and area-related costs (e.g. the cost of the mounting structure). Area-related costs are currently between ٣٠ and ٧٠% of the BoS costs, depending on application. Since the array area depends on module efficiency, increasing this efficiency can help significantly in achieving the system-related goals.

The relationship between kWh cost and Wp cost is also a function of the i) lifetime of all components ii) the performance of the system over its lifetime and iii) the value of other features of the installation (shading, noise barrier).

The quality of a PV system can also be expressed in terms of environmental parameters such as the energy pay-back time, which R&D should aim to reduce. The prolongation of component lifetimes and the increases in system productivity both augment the positive environmental impact of PV systems.

Roof mounted PV system with copper-indium-diselenide modules
Source: Wurth Solar

PV on roofs in "City of the Sun", Heerhugowaard, The Netherlands
Source : Municipality of Heerhogowaard

٥ Research funding

٥.١ Project methodology: basic considerations

Collaborative research projects have played a crucial role in establishing Europe as a world-leading R&D region. The list below introduces our general thinking on funding schemes for collaborative research and research by individual teams, with more detailed proposals following later:

The funding schemes supporting the intended research should be flexible and tailored to the timescale for the use of the research results in commercial products.

For R&D results that will be commercialised in the short term, the consortia bidding to undertake the research should be composed of partners with complementary expertise and financial interests to avoid disputes over the ownership of intellectual property created during the project, which could affect the exploitation of the research results. This will limit in many instances the choice of partners. The yardstick of success for this kind of research is the degree to which the project's results are patentable, the number of successful prototypes realised and the extent of take-up in industrial production and products.

The research funding instruments supporting R&D for the long-term, such as 'emerging' and 'novel' PV should be flexible and adapted to the area's relatively high level of risk. It is essential that the knowledge created within R&D projects is suitably protected, for example by patents or by publication if the aim is both to prevent one particular company seizing all the rights to the knowledge and to disseminate it to the broader PV community. Including industrial partners in these research projects is not necessarily conducive to meeting this last objective. It would be better to set up "user commissions" consisting of interested industrial partners to whom the main achievements are presented on a regular basis or to organise workshops where project results are discussed with scientists and researchers from outside the research project. The success of long-term research projects should be measured by the number of patents they give rise to, scientific publications, citation indexes, the interest of the "user commission" and a quantitative assessment of the effectiveness of the workshops.

Combining different sources of funding is desirable, providing this imposes no significant administrative burden. The deadlines of calls for proposals in the same area issued by regional, national and European funding agencies should be synchronised so that the start of projects that combine funding from these different sources is not needlessly delayed.

٥.٢ Proposed schemes

Collaborative research

It is vitally important to continue with the collaborative research model and apply it to the topics identified in chapter four. Consortia proposing projects should be given the freedom to include as many or as few partners as they want, and, during the project, to allow in or exclude partners and to adjust the focus of their work. The administrative burden of participating in and preparing projects should be reduced.

Comments on a few of the instruments for funding European-level research are given below. There are, of course, many others that are also potentially of interest to PV researchers.

Collaborative research in neighbouring fields

The research to be carried out in the area of ‘emerging’ and ’novel’ PV-technologies could also be financed under budgets related to materials, nanotechnology, self-assembly and photonics. The PV Technology Platform will endeavour to interest communities more directly involved with these fields in our proposals for research. The PV Technology Platform has already initiated a dialogue with SUSCHEM, the European Technology Platform of the chemical industry, the European Construction Technology Platform, and the Smart Grids Technology Platform, which should all send representatives to the ‘user commissions’ described above. There may be knowledge to be gained from the heavy construction industries, as described under the heading ‘Materials and components’ of section ٤.٥ on concentrator technologies.

European Research Council (ERC)

The European Research Council was set up specifically to award excellent individual research teams with ١٠٠% funding for a basic research project that they propose. This is an instrument that could be used to fund longer-term R&D subjects of relevance to PV. The PV Technology Platform will increase awareness of this new instrument within and outside the PV-community, and would like an opportunity to brief the ERC’s Scientific Council on the kinds of fundamental research that would be most useful to PV. The ERC should alert the Platform to any projects related to PV that it decides to fund. In order to avoid a completely random process of new R&D-groups being set up, resulting in a scattered R&D landscape, it is proposed to use the existing R&D-infrastructure in Europe to get connected to these grants. In other words, it is vital to ensure an early dialogue between researchers new in the PV field and researchers with experience in the areas of interest. This has the additional benefit of avoiding proofs-of-concept on suboptimal cell configurations, which might lead to erroneous conclusions.

Support for PV-R&D-infrastructures

European-level funding is available for the construction of new research facilities and the upgrading of existing facilities. Where feasible, the PV Technology Platform prefers approaches that reinforce the “multi-polar” situation that currently exists in Europe above those striving for a single European facility. In the long term, research infrastructure that combines nanotechnology R&D and PV technology will be needed to develop novel types of super-efficient solar cells and organic solar cells.

Cooperation between national programs

Most funding for PV R&D in Europe comes from the national level. With this SRA, the PV Technology Platform aims to help national funding agencies align their priorities with those considered by the sector to be of greatest strategic significance.

The PV-ERA-NET project, which encourages national funding agencies to fund their countries’ PV research in a manner that fits logically with the intentions and strategies of other funding agencies, does very useful work. The co-ordination of PV research is more straightforward for research topics further from the market, where countries are less likely to feel pressure from their industry to defend industry’s short-term interests regardless of whether, from a European perspective, this is a rational use of public money. Initiatives like PV-ERA-NET should focus on co-ordinating research that could give rise to “win-win” situations, for example where one country’s expertise in device science is coupled with another’s equipment manufacturing capabilities. This transnational co-operation could take the form of clustering similar national projects in different countries. It could also involve issuing common calls, simultaneously in different countries, with the proposals evaluated jointly.

٥.٣ Budget allocation

This SRA comprehensively describes the type of R&D needed to realise the goals of the Vision Report, but determining the volume of research and the corresponding budgets that this volume implies is further work that remains to be done.

Nonetheless, the Platform thus encourages funding agencies to define at the start of their funding programmes the amounts (shares) they intend to spend on research for the short, medium and long term. Unless this step is taken, research focused on technology that is far from the market is likely to be underfunded because the rapidly growing PV industry will attract and absorb the corresponding funding to support its short-term commercial interests. Such a situation is neither in the interest of the researchers working on long term developments, nor of that of the PV industry.

We consider a rational approach to structuring research spending to be a division according to the ratios below. This division is to be pre-defined on the basis of strategic considerations: how can we adequately support ambitious EU industry development in the short term and ensure a sufficient supply of improved and new technologies to retain competitiveness in the medium and long term? ‘Short’, ‘medium’ and ‘long’ refer to research that finds commercial application in the period before ٢٠٠٨٢٠١٣, in the period between ٢٠١٣ and ٢٠٢٠ and in the period after ٢٠٢٠, respectively. This is the convention used throughout this report.

Private sector spending short:medium = ٣:١ Public sector spending short:medium:long = ٢:٢:١

In the near term, the total private R&D spend is expected to be approximately equal to the total public R&D spend, so total research spending is typically in the ratio short:medium:long = ٦:٣:١ (rounded figures). As the PV industry grows, it is expected that private sector spending will increase relative to public sector spending, so that the two are in the ratio ٢:١. In this case, the total research spending ratio should change roughly to short:medium:long = ١٠:٥:١ (rounded figures).

6 Appendices

Appendices covering the topics and themes presented in this report in further detail are downloadable from the European PV Technology Platform's website: http://www.eupvplatform.org/index.php?id=125

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