A Strategic Research Agenda

for Photovoltaic Solar Energy Technology

EDITION 2 2011

PhotoVoltaic
TECHNOLOGY PLATFORM

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Preface

This second edition of the Strategic Research Agenda (SRA) was prepared by the Science, Technology and Applications Group of the EU Photovoltaic Technology Platform based on consultations with representatives of research, industry and other stakeholders. The members of the Working Group are experts in photovoltaic (PV) technology, working as senior researchers in the public and private sectors.

Although the group has attempted to cover all the most important parts of PV science, technology and applications and to address all the most important research topics, the reader may find some aspects insufficiently treated. Comments are, therefore, welcome through the PV Technology Platform secretariat (see www.eupvplatform.org).

The SRA will be updated as required in order to reflect developments in the photovoltaic solar energy sector.

On behalf of the Working Group,

Nicola Pearsall
Chair, Working Group 3: Science, Technology & Applications
September 2011

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PV tiles made of multi-crystalline silicon solar cells replacing slates on a residential roof
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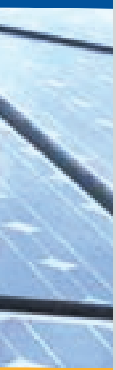


1 Summary

Photovoltaics (PV) is the direct conversion of sunlight into electricity. It is a very elegant process to generate environmentally-friendly, renewable electricity. PV technology is suited to a broad range of applications due to its modular nature and emission-free, silent operation and can contribute *substantially* to our future electrical energy needs.

In recent years the cost of electricity generated from PV has declined steadily as the technology behind it has become more efficient and as the number of installations has grown, often more rapidly than even the most optimistic predictions. Over the next few years, these trends are expected to continue and intensify. A recent study carried out by the European Photovoltaic Industry Association (EPIA), with support from strategic consulting firm A.T. Kearney and based on an extensive analysis of five EU markets (Germany, France, Italy, United Kingdom and Spain), has considered how rapidly PV will become more cost-effective in the coming years. The study concludes that, under the right policy and market conditions, PV can be competitive with grid supplied electricity in some markets as early as 2013 and across all market segments in the EU by 2020. Moreover, PV electricity is today already a notable alternative to diesel generators in stand-alone applications (especially in areas with significant hours of sunlight). As a result of the expected significant reduction in PV system prices, PV will be able to fulfil its potential as a major source of the world's electricity generation [EPIA 2011a].

In addition to appropriate market conditions, Research and Development – "R&D" – is crucial to the further development of PV technology. 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. The European PV Technology Platform recognised the necessity of PV R&D when it produced a Strategic Research Agenda (SRA) to realise the 2005 Vision document of the Photovoltaic Research Advisory Council, set up as a precursor to the Platform. The first edition of the SRA was published in 2007 and was used as input for the definition of the Seventh Framework Programme for Research of the European Union and also to facilitate a further coordination of research programmes in and between Member States.

Recognising the rapid development of the market and increased ambition for the contribution of photovoltaics in the near to medium term, evidenced by the adoption of binding 2020 renewable energy targets in Europe and the establishment of the Solar Europe Industry Initiative as part of Europe's Strategic Energy Technology Plan, the Platform decided to update the SRA to address the rapid technological developments required for these new challenges and opportunities. This second edition is intended to perform a similar function to its predecessor in terms of informing the research programmes of the EU and the Member States. These are key programmes to support the European PV industry in maintaining and strengthening its position in a highly competitive and rapidly innovating global market.

The table below summarises the key targets contained in the SRA. The 2020 targets are in line with the Key Performance Indicators defined for the Solar Europe Industry Initiative.

	1980	TODAY	2020	2030	LONG TERM POTENTIAL
Typical turn-key price for a 100 kW system (2011 € / W, excl. VAT)	>30	2.5	1.5	1	0.5
Typical electricity generation costs in southern Europe (2011 € / kWh)	>2	0.19	0.10	0.06	0.03
Typical system energy payback time Southern Europe (years)	>10	0.5-1.5	<0.5	<0.5	0.25

The conversion from turn-key system price to generation costs requires several assumptions since it is dependent on location, system lifetime, system performance and economic factors. This report assumes:

- an average performance ratio of 80%, i.e. a system yield of 800 $^{kWh}/_{kW \cdot yr}$ at a solar irradiation level of 1000 $^{kWh}/_{m^2 \cdot yr}$. A location in southern Europe, with a global solar irradiation at optimum angle of 1800 kWh / m^2 is assumed and a performance ratio of 80% translates into 1440 $^{kWh}/_{kW \cdot yr}$
- on average, 1% of the system's price is spent each year on operation and maintenance
- the economic system lifetime is 25 years
- a discount rate of 6.5% is used.

For the values in 2030 and beyond, longer system lifetimes and improvements in performance ratio are assumed.

The current and 2020 values used in Table 1 are consistent with the Key Performance Indicators used for PV in the Solar Europe Industry Initiative and are based on their Case Study 2, a 100 kW commercial roof system in Italy. For clarity, we have chosen to use the figures for a specific reference system to define the targets. However, it is acknowledged that prices and generation cost values for PV systems in Europe cover quite a large range. The range in system prices reflects differences in the prices of the components of a PV system, as well as in the cost of installation. Moreover, the price differs depending on the market segment / type of application (residential, commercial, industrial and utility-scale). In addition, differences in irradiation levels and in other operating and financial conditions for different locations will result in a different electricity generation cost for the same system capital cost.

For PV systems using concentration of sunlight or those incorporating tracking, a different energy output would be expected for the same global irradiation conditions when compared to the fixed flat-plate system assumed above. Therefore, similar electricity generation costs would be achieved at a different system cost. In this case, the overall generation cost should be considered as the target value.

The table does not include efficiency targets since these differ between technologies for the same resultant generation costs. Efficiency targets for each technology are provided within the detailed discussions of research priorities in the main body of the report.

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

- PV cells and modules:
  – materials
  – conversion principles and devices
  – processing and assembly (incl. equipment)

- PV systems:
  – system components and installation materials
  – installation
  – operation and maintenance
  – grid integration and integration into the built environment

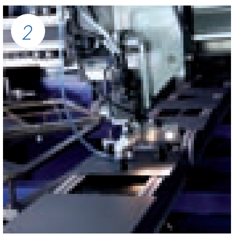
- concentrator systems
- environmental quality
- applicability
- socio-economic aspects of PV

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 reflected by the investments being made worldwide in production capacity based around many different technologies, and in the numerous concepts with large commercial potential being developed in laboratories. 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 investigating 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

In the area of "cells and modules", a distinction is made between existing technologies (wafer-based crystalline silicon, thin-film silicon, thin-film polycrystalline materials and organic materials) and 'novel' technologies and concepts (advanced versions of existing technologies, intermediate band semiconductors, hot-carrier devices, spectrum converters, etc.). Concentrator PV cells and modules are discussed in a separate section.

The main R&D topics per technology area are summarised immediately below. More detailed descriptions can be found in Chapter 4.



1. CIGS façade in a reconstructed office building at the University of Erfurt, Germany ©WURTH SOLAR

2. Automatic loading station of an in-line PE-CVD deposition system for anti reflective and passivation coatings on c-Si solar cells ©SINGULUS TECHNOLOGIES AG

1.1. Cells and modules

1.1.1. Topics common to all technologies

- 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 (€ / W), but on the energy yield (kWh / W) 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.

- 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

Moving towards a degree of standardisation and harmonisation in the physical, mechanical and electrical characteristics of PV modules can contribute to reducing installation costs. Ease of installation and the aesthetic quality of modules (and systems) are important if they are to be used on a large scale in the built environment.

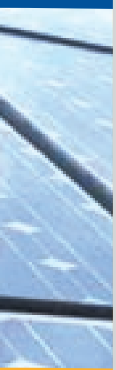
1.1.2. Wafer-based crystalline silicon (Si) technology

- 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 ensure high quality devices
- Increasing the efficiency through the optimisation of existing concepts for cells and modules as well as through new and integrated concepts in the long term
- New and improved materials for all parts of the manufacturing chain, including encapsulation and metallisation
- Integrated processes for cell and module manufacturing, thereby combining features of crystalline Si and thin-film PV technology
- High-throughput, high-yield, integrated industrial equipment, processing and quality assurance
- Finding safe processing techniques with lower environmental impact, including waste reduction

1.1.3. Thin-film technologies

Common aspects for existing thin-film technologies:

- 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 modules that have reached the end of their lives
- Alternatives for scarce chemical elements such as indium, gallium, tellurium



Thin-film silicon (TFSi)

- Processes and equipment for low-cost, large-area plasma deposition of micro / nanocrystalline silicon solar cells
- Development of high-quality, low-cost TCOs suitable for large-area, high-performance (>12% efficiency) modules
- Demonstration of higher efficiency TFSi devices (above 15% on laboratory scale), improved understanding of interface and material properties, light trapping, and the fundamental limits faced by TFSi-based materials and devices

Copper indium gallium diselenide (CIGSS)

- Improvement of throughput, yield and degree of standardisation for processes and production equipment
- Module efficiency >16% (or >20% at prototype scale) through improved TCO / heterojunctions, absorber quality, contact passivation and deeper understanding of the fundamental physics of these devices
- Alternative / modified material combinations and processing (roll-to-roll coating, combined or non-vacuum deposition methods), highly reliable and low-cost packaging to reduce material costs
- Device concepts for high efficiency

Cadmium telluride (CdTe)

- Activation / annealing treatments to control the electronic properties of the CdTe layer
- Improved and simplified back-contacting for enhanced yield and throughput
- Enhanced fundamental knowledge of materials and interfaces for advanced devices with high efficiencies (up to 20% at laboratory scale)
- Device concepts for reduction of CdTe layer thickness
- Device concepts for high efficiency

Organic photovoltaics (OPV)

- Fundamental understanding of the physics of dye and full-organic solar cells including the effect of nanomorphology and order on electrical transport and exciton transport and dissociation
- Improvement of stability, including low-cost encapsulation layers
- Extrinsic doping of organic materials
- Behaviour and time evolution of contact-organic semiconductor interface
- Development of new materials (sensitisers, donor and acceptor materials) and *ab initio* modelling of properties
- Materials and processes for multiple band gap approaches
- Optical optimisation in thin layers taking into account interference effects
- Development of high-throughput processing equipment

1.1.4. Novel PV technologies

- Demonstration of new conversion principles and basic operation of new device concepts
- *Ab initio* material modelling
- Opto-electrical modelling and simulations
- Nanoparticle synthesis
- Stability of boosting layer material for up-down converters and photonic structures
- Investigation of deposition techniques

1.1.5. Concentrator photovoltaics (CPV)

Materials and components

- Optical systems: find reliable, long-term stable and low-cost plane and concave mirrors, lenses and Fresnel lenses as well as secondary concentrators
- Module assembly: Develop materials and mounting techniques for assembling concentrator cells and optical elements into highly precise, long-term stable modules using low-cost, fully automated methods
- Tracking: Find constructions that are optimised for size, load-capacity, stability, stiffness and material consumption

Devices and efficiency

- Develop materials and industrial production technologies for very high efficiency concentrator solar cells:
  – Si cells with efficiencies of 26%
  – multijunction III-V-compound cells with efficiencies above 45% (48% in the laboratory)
- Identify the optimum concentration factor for each approach

Manufacturing and installation

- Find optimised design, production and testing routines for the integration of all system components
- Scale up production with fully automated production lines for high volumes
- Optimise methods for installing, outdoor testing and evaluating the cost of CPV systems

1.2. PV components and systems: integration with the electricity grid and buildings

PV Components

- Increasing inverter lifetime and reliability
- New storage technologies for small and large applications and the management and control systems required for their efficient and reliable operation
- Harmonising components, including lifetimes, dimensions and options for modularity to decrease site specific costs at installation and replacement costs during system life
- Assessing and optimising the added value of PV systems for different system configurations
- Innovative BIPV components that enhance multifunctionality
- Components and system designs for island PV and PV-hybrid systems

PV Systems

- Grid codes with appropriate requirements on distributed generation devices in terms of reactive and active power control, fault-ride-through capabilities, etc
- Local consumption of electrical energy at the point of generation in order to reduce the grid overload
- Implementation of smart-metering concepts in order to gain more transparency in energy generation and consumption
- In order to increase the utilisation of PV, the storage capabilities of electric vehicles have to be taken into account

1.3. Standards, quality assurance, safety and environmental aspects

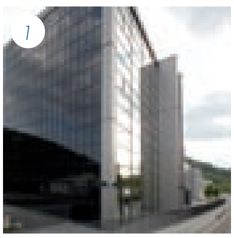
- Further develop performance, energy rating and safety standards for PV modules, PV building elements and PV inverters and AC modules
- Harmonise conditions for grid connection across Europe, including in relation to smart grids
- Develop quality assurance guidelines for the whole manufacturing chain
- Develop recycling processes for thin-film modules and balance of system (BoS) components
- Conduct lifecycle analyses on thin-film and CPV modules and BoS components, and in the longer term, on novel cell / module technologies

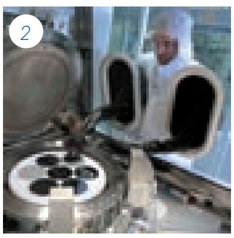
1.4. Socio-economic aspects and enabling research

- Identify and quantify the non-technical (i.e. societal, economic and environmental) costs and benefits of PV
- Address regulatory requirements and barriers to the use of PV on a large scale
- Establish the skills base that will be required by the PV and associated industries in the short and medium term and develop a plan for its provision
- Address the administrative and public relations aspects of a cost-effective and workable infrastructure for reuse and recycling of PV components
- Develop schemes for improved awareness in the general public and targeted commercial sectors

It is envisaged that this edition of the SRA will be used in a similar manner to the first edition, to inform R&D programmes at both the European level (FP7 and its successor) and at national level. By interpreting the research priorities described here in their own national contexts (national R&D strengths, presence of industry), Member States can align their publicly-funded R&D with the SRA's recommendations, to the benefit of PV in Europe. The SRA also supports the Solar Europe Industry Initiative in its description of short- to medium-term research needs.

PV 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 electrical energy system in the long term and will be a key component of our future, green electrical energy supply system. However, PV also has a clear role to play in meeting Europe's renewable energy targets for 2020. The rapid growth of the PV sector offers economic opportunities for Europe that must be seized now, both in terms of maintaining market share and promoting widespread implementation of the technology. The next few years will be decisive for the future role of the European PV industry.





1. CIGS façade integrated into a university building (Reinhold-Wurth-Hochschule, Künzelsau, Germany) ©WURTH SOLAR

2. CRIUS Showerhead MOVPE reactor for the growth of III-V multijunction solar cells ©FRAUNHOFER-ISE

2 Introduction

2.1. What is photovoltaic solar energy?

Photovoltaics (PV) is the direct conversion of sunlight into electricity. It is a very elegant process to generate environmentally-friendly, renewable electricity. PV technology is suited to a broad range of applications due to its modular nature and emission-free, silent operation, and can contribute *substantially* to our future electrical energy needs. Although the photovoltaic effect was first observed in the 19th century, it was not until the 1950s and 1960s 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, using different materials, device structures and manufacturing processes, is available on the market and under development in laboratories.

Complete PV systems consist of two basic 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, optics and sun trackers.

2.2. Why a Strategic Research Agenda (SRA)?

In recent years the cost of electricity generated from PV has declined steadily as the technology behind it has become more efficient and as the number of installations has grown, often more rapidly than even the most optimistic predictions. Over the next few years, these trends are expected to continue and intensify. A recent study carried out by the European Photovoltaic Industry Association (EPIA), with support from strategic consulting firm A.T. Kearney and based on an extensive analysis of five EU markets (Germany, France, Italy, United Kingdom and Spain), has considered how rapidly PV will become more cost-effective in the coming years. The study concludes that, under the right policy and market conditions, PV can be competitive with grid supplied electricity in some markets as early as 2013 and across all market segments in the EU by 2020. Moreover, PV electricity is today already a notable alternative to diesel generators in stand-alone applications (especially in areas with significant hours of sunlight). As a result of the expected significant reduction in PV system prices, PV will be able to fulfil its potential as a major source of the world's electricity generation [EPIA 2011a].

In addition to appropriate market conditions, Research and Development – "R&D" – is crucial to the further development of PV technology. 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. The European PV Technology Platform recognised the necessity of PV R&D when it produced a Strategic Research Agenda (SRA) to realise the 2005 Vision document of the Photovoltaic Research Advisory Council, set up as a precursor to the Platform. The first edition of the SRA was published in 2007 and was used as input for the definition of the Seventh Framework Programme of the European Union and also to facilitate a further coordination of research programmes in and between Member States, and internationally, notably through the IEA [IEA 2010].

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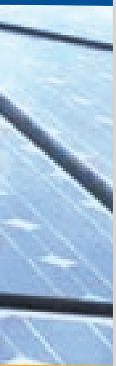

Energy Technology Plan, the Platform decided to update the SRA to address the rapid technological developments required for these new challenges and opportunities. This second edition is intended to perform a similar function to its predecessor in terms of informing the research programmes of the EU and the Member States. These are key programmes to support the European PV industry in maintaining and strengthening its position in a highly competitive and rapidly innovating global market.

2.3. PV state-of-the-art and potential

PV modules and other system components have undergone an impressive transformation in recent years, leading to higher efficiencies, better environmental performance and substantially lower costs. Nevertheless, PV technology has by no means demonstrated its full potential. Table 1 gives an indication of where PV was 30 years ago, where it stands today and what it could realistically achieve in the future.

Table 1. Targets for the development of PV that are used as the basis for the research objectives, together with current and historical data (see below for summary of assumptions used in the cost calculations).

	1980	TODAY	2020	2030	LONG TERM POTENTIAL
Typical turn-key price for a 100 kW system (2011 € / W, excl. VAT)	>30	2.5	1.5	1	0.5
Typical electricity generation costs Southern Europe (2011 € / kWh)	>2	0.19	0.10	0.06	0.03
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The conversion from turn-key system price to generation costs requires several assumptions since it is dependent on location, system lifetime, system performance and economic factors. This report assumes:

- an average performance ratio of 80%, i.e. a system yield of 800 kWh / kW•yr at a solar irradiation level of 1000 kWh / m^2•yr. A location in southern Europe, with a global solar irradiation at optimum angle of 1800 kWh / m^2 is assumed and a performance ratio of 80% translates into 1440 kWh / kW•yr
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For PV systems using concentration of sunlight or those incorporating tracking, a different energy output would be expected for the same global irradiation conditions when compared to the fixed flat plate system assumed above. Therefore, similar electricity generation costs would be achieved at a different system cost. In this case, the overall generation cost should be considered as the target value

The table does not include efficiency targets since these differ between technologies for the same resultant generation costs. Efficiency targets for each technology are provided within the relevant technology sections in Section 4.

2.4. The value of PV for Europe and the world

2.4.1. Energy and climate

The solar energy resource is larger than all other renewable energy resources [UND 2000, WBG 2004]. By the end of 2010, around 40 GW of PV was installed worldwide, with about 75% of that capacity in Europe [EPIA 2011b]. In terms of newly installed capacity in Europe, PV was the largest renewable energy source in 2010, followed by wind and second only to gas [EPIA 2011b]. Although still a small contributor to electrical energy demand with a total output of around 50 TWh per year, the recent rapid market growth shows that PV can make a significant contribution by 2020 and continue to grow thereafter. In 2020 PV may contribute up to 4% of the world's electricity demand and 9% in 2030, according to the most recent report from Greenpeace and EPIA [EPIA 2011c]. In addition, PV requires almost no water in its operations. It is also compatible with dual usage of land (when applied on rooftops or when installed on raised support structures on grazing land).

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 bringing electricity to many millions of people in developing countries.

2.4.2. PV within the EU Strategic Energy Technology Plan

In 2009, the European Union adopted Directive 2009 / 28 / EC with binding targets for renewable energy generation, energy efficiency and reduction of greenhouse gases by 2020 [EC 2009], based on the agreements of the European Council in 2007 [EC 2007]. The requirement for 20% of European energy demand to be met from renewable technologies by 2020 is challenging and is likely to require renewable sources to provide 35-40% of European electricity supply at this time. Clearly, PV has the potential to play a significant part in this provision and create a foundation for increasing contribution after 2020.

The Strategic Energy Technology (SET) Plan addresses the move to a low carbon energy future and, in 2010, the Solar Europe Industry Initiative (SEII) was launched [SEII 2010]. This mainly addresses the research and development needs to meet 2020 targets and is a major contribution to the fulfilment of the near term potential of PV. This updated SRA from the European Photovoltaic Technology Platform is consistent with the SEII Implementation Plan, whilst also considering research in the post-2020 timeframe.

2.4.3. The PV market, revenues and jobs

The annual global PV shipments in 2010 were over 17 GW, with the market showing a compound annual growth rate of 65% over the period 2005-2010 despite the general economic downturn in the last few years [NAV 2011, EPIA 2011b]. This impressive growth is due to successful market development policies in several countries, but most notably in Europe where over three quarters of all installations took place in 2010.

Using an average system cost of 2.5 €/W (see Table 1), this gives an estimated global annual revenue of about €44 billion in 2010, where around half of this is related to the module revenues. Projecting to 2020 and assuming that the cost targets in Table 1 are achieved, we can estimate a global annual revenue of over €200 billion for an annual market size of around 135 GW, as forecast in EPIA's "paradigm shift" growth scenario [EPIA 2011c]. EPIA also notes, "at least 50-55% of the total value of a PV system is created close to the end market", i.e. where the system is installed.

To meet the challenge of this market expansion, the sector needs a diverse and qualified workforce including engineers who install and maintain the PV systems, skilled operators and technicians in high-tech solar factories and expert semiconductor specialists in R&D departments. To estimate the employment potential, EPIA currently uses an assumption of 30 jobs per MW installed resulting in a forecast of 3.8 million jobs worldwide by 2020 under their paradigm shift growth scenario [EPIA 2011b]. 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.

In 2005, the European Commission acknowledged [EC 2005a]:

The renewable energy sector is particularly promising in terms of job and local wealth creation. The sector invests heavily in research and technological innovation and generates employment, which to a very high degree means skilled, high quality jobs. Moreover, the renewable energy sector has a decentralised structure, which leads to employment in the less industrialised areas as well. Unlike other jobs, these jobs cannot be "globalised" to the same extent. Even if a country were to import 100% of its renewable energy technology, a significant number of jobs would be created locally for the sale, installation and maintenance of the systems.

Electricity generated with photovoltaic systems has additional benefits for the European economy in the long term. Firstly, it can help to reduce the European Union's dependence on energy imports. The European Commission's 2005 report also acknowledged:

Rising oil prices and the concomitant general increase in energy prices reveals the vulnerability and dependency on energy imports of most economies. The European Commission's DG ECFIN predicts that a $10/bbl oil price increase from $50 to $60/bbl would cost the EU about 0.3% growth and the US 0.35% [EC 2005b]. For the European Union, the negative GDP effect would be roughly €40 billion from 2005 to 2007. Further price increases would worsen the situation.

Since this report was published, a significantly higher oil price has been reached, with the US Energy Information Adminstration quoting an average price for crude oil of over US$79 per barrel in 2010 and predicting around US$103 per barrel for 2011 [EIA 2011].

Electricity from photovoltaic systems can be well matched to peaks in demand during the middle of the day, when high marginal costs of electricity production are experienced in some parts of Europe. In southern European climates, where the seasonal peak in electricity demand occurs in the summer, again the output of photovoltaic capacity is at its greatest and it can be relied upon in rare cases of extreme heat and water shortage when thermoelectric power plants have to reduce their output due to a lack of cooling water.

The reduction in system prices observed over the last few years, coupled with relatively high electricity prices in some southern European countries, means that economic parity with conventional electricity generation is likely to be achieved in several countries before 2015 and the SRA takes account of this in its detailed consideration of issues relating to widespread connection of PV system to the electrical grid.

2.4.3.1. International competition

Europe's photovoltaic industry competes with companies from Asia, the USA and other parts of the world in terms of manufacture of the main components of the PV system. Since the publication of the first edition of the SRA in 2007, the market leadership in module production has moved from Europe (32% market share in 2007) to China and Taiwan (54% market share in 2010) due to major investments in manufacturing capacity in the latter region in the last five years [NAV 2011]. Nevertheless, Europe has increased its own shipments by 260% over this period and retains significant market share in regard to other system components, particularly inverters, and relating to materials and manufacturing equipment for PV module production lines.

China has an industrial strategy geared towards building up a highly competitive PV industry. Manufacturers in China are often vertically integrated, some across the whole value chain from silicon feedstock to complete systems, including distribution houses for holding excess inventory. Given the current difference in investment strategies in Europe and China, it is likely that China will remain the dominant module manufacturing region in the near future and other regions such as the Philippines and India may also be strong in PV module production. History has shown, however, that regional dominance tends to shift as markets develop and this trend does not preclude a strong European PV industry both now and in the future.

In February 2011, the U.S. Energy Secretary Steve Chu formally unveiled the Sun Shot Initiative, which is labelled after President Kennedy's famous *moon shot* speech in 1962. According to the Department of Energy (DoE) it is a *"collaborative national initiative to make solar energy technologies cost-competitive with other forms of energy by reducing the cost of solar energy systems by about 75% before 2020."* The aim of the initiative is to accelerate and advance existing DoE research efforts by refocusing its solar energy programmes, valued at approximately $200 million (€154 million) per year, to make large-scale solar energy systems cost competitive without subsidies by the end of the decade.

Europe could maintain a competitive position due to the excellent knowledge base of its researchers and engineers and the introduction of new module and system technologies. This needs to be underpinned by a strong R&D agenda allowing European companies to develop innovative solutions to capture market share.

2.4.3.2. PV for development and poverty reduction

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, fuel free (except for sunlight) energy source, PV has the potential to create economic and political stability, with clear implications for improved international security. 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 1 billion people in the world do not have access to electricity.

The Asian Development Bank (ADB) launched an Asian Solar Energy Initiative (ASEI) in 2010, which should lead to the installation of 3 GW of solar power by 2012 [ADB 2011]. In their report, ADB states, *"Overall, ASEI aims to create a virtuous cycle of solar energy investments in the region, toward achieving grid parity, so that ADB developing member countries optimally benefit from this clean, inexhaustible energy resource."*

The steady growth in off-grid applications of PV in recent years has been overshadowed by the much more rapid growth in grid-connected capacity under strong market development policies. Nevertheless, the off-grid sector as a whole grew by 70% in the five years from 2005 to 2010 reaching a global total of around 370 MW [MINTS 2011]. Of that, the remote habitation market represents about 66%. It is easy to overlook this important market segment in favour of the much larger implementation of grid-connected systems, but this would also ignore the comparatively larger social impact of rural electricity provision and so the SRA includes R&D requirements for the development of stand alone PV systems. Alongside technical advances, it is also important to consider the financial and social requirements to ensure the successful implementation of PV to meet development targets for the most disadvantaged communities.

2.5. Targets and drivers for PV development

2.5.1. What are the PV implementation targets?

Since the publication of the first SRA in 2007, the targets for implementation of PV (and other renewable energy technologies) have changed substantially. The binding target of 20% of Europe's energy supply to come from renewable energy sources by 2020 has increased the urgency for their development. Whilst there is no requirement for individual targets for different technologies, all but one of the European Union countries included photovoltaics in their National Renewable Energy Action Plans submitted in 2010, with a cumulative value of 2.4% of Europe's electricity supply expected to be achieved [EPIA 2010]. Of course, this is a much lower percentage contribution than would be expected by current market growth rates.

2.5.2. Conditions for PV to meet the targets

Very large-scale deployment of PV is feasible if PV electricity generation costs are reduced by a factor of 2-3 over the next two decades. 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 in some locations), PV can continue to make use of "lead markets" on its way to eventually matching the cost of wholesale electricity. In particular PV already competes with peak power prices and will match consumer prices in the short term in southern Europe.

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

- 2011 – 2016: short term
- 2016 – 2025: medium term
- 2025 – 2035 and beyond: long term

Note that these timescales are not the same as those in the first edition of the SRA. As before, 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.

The overall targets of the SRA are in line with the objectives of the Solar Europe Industry Initiative up to 2020 [SEII 2010].

2.5.3. Drivers and enablers for PV development

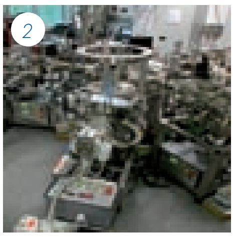
Generally, the cost and performance of PV technology is the focus of research effort, but the importance of other drivers should also be emphasised.

Firstly, R&D also needs to address the *value* of PV electricity. For example, if the PV supply pattern could be fully matched with the electricity demand rather than following the availability of sunlight, its value at times of high demand would be greater. The benefits of storage to the widespread integration of PV into the electricity grid are discussed in the section on PV systems research (Section 4.5). (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, but also increase the overall energy produced and ease the integration of PV in buildings.

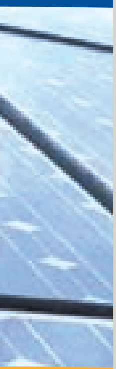
Thirdly, it is essential that energy and materials consumption in manufacturing and installation be addressed. Further shortening of the energy payback time of systems will add to the advantages of PV as an energy source and, in the longer term, its ability to avoid carbon dioxide emissions. Avoiding the use of scarce or hazardous materials and closing material-use cycles are also important topics with significant R&D challenges.

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



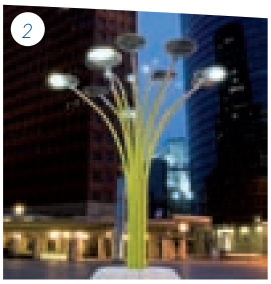
1. *Ten solar cell assemblies with substrates, solar cells and bypass diodes on a transport magazine. The assemblies are later placed in CPV modules.*
   ©FRAUNHOFER-ISE

2. *Integrated System for Solar Energy Research at TU Darmstadt: Research cluster tool for CdTe thin-film solar cell research*
   ©PROF. W. JÄGERMANN



In addition to the *technical* issues described above, the document addresses *socio-economic* aspects related to the large-scale implementation of PV. In summary, the SRA identifies and addresses the following drivers for PV development:

ELECTRICITY GENERATION COSTS AND VALUE	INTEGRATION
■ 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	■ method and ease of mounting, cabling, etc. (also for maintenance and repair) ■ flexibility / modularity ■ aesthetics and appearance ■ lifetime ■ integration into buildings ■ integration into the electrical grid ■ smart components and electrical control
ENVIRONMENTAL QUALITY	**SOCIO-ECONOMIC ASPECTS**
■ energy payback time: – modules – BoS ■ substitution of hazardous materials ■ options for recycling	■ public and political awareness ■ user acceptance ■ training and education ■ financing



1. *Semitransparent CIGS façade with varying transparency in insulated glass panels and with invisible junction boxes the sports arena of Anne-Sophie-School (Künzelsau, Germany)* ©WURTH SOLAR

2. *'Solar Tree' developed for street lighting by Sharp and Artemide, in operation in Berlin. The Solar Tree combines LED lighting, storage, and PV generation.* ©SHARP ELECTRONICS (EUROPE) GMBH 2010

3. *CdTe module manufacturing (Bitterfeld-Wolfen / Thalheim, Germany)* ©CALYXO

3 Governing principles of the SRA

Short-term research should be fully dedicated to the competitiveness of the EU industry.
The Solar Europe Industry Initiative has been established to promote the short term R&D required to meet 2020 targets, with projects being predominantly defined and led by European Industry. The SRA supports the SEII in this regard.

No exclusivity
PV comes and will come in different formats, suited to different applications. The SRA does not exclude technologies but sets overall targets that any PV format must reach and describes the research priorities for each format in order for it to succeed in meeting those targets. Inspection of the historical market share of different technologies shows that, whilst crystalline silicon has dominated the market, the thin-film technologies already have a significant presence and the relative shares vary with market conditions (Figure 2). There is an opportunity for all module technologies to make a significant contribution in the future.

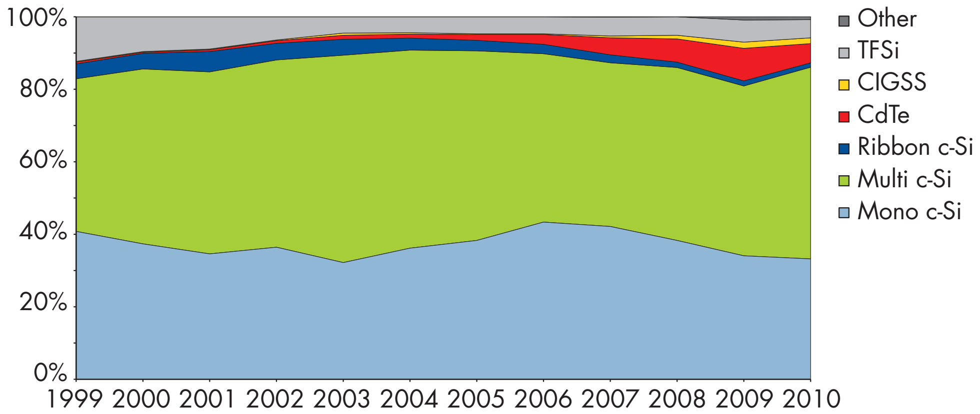
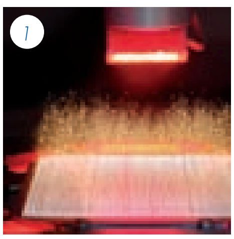
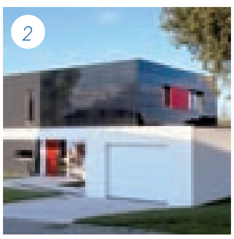


Figure 2. Fraction of different technologies in the PV market in the period 1999 - 2010 [PHOT 2011a].

Both revolution and evolution are needed
Whilst some topics in the SRA consider radically new concepts and approaches, so-called revolution, other areas recognise the progress that is made through the incremental improvement of manufacturing and implementation processes, so-called evolution. Both of these are needed to balance risk and make sure that advances are maintained from the basic R&D right through to the ability to manufacture at large scale.





1. Laser processing of the via holes of an EWT (Emitter wrap through) silicon solar cell ©FRAUNHOFER-ISE

2. CIGS integrated modules into a zero emission house with no visible fixing elements (P_{el} = 6.4kW) ©WURTH SOLAR

Public money is required to contribute to funding short, medium and long-term research into all parts of the value chain, as well as on socio-economic issues

To achieve the required cost reductions, research should address all parts of the value chain, from raw materials to the complete system. As PV provides a growing proportion of our electricity requirements, the integration of PV into the electricity delivery system needs to be fully addressed. Public funding agencies should adopt a strategic top-down decision on how to allocate funding between short, medium and long-term research.

All technologies have the same overall cost targets

The same cost targets are used for all flat-plate PV module technologies considered and these are expressed as **installed system level costs**: 1.5 €/W in 2020 and 1 €/W in 2030. To meet the overall, cross-technology cost target, lower efficiency modules need to be cheaper than higher efficiency modules, due to the area-related component of the BoS costs. System costs are dependent on the specific application. Therefore the cost targets provided in Table 1 are for medium scale systems and not building integrated. The other systems included in the KPIs for the Solar Europe Industry Initiative address alternative system types and range from 85% to 125% of the cost shown for 2010 values.

A 16 000 m² PV system consisting of customised modules with laminated glass-backsheet, integrated onto the flat roof of BMW World (Munich, Germany) ©SOLARWATT

4 PV development options, perspectives and R&D needs
(short-, medium- and long-term)

4.1. Cell and module technologies for flat-plate systems

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 substrate. For end-users, the nature of the cell technology used is seldom of concern.The important parameters from their perspective are the price per watt of the module, the energy yield per watt under field conditions, the module efficiency, its size and weight, flexibility or rigidity, and appearance. Customers will also be interested in the provisions for taking back and recycling the modules at the end of their life. 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:

1. Wafer-based crystalline silicon
2. Thin-film technologies
3. Novel PV technologies

The R&D issues relating to concentrator systems need to be addressed in a more integrated manner moving through to the system level, so they are covered here in a separate section, 4.4. Research described in the "Novel PV technologies" section (4.5) is also relevant to concentrator systems.

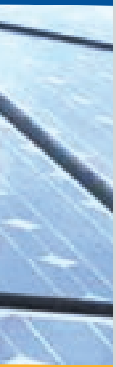
In the following paragraphs the R&D needs of the technology categories are analysed in detail. They have a number of R&D issues in common, which are briefly summarised here:

4.1.1. Efficiency, energy yield, stability and lifetime

Research aims to optimise combinations of these parameters rather than one parameter at the expense of another. This requires careful analysis of the costs and benefits of individual technological improvements. It is important not to focus only on initial costs (€/W), but also on the system's energy yield (kWh/W) over its economic or technical lifetime.

4.1.2. High productivity manufacturing, including in-process monitoring and 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.



4.1.3. Environmental sustainability

The energy and material requirements of manufacturing as well as recyclability are important parameters in the overall environmental quality of the product. Shortening still further the energy payback time of modules, designing products in a way that makes them readily recyclable and avoiding the use of hazardous materials are the most important issues to be addressed here.

4.1.4. Integration

As its contribution increases, there is a need to consider the integration of PV technology into the existing infrastructure, most notably in terms of penetration into the electricity distribution network (control, safety, storage) and into the built environment (building integrated systems).

4.2. Wafer-based crystalline silicon

4.2.1. 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 characteristics are well understood, in part thanks to its relevance to the microelectronics industry. A learning curve for the progress in silicon wafer-based technology spanning three decades can be drawn, showing that the price of the technology has decreased by 20% for each doubling of cumulative installed capacity. The driving forces behind this process are market size and technology improvement. These are the combined result of research, market-stimulation measures and development and demonstration activities with both private and public support.

The pillars of crystalline silicon photovoltaics are

- Research and development at universities, institutes and companies
- Equipment industry
- Materials industry (i.e. inks, encapsulants, chemicals)
- Silicon material manufacturing
- Solar cell manufacturing
- Module assembly

There is a clear trend towards an increasing vertical integration in many of the large PV companies, i.e. covering most of the value chain from silicon to module fabrication and even into the system field.

Crystalline silicon modules are manufactured in six steps: (i) silicon production, (ii) silicon purification, (iii) silicon crystal growth, (iv) wafer slicing, (v) cell fabrication and (vi) module assembly. Although considerable progress has already been made in each step, there is significant potential for further improvement. For example, wafers have decreased in thickness from 400 µm in 1990 to 180 µm in 2010 and have increased in area from 100 cm^2 to 240 cm^2; modules have increased in efficiency from about 10% in 1990 to typically 15 % today and manufacturing facilities have increased from the annual outputs of typically 1-5 MW in 1990 to GW levels for today's largest factories.

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 including advanced process control. Other important measures that should receive attention include reducing embedded energy content (and hence the energy payback-time), the environmental impacts of PV systems over their lifecycle and the definition of accepted standards for crystalline silicon products (see section 4.7).

Crystalline silicon is a technology with the ability to continue to reduce cost at its historic rate. The direct production costs of crystalline silicon modules are already in the region of 1 €/W and expected to be significantly less than this in the medium term. Since the cost distribution is dominated by the silicon wafer, an increase of efficiency is seen as one of the best ways to reduce production costs.

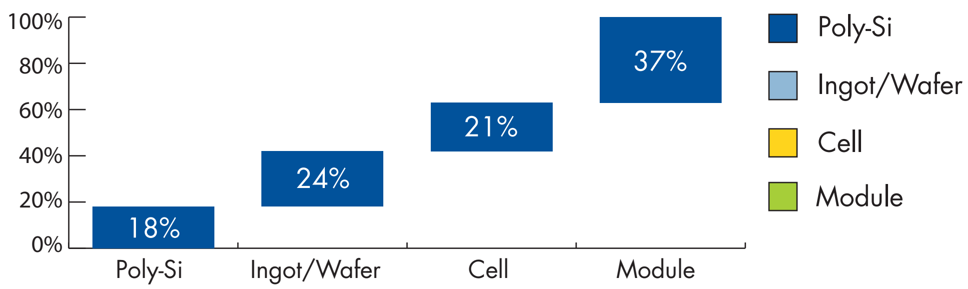


Figure 3. Relative cost distribution of the production of crystalline silicon PV module.

4.2.2. What has happened since 2007?

Since the last SRA in 2007 a very strong development of crystalline silicon photovoltaics was observed. Many of these trends were predicted by the first edition of the SRA in 2007, showing the quality of the previous study.

1. The efficiency of cells increased by about 1% absolute for mono- and multi-crystalline silicon. In most cases, this was achieved by further optimisation of the existing cell structure (screen-printed Al-BSF solar cell).
2. Increased production capacity (36 GW/yr in total, with six companies with >1 GW/yr [PHOT 2011b] and optimised production sequence and process control has led to lower cost per cell.
3. During the time of silicon shortage the price curve remained slightly above the historical price curve. The large increase in production capacity and a return to reasonable silicon prices has moved the price back to and then below historical price curve. This is a combined effect of increased efficiencies and lower production costs (Figure 4).
4. Cell thickness was reduced although not as much as expected since silicon feedstock prices returned to a reasonable level (see Figure 5).
5. New cell technologies such as selective emitter formation are currently being transferred to industrial production.
6. There was important progress on cells in epitaxially grown Si layers with efficiencies between 17% and 19% for different approaches based on monolithic epicells on highly doped Si-substrates or lifted-off epitaxially grown Si-foils.

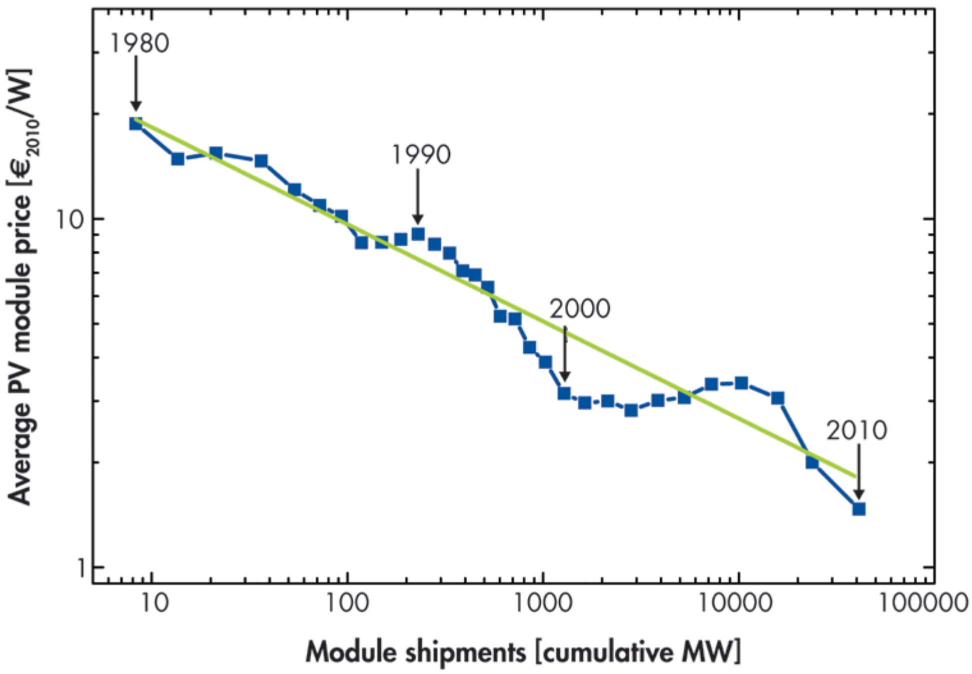


Figure 4. Historical development of PV module prices (PSE AG/Fraunhofer-ISE, data based on Strategies Unlimited and Navigant Consulting). The green curve is a fitted trend line of the historical price data.

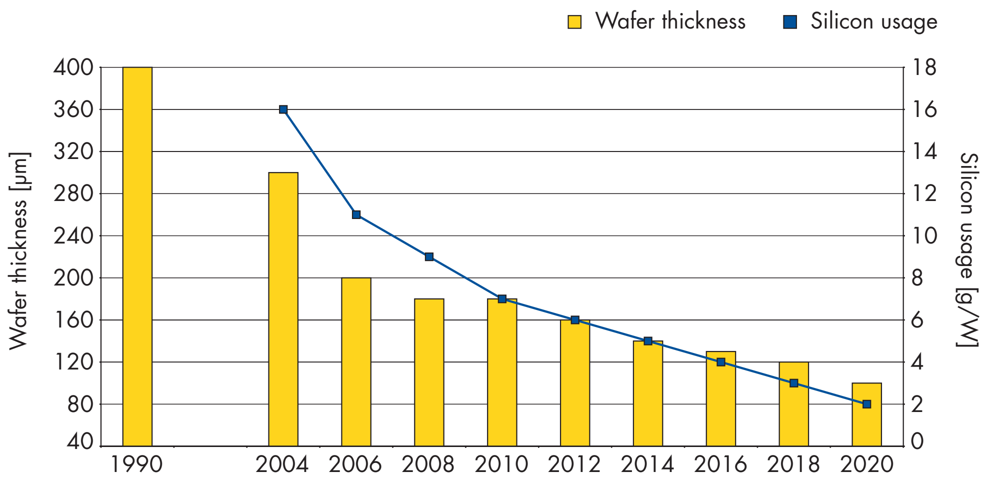


Figure 5. Development of wafer thickness and silicon usage (data and graph: EPIA)

4.2.3. 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 most relevant crystallisation technology is directional solidification resulting in multicrystalline silicon (2010: 53% of the market). This is followed by monocrystalline silicon fabricated by the Czochralski-method (2010: 33% of the market). The ingots formed by both methods are sliced into thin wafers by wire sawing. This results in a severe loss of silicon. An alternative method is ribbon silicon where thin ribbons are directly fabricated from the silicon melt (2010: 1.2% market share). Wafers and ribbons are processed into solar cells and interconnected in weatherproof packages designed to last for at least 25 years. The processes in the manufacturing chain have improved significantly during recent years but can be further improved.

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 (up to 260 €/kg in 2008) 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 clearly shown by the lower silicon consumption per W of module power produced. Silicon usage is currently 7 g/W, whereas it was typically 10 g/W in 2007. Since the feedstock price has now reduced, the pressure to reduce silicon usage is relaxed a little but still has a high priority.

The conventional Siemens process is a chemical process with a large footprint, high investment costs (>100 €/kg annual production) and a long time span for plant building (>3 years). High purity silicon with impurity levels in the parts per trillion range – the standard for electronic industry – can be produced for PV. However, it is possible to produce solar cells with less pure material and reach comparable efficiencies. The development of new techniques for silicon feedstock production with lower cost and less energy consumption is underway. This feedstock is expected to achieve prices in the range 10-20 €/kg (now 30-50 €/kg) and will thus be a key enabler for future PV growth and cost reduction. This type of feedstock is commonly known as "umg-Si" (upgraded metallurgical-grade silicon) or "SoG-Si" (solar-grade silicon).

During the manufacturing process, 50% or more of the polysilicon starting material is lost, even after recycling of sides, bottoms, and top cuts from ingots. There are currently no commercial methods to recycle silicon dust produced during wire sawing. To improve casting and wafering, waste during polysilicon crystallisation should be reduced, sawing dust and other silicon off-cuts recycled and material handling in the production process improved through automation. In the long term polysilicon consumption below 2 g/W is targeted. For wafer equivalent or crystalline Si on non-Si carrier technologies, the challenge is to develop high throughput low-cost silicon film deposition techniques with suitable low-cost substrates.

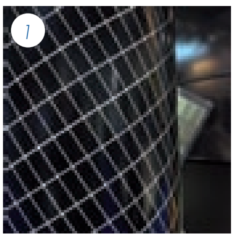
Module assembly is also material-intensive. The assembly must protect the cells from the outdoor environment typically for a minimum of 25 years while allowing the cell to function efficiently. The current standard design, using rigid glass-polymer encapsulation in an aluminium frame, fulfils these basic requirements but represents about 30% of the overall module cost, contains a lot of embedded energy (increasing the energy payback time of the module) and is a challenge for manufacturing on automated lines even at current wafer thicknesses.

The biggest influences on the cost effectiveness of the conversion of cells to modules are, firstly, the optimisation of cell efficiency and durability and, secondly, the optimisation of the combined module manufacturing cost and installation cost. Shallow emitter cells benefit from lower UV cut-off frontside materials (which increases the UV challenge to the backside materials), heterojunction cells require more moisture protection and ultrathin (eg epitaxial) cells may require different module materials. To further improve the cost effectiveness of the module components, the amount of material consumed per m^2 and the cost of processing should be reduced by minimising the number of process steps used in the overall supply chain and facilitating high speed processing.

CELL	MODULE MATERIAL IMPROVEMENT NEEDED
Shallow emitter, selective emitter	Improved blue light transmission (<500nm) in glass and encapsulant
Rear surface passivation	None
n-type Si	None
New metallisation	Reliable alternative interconnection technologies
Heterojunction	Moisture-proof components, low melt temperature contacting
Back contact	Back circuit sheets
Thin cells	Encapsulants with more mechanical protection, added optical functionality
Increased module lifetime	High durability encapsulation, low-cost but durable backsheets, durable anti-reflective coating on glass

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 deviate 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, partly due to improved cell design and to newly developed metallisation techniques, may eliminate discrete soldering steps as the interconnection scheme could be embedded in encapsulation sheets.

Finally, sufficient attention has to be given to the development of sustainable solutions. Although crystalline Si is not in principle limited in terms of supply, this should also be the case for the other materials used. Very large-scale manufacturing may require alternatives to be found for scarce chemical elements currently used in the module assembly, such as silver, which is consumed at an average of 80-90 mg / W summing up to around 1300 tonnes / yr. Copper, which is also used in microlectronics, might be a good alternative, although, due to its higher diffusity in silicon, long-term stability has to be studied in detail.



1. Ultra-light, flexible module made on mono-crystalline silicon solar cells. This module is used in space applications.
©SHARP LABORATORIES OF EUROPE 2009

2. 20000x scanning electron microscope picture of ZnO films with nanorods prepared by electrochemical deposition for application in nanostructured thin-films solar cells. ©D. DIMOVA-MALINOVSKA, ET AL

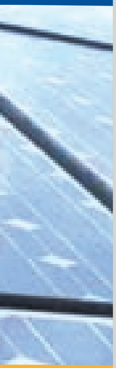
Table 2. Research priorities for **silicon materials needed for crystalline silicon photovoltaics** – time horizons for first expected application of research results in (pilot) manufacturing and products. Targets to be achieved in those time horizons are also shown.

MATERIALS	2011 – 2016	2016 – 2025	2025 – 2035 and beyond
Industry manufacturing aspects	Target: polysilicon ■ Consumption 5 g / W ■ Cost 15-25 € / kg (depending on quality) ■ Wafer thickness <150 µm	Target: polysilicon ■ Consumption <3 g / W ■ Cost 10-20 € / kg (depending on quality) ■ Wafer thickness <100 µm	Target: polysilicon ■ Consumption <2 g / W ■ Cost <10 € / kg (depending on quality) ■ Wafer thickness <50 µm
Applied / advanced technology aspects	■ New Si feedstock ■ Improved crystal growth ■ Reusable crucibles with low-impurity inclusion ■ Reduced kerf loss in sawing ■ Fracture mechanics of thin wafers ■ Metal pastes suited for low-temperature firing and high-resistivity emitters ■ Avoidance of hazardous materials ■ Encapsulants with low total cost of ownership ■ New frames and supporting structures ■ Reduction of glass thickness ■ Improved recycling ■ Low-impact, safe manufacturing ■ Development of Cu-based contact systems	■ New Si feedstock ■ Low-defect (high electronic quality) silicon wafers ■ Improved wafering ■ Wafer equivalents ■ High-throughput reactors for Si (epitaxial) deposition ■ Improved encapsulants ■ Safe processes ■ Conductive adhesives or other solder free solutions for module interconnection ■ Recycling of kerf ■ Si yield >75% ■ Kerfless methods for Si-foil or ribbon production with thickness <75 µm	■ New Si feedstock ■ Low-defect (high electronic quality) silicon wafers ■ Improved wafering ■ Wafer equivalents ■ New encapsulants ■ Safe processes ■ Si yield >90% ■ Kerfless methods for Si-foil production with thickness <<50 µm ■ Integration of up and down-convertors in crystalline Si cells and modules
Basic research and fundamentals	■ Defect characterisation and control in silicon ■ New feedstock technologies ■ Advanced wafering technologies ■ Wafer-equivalent technologies ■ Reliability and ageing of Cu-based contact systems ■ New encapsulants	■ Defect control in silicon ■ New feedstock technologies ■ Novel wafering technologies ■ Wafer-equivalents technologies ■ New materials for metal contacts ■ New encapsulants ■ Material development for up and down-conversion layers	■ Wafer-equivalent technologies ■ New materials for metal contacts and cell / module manufacture ■ Material development for up- and down-conversion layers

4.2.4. Performance and devices

Cell and module efficiencies have a direct impact on the overall € / W cost (and price) of a PV module and have always 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 1% in efficiency alone is able to reduce the costs per W by 5-7%.

Small cells with efficiency values up to 25% 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 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 of 13-16% for screen-printed cells and over 17% and 19% for the best performing multi- or monocrystalline cells, respectively. Device designs capable of achieving module efficiencies of over 18% for multicrystalline silicon and over 20% for monocrystalline silicon are expected to be achieved at production scale in the short to medium term. Promising candidates for such cell types are heterojunction cells of crystalline silicon wafers with doped amorphous silicon layers as well as 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 module efficiency, silicon consumption, cell and module architecture and nature of the cell raw materials after 2020, when the market size is expected to be several hundreds of GW/yr. By this time, it is likely that silicon technology will incorporate technologies covered in the category "Novel PV-technologies" (see Section 4.5) that are currently only at very early stages of development. These developments should allow the traditional efficiency limits to be exceeded by tailoring the solar spectrum to the absorption characteristics of crystalline Si. Also, the separate steps for cell fabrication and module assembly may become one single integrated production step with thinner wafers, deposited Si-layers or wafer-equivalent approaches. For this reason, basic and applied research on advanced concepts and materials should be included in crystalline silicon research programmes.

4.2.5. Manufacturing and installation

Material consumption must be reduced to avoid scarcity and to reduce costs as well as the energy payback time and other environmental impacts associated with PV module production.

The investment for setting up a manufacturing line also has to be considered for further cost reduction since depreciation accounts for about a quarter of the total manufacturing costs. Currently the total capex per W of annual module production capacity is around 2 € and it is expected that this can be reduced by about 50% in the next five years. Investment in modern, more effficient production technology will save energy and raw materials.

Cell manufacturing processes have been improved significantly in recent years. Both, individual machine uptime and yield as well as factory uptime (e.g. by clustering of equipment) have been increased. Evolutionary integration of additional processes like selective emitters or dielectric back passivation leads to higher efficiency while installed capacities and screen print technology can be further used. However, high-efficiency cell concepts require more specifically designed equipment and new or adapted module structures.

Factory size is also important for cost reduction. It is expected that the current typical capacity of 500 MW/yr plant will grow to several GW/yr in the short term and probably an order of magnitude higher in the long term. Improved process control and quality assurance will become essential, together with parallel line processing and automated module assembly. Manufacturing lines should be developed with no or minimal wafer handling. Other important issues are product and process safety and the environmental impact of PV.

Table 3. Research priorities for **processes and designs needed for crystalline silicon photovoltaics** – time horizons for first expected application of research results in (pilot) manufacturing and products. Targets to be achieved in those time horizons are also shown.

CELLS & MODULES	2011 – 2016	2016 – 2025	2025 – 2035 and beyond
Industry manufacturing aspects	■ Integrated high-yield in-line processing ■ Evolutionary improvement of screen-printed cell efficiencies (e.g. selective emitter, back passivation, fine-line print) ■ Safe processing and products ■ Improved process control Target: ■ Module η >19% on mono- and >17% on multi-Si	■ High speed processes ■ Mass production of non-screen-printed cells ■ Frameless structure ■ Safe processing and products Target: ■ Module η >21% on mono- & >19% on multi-Si	■ Safe processing and products Target: ■ Module η > 25% ■ Energy payback time < 6 months
Applied / advanced technology aspects	■ Back-contact cell structures ■ New technologies for electrical contacts ■ Heterojunctions for emitters and passivation ■ Advanced surface treatment and passivation ■ Selective emitters ■ Laser processing ■ Roll-to-roll / automatic module manufacturing ■ Low-cost framing / mounting ■ Modules designs to assure 30 year lifetime	■ Module lifetimes >35 years ■ Metal contacts (processes, schemes and materials) ■ Improved device structures and interconnection schemes for modules ■ Low recombination contacts ■ Epitaxial and polycrystalline Si films on low-cost substrates Target: ■ Module lifetimes >35 years	■ Improved device structures integrating cells / modules ■ Metal contacts (processes, schemes and materials)
Basic research and fundamentals	■ Epitaxial and polycrystalline Si films on low-cost substrates ■ Low recombination contacts ■ New device structures ■ New passivation techniques	■ Epitaxial and polycrystalline Si films on low-cost substrates ■ Low recombination contacts ■ New device structures	■ New device structures including up / down converters and other novel concepts ■ Quantum dot all-silicon tandem cells

4.2.6. Wafer-based crystalline silicon: summary

In conclusion research into crystalline silicon based 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 ensure high quality devices
- Increasing efficiency through the optimisation of existing concepts for cells and modules as well as through new and integrated concepts in the long-term
- New and improved materials for all parts of the manufacturing chain, including encapsulation and metallisation, using low hazard materials and precursors
- Integrated processes for cell and module manufacturing thereby combining features of crystalline Si and thin-film PV technology
- High throughput, high yield, integrated industrial processing equipment and quality assurance
- Finding safe processing techniques with lower environmental impact, including waste reduction

4.3. Thin-film PV technologies

4.3.1. Introduction

Thin-film materials for solar cells are suited as light absorbers as they have a direct band gap to absorb photons effectively. These materials have very high absorption coefficients, absorbing light in thicknesses of less than 1 micrometer (μm). Combined with suitable contact materials and highly doped semiconducting properties the resulting solar cells are usually less than 10 μm in total thickness, so material usage is very low (about a factor of 30-100 less than in crystalline wafer based materials). Thin-film solar cells are deposited directly on large area substrates, such as glass panels or foils. Thin-film PV has the potential for low-cost because of the small material usage and suitability for fully integrated processing and high throughputs.

There are three major inorganic thin-film technologies, all of which have been manufactured at pilot scale (1-2 MW) and have been transferred to high volume production (100 MW up to GW). These are amorphous / microcrystalline silicon (TFSi – 13% stabilised efficiency as the maximum laboratory value), and the polycrystalline semiconductors cadmium telluride (CdTe - 16.5% efficiency) and $Cu(In,Ga)(S,Se)_2$ (CIS, CIGS or CIGSS – 20.3% efficiency. Note that this document uses CIGSS to denote this family of technologies collectively). Thin-film technologies using organic materials are also under development with dye solar cells having yielded 11% on small areas. The use of crystalline silicon in thin-film form (TF-c-Si) was discussed in the previous section, 4.2.

All the technologies have all shown long-term stability under outdoor conditions, except for the organic solar cells where activities in relation to stability assessment are ongoing. The energy payback time of thin-film modules is already less than one year in Southern Europe and there is potential for further reduction.

The present market share of thin-film PV within total PV production is around 15-20%, but could grow beyond 30% within the next decade. The availability of large area deposition equipment and process technology, as well as the manufacturing experience, from other industries (e.g. architectural glass or flat panel display industries) offer significant technological synergies and 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, although currently the majority of commercial products use glass-glass designs.

Thin-film PV technologies still have major potential for improvement in efficiency, material usage and design improvements. There is a wide range of deposition techniques in use, although many thin-film deposition processes are still in the prototyping phase, offering the potential for significant further cost reductions. Experience from the first high volume manufacturing lines indicates that thin-film PV exhibits a steeper cost learning curve than the overall PV industry and can reach specific cost levels at lower cumulative production volumes than for wafer based approaches.

One of the main challenges for thin-film PV is the scaling up of production capacity. The global production capacity of thin-film PV exceeded 7 GW / yr in 2010 (although actual production was much less than this) and will surpass 15 GW in 2012-13 according to announced capacity increases. More than 60% of the new production plants are planned in Asia and thus thin-film PV follows the trend of the electronics and semiconductor industry. Europe is expected to account for about 20% of thin-film production capacity in 2011, which is almost double its percentage share of total PV module manufacturing capacity. This trend can be attributed to Europe's excellent thin-film R&D infrastructure.

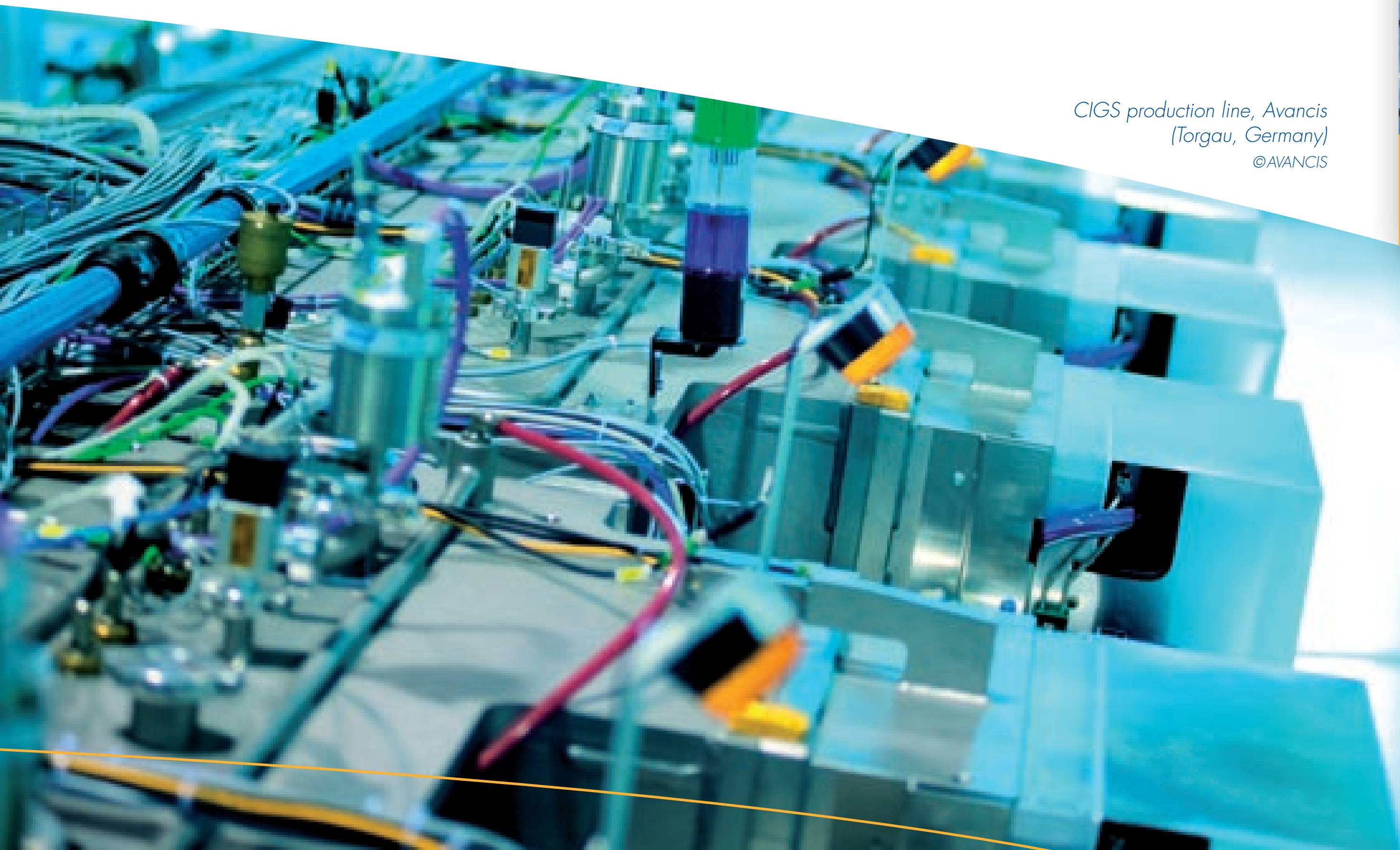
In 2010 the total module manufacturing costs have already been reduced to 0.8 - 1.2 €/W (at production volumes between 20 MW/yr - 1 GW/yr) and are expected to decrease to 0.5 €/W by 2020. Cost levels of well below 0.5 €/W should be reached by 2030. In the long term, there is expected to be little difference in processing costs between the different thin-film technologies. Material costs will play an increasing role in total costs and the realisation of high efficiency levels and yields in large scale manufacturing will be a major driver of cost reduction at the system level, when BoS costs are taken into account.

4.3.2. What has happened since 2007?

R&D activities in all technologies have focussed on the development of materials and processes, such as flexible web based substrate or superstrate configurations. Equipment development has become a much higher priority, mainly carried out by companies specialising in thin-film processing equipment, and has led to major reductions in cost for thin-film modules.

TFSi manufacturing installations were dominated during this period by a few turn-key suppliers (around 10 lines with about 30 to 60 MW each) and a few companies developing their own technologies. Efficiency increases for thin-film silicon have been slower than expected. The maximum stabilised efficiency in the laboratory is still at 13%. The best module efficiencies are above 9% but only prototypes have exceeded 10%. This fact is seen as a key milestone for the short term to allow TFSi to remain competitive.

In CIGSS the situation has evolved from several tens of MW/yr pilot operation to several hundred MW/yr of production. The efficiency evolution of CIGSS during the last two years has been the most impressive within the thin-film materials. The maximum laboratory cell efficiency has increased to 20.3%, comparable to the best polycrystalline silicon material. A sub-module efficiency of 17.2% has been achieved recently, decreasing the gap between cell and module efficiency, and the best efficiency for a commercial size module has increased to 14.7%.



CIGS production line, Avancis (Torgau, Germany)
©AVANCIS

At present, CdTe module production is dominated by a single company with worldwide production facilities of about 2 GW / yr in capacity, although a few new activities in the US seem to be growing rapidly. There has been relatively slow progress in increasing efficiency for laboratory cells. Neverthess, large-area module efficiencies of 11.7% on a regular production plant and a record module efficiency of 12.5% on glass substrate are indicators of technological advancements on the industrial scale. Flexible CdTe is gaining interest as laboratory cell efficiencies approaching 14% have been reached.

Dye-sensitised solar cells have shown continuous improvement with respect to efficiency and stability and they are currently in the pilot production phase.

Figure 6 shows the expected evolution of laboratory cell efficiencies and relevant module efficiencies. These data have been collected from a number of experts from the R&D community as well as industry.

CIGSS has the highest starting efficiency among the flat-plate thin-film materials considered and is projected to approach cell efficiencies of 24% by 2040. All other materials are thought to be able to approach 20% at the cell level. TFSi and CdTe module efficiencies are likely to be limited to around 17%, a little below CIGSS at around 19%, whereas dye and organic modules approach 14% in the long term. To reach the efficiency levels shown in Figure 6, intensive R&D programmes are required.

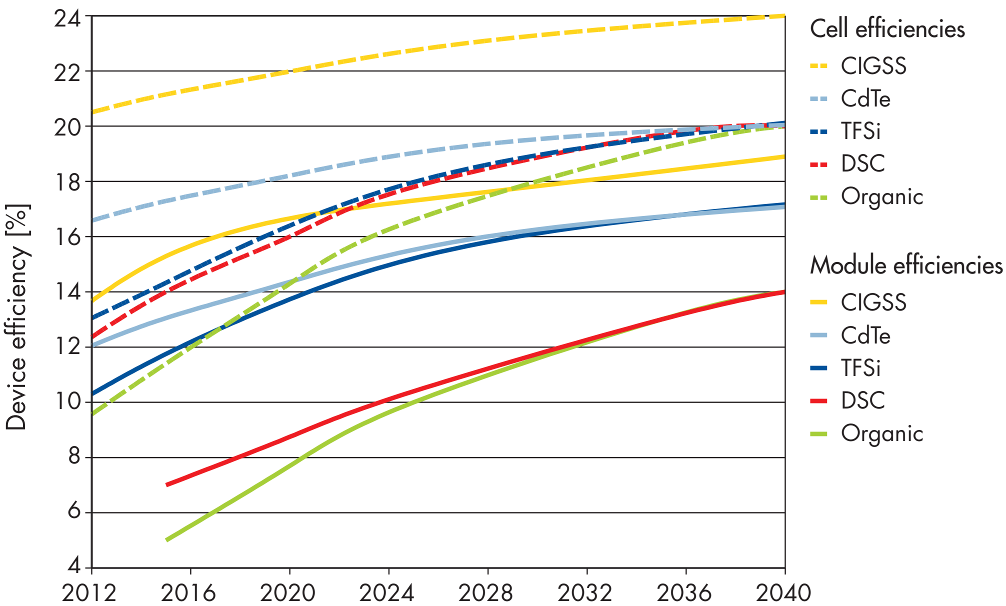


Figure 6. Comparison of expected efficiency evolutions for all thin-film materials in lab record devices (dashed lines) and relevant modules in manufacturing (full lines) (estimation by a group of European thin-film PV experts for the SRA). "DSC" refers to dye solar cells, detail in 4.3.7.1

1. 250 CIGS modules integrated in a house designed and built by the University of Darmstadt as an example of a CO_2 neutral construction. P_{el} = 7kW (USA's Solar Decathlon 2009 winner.)
©WURTH SOLAR

2. In-line RTP furnace for CIGS absorber formation
©SINGULUS TECHNOLOGIES AG

4.3.3. Common features of all thin-film technologies

As thin-film PV modules have essentially similar structures and the key steps in their production process resemble one another, some R&D effort could be applied across technologies. This section analyses common aspects of all thin-film technologies.

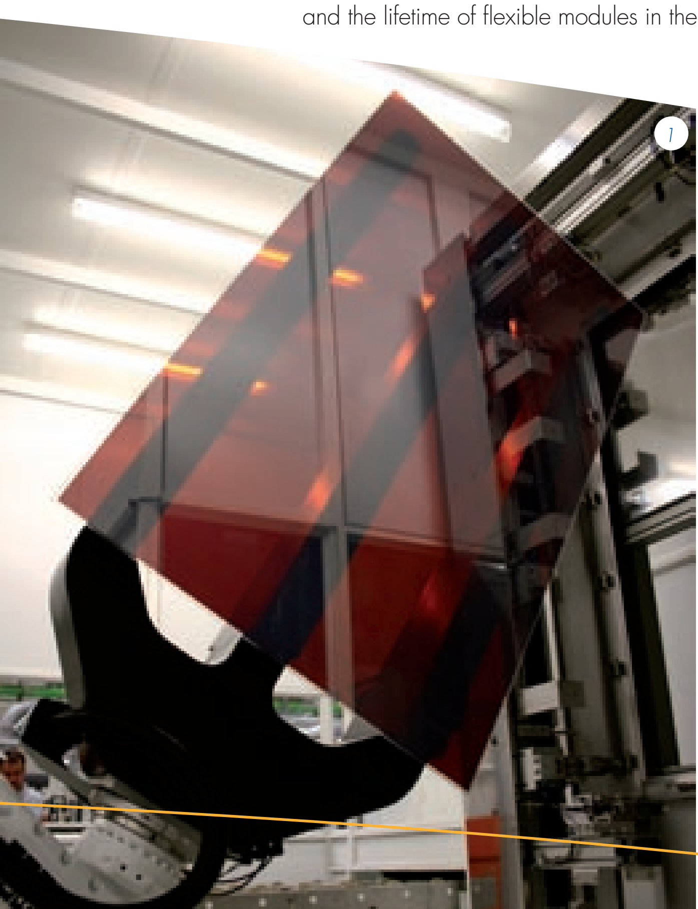
4.3.3.1. Manufacturing and product issues

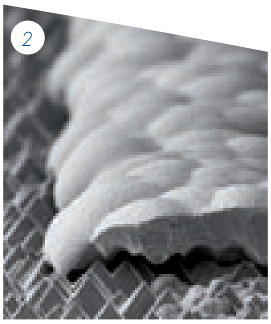
Production equipment plays a crucial role in cost reduction. Standardisation of equipment needs to be developed in conjunction with well defined processes to achieve higher throughputs and yields. Equipment manufacturers play a vital role in this development and knowledge gained in relevant industries outside PV should be exploited (e.g. deposition equipment from the flat panel display industry, sputtered coatings on glass, roll to roll coating equipment originally developed for the packaging industry). 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 should also help to reduce production costs.

Standardised substrates for modules and other common elements for the different technologies will help to reduce the capital costs of a production plant. Jointly pursuing the standardisation of equipment and building construction elements 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 manufacture on polymer and metal foils have to be developed to take full advantage of roll-to-roll production technologies and monolithic or other advanced interconnection. Roll-to-roll coating techniques have to be established for vacuum or non-vacuum deposition, with the key parameters for cost reduction being module efficiency and deposition speed. In comparison to glass based modules, the achievable efficiency in the production environment and the lifetime of flexible modules in the field have still to be proven.

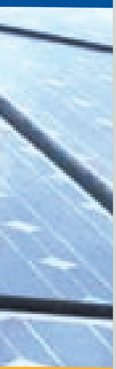




1. Handler carrying a-Si on glass at the Brilliant 234 factory (Thalheim, Germany) ©BERND STANNOWSKI

2. Scanning electron microscope photo of metal contact on a monocrystalline silicon solar cell. The contact finger consists of a nickel thin seed layer (front) which is thickened by silver plating (rear). ©FRAUNHOFER-ISE

3. Frameless CIGS modules with invisible fixing elements integrated the south and east façade in a production building for electronic components. P_{el} = 146kW (Neckarsulm, Germany) ©WURTH SOLAR



Low-cost module encapsulation (also known as "packaging") needs to be developed. Packaging includes the back side for superstrate modules (or front side for substrate modules), junction box (with bypass diodes), frames and laminating foils. In addition new module concepts are required which allow for higher system voltages or better tolerate shading. Thin and partially flexible laminates / coatings have shown substantial progress within the last two years. Nevertheless long-term stability is still not proven as these encapsulants have to withstand harsh environments for decades. Finally, costs competitive with the standard glass based encapsulants must be achieved.

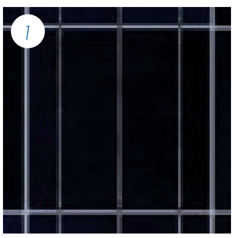
Common R&D needs for all thin-films are summarised as follows:

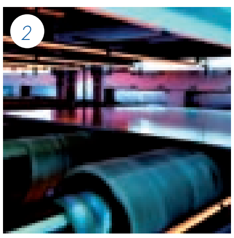
- Increase of efficiency by improved materials, material processing and device concepts
- Transparent electrodes using lower-cost materials and with improved optical and electrical properties
- Standardised deposition techniques with improved productivity (throughput, yield, etc.); of particular importance is increasing the rate of manufacture
- Patterning processes for monolithic integration that reduce the loss of active area and improve cycle time and yield (e.g. laser scribing), novel series interconnection technologies, especially for flexible substrates
- Alternative encapsulation materials and processes with longer lifetimes and suitability for high-throughput manufacturing
- BIPV module designs with improved appearance and performance and adapted to the needs of the construction sector
- Quality control methods and in-line quality assurance in manufacturing

4.3.3.2. Efficiency and material issues

The fundamental properties of both organic and inorganic thin-films (with some exceptions in the case of TFSi) are only partially understood. 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. In particular, the following developments are required:

- Better fundamental understanding of the electronic properties of thin-film materials and their interfaces
- Photon management methods for optical confinement to reduce reflection losses so that active layers can be thinner to reduce material costs
- Modelling of heterostructures with respect to their optical and electronic properties (including substrates and encapsulants)
- High-efficiency concepts using materials with different band gaps for wide spectrum absorption (long-term potential)
- Alternatives to existing absorber materials to replace or reduce scarce or critical materials and further improve efficiency





1. Close-up view of textured multi-crystalline solar cells assembled into a module (ND-F230A1)
©SHARP ELECTRONICS (EUROPE) GMBH 2010

2. CIGS production line, Avancis (Torgau, Germany)
©AVANCIS

4.3.3.3. Performance

Although thin-film modules have been in use for over 30 years, field experience of today's technology is limited. Material modifications and continuous process optimisations in thin-film module production have changed the characteristics and performance of devices. Although no fundamental problems have arisen so far, there is a need for accelerated ageing tests of new thin-film modules to assess their designs and acquire basic understanding of their ageing mechanisms. The further development of standard procedures for measuring the performance and energy yield of thin-film modules is also important.

Due to their heterogeneity thin-film materials offer high flexibility for designing optimum solar cell properties. Therefore more efforts are needed to optimise module performance in terms of energy harvesting, including adapting to the range of climatic conditions in different locations.

4.3.3.4. Recycling and energy payback time - lifecycle assessment

Dedicated recycling processes need to be improved or developed for production waste and end-of-life modules, depending on technology. The processes should include closed material cycles with minimisation of toxic waste and allow high-value metals and module elements to be recuperated. Even though energy payback time is usually less than one year, there is still the potential for further reductions. Recycling and lifecycle assessment are discussed further in Section 4.7.

Table 4. Research priorities for **thin-film PV technologies – common aspects –** time horizons for first expected application of research results in (pilot) manufacturing and products. Targets to be achieved in those time horizons are also shown.

	2011 – 2016	2016 – 2025	2025 – 2035 and beyond
Industry manufacturing aspects	■ Assessment of advanced materials and processes ■ Integration of advanced quality control ■ Piloting roll-to-roll-concepts	■ Proof of concept for modified / new deposition methods, and combinations of processes and materials ■ Standardisation of processes and equipment	■ Concepts for manufacture of different material combinations
Applied / advanced technology and installation (incl. O&M) aspects	■ Improvement of deposition and patterning concepts ■ Development of quality control methods ■ Increase aperture and active area efficiency (e.g. by reduction of non-active interconnection zones) Target: ■ Increase of current module efficiency by ≥2% (absolute).	■ Demonstration of low-material-cost manufacture ■ Novel deposition methods and sealing concepts Target: ■ Increase of current module efficiency by at least a further 2% (absolute).	■ Non-vacuum deposition methods established Target: ■ Increase of current module efficiency by at least a further 2% (absolute).
Basic research / fundamental science	■ Basic understanding of the physics and chemistry of TF materials ■ Basic understanding of bulk heterojunction concepts ■ Photon management and optical confinement	■ Cost-effective concepts for deposition, patterning, sealing ■ Multijunctions ■ Roll-to-roll compatible high-speed concepts ■ Non-vacuum deposited high-quality contacts and absorbers	■ Combination of new materials and layers for superior performance ■ Transfer of novel high efficiency concepts into TF PV

4.3.4. Thin-film silicon (TFSi) based on amorphous silicon (a-Si) and combinations (hybrid)

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. The TFSi industry has seen a recent revival due to new technologies like µc-Si and the development of large-area deposition equipment. Large companies in the USA, Japan and Europe are offering high quality products manufactured using equipment and processes that have been developed with substantial governmental support. The TFSi sector benefits directly from the advances that have been made by the flat panel display sector in plasma-enhanced chemical vapor deposition (PECVD), which can be applied to the deposition of TFSi on large areas. Nevertheless, several European and Asian companies, which had started mass production using such equipment, are facing problems due to market prices that are already lower than expected and slower than expected ramping-up phases. The presence of a competent pool of module producers, equipment manufacturers and research institutes in Europe creates a favourable environment for the advancement of TFSi.

4.3.4.1. Materials and components

The long-term cost of TFSi modules is determined by the module efficiency, the cost of active layer material, 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 for technologies based on µc-Si, finding ways to produce materials at industrial scale, and developing adequate transparent conductive oxides (TCOs) and substrates. The most important aims are listed here:

- Increased efficiencies by improved understanding of the properties of materials, for example, the transport of electrons in µc-Si and of interfaces in single and multijunction devices:
  – low recombination loss junctions
  – the use of optical reflectors between cell stacks
- 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)
- Low-cost back reflector materials and layer stacks for improved light trapping within the cell.
- New lower-cost materials / components for packaging
- New absorber 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 non-plasma techniques)

4.3.4.2. Performance and devices

Several possibilities exist for efficiency improvement in single-junction amorphous silicon modules. For example, 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 is the key for 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 10% (a-Si), 12% (tandem a-Si / µc-Si) and 13% (triple junction using SiGe alloys). This translates to commercial module efficiencies of 6-7%, 8.5-9.5% and 7-8%, respectively but large-area module efficiencies exceeding 10% have been demonstrated at the prototype scale. Achieving a laboratory-scale performance from production modules and mastering the production of multijunction 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. Targets to be achieved in those time horizons are also shown.

	2011 – 2016	2016 – 2025	2025 – 2035 and beyond
Industry manufacturing aspects	■ High-rate μc-Si deposition ■ Production of high-quality TCO ■ Low-cost packaging solutions / reliability ■ Roll-to-roll processing ■ Simplified production processes and reduced interconnection losses Target : line demonstration ■ ≤0.7 € / W for 200 MW / yr, η >11% (rigid) ■ <0.6 € / W at 200 MW / yr, η >10% (flexible)	■ Next generation equipment with lower material use, higher throughput and higher efficiency Target: concept demonstration ■ ≤0.5 € / W at 500 MW / yr, η >14% (rigid) ■ <0.4 € / W at 500 MW / yr, η >13% (flexible)	■ Ultra-low-cost packaging Target: concept ■ ≤0.3 € / W at 1 GW / yr, η >16%
Applied / advanced technology aspects	■ Large area plasma processes for microcrystalline Si ■ Advanced encapsulation materials ■ Improved TCO and light trapping (optimised for large area) Target : ■ Demonstrate modules with η >12%; concept for modules with η >13%	■ New deposition reactor concepts ■ Process simplification ■ Rapid high quality TCO / substrate preparation ■ Process gas recycling / full gas use Target : ■ Fast low-cost deposition; concept for modules with η >15%	■ Designs for ultra-high throughput lines / reactors ■ Non-vacuum absorber deposition methods (e.g. printing) ■ Fully integrated production line
Basic research / fundamentals	■ Quantitative understanding of all interfaces and light trapping ■ Developments of improved selected cell layers (e.g. μc-SiGe, SiC, nanocrystalline-diamond) ■ Understand fundamental limitations of thin-film Si Target: ■ Increase efficiencies and demonstrate stable cells with η >15%	■ Provide 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 technologies ■ Tuned nanostructured substrates Target: ■ concepts for stable cells with η >17%	■ Higher performance materials ■ p-type TCOs ■ Photonic crystals, diffraction effects, effective medium approaches, etc. Target: ■ to determine promising routes for cost reduction

The most important aims are listed here:

- Manufacture of high efficiency tandem and triple junction devices at industrial scale
- Plasma process control and monitoring
- Quantitative understanding of the fundamental limits of μc-Si solar cells incorporated into multijunction cells
- Concepts for improved light trapping (e.g. plasmonics, mechanical nanotexturisation)
- Demonstration of TFSi cells with stabilised efficiencies above 15%, and over 12% at the module scale

In the long term, higher stabilised cell efficiencies should be demonstrated (above 17% by 2030). 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).

4.3.4.3. Manufacturing and installation

Within the next 2-3 years, production costs in the range of 0.5-0.7 €/W could be achievable for a-Si/µc-Si modules (efficiencies of ≥10%) using production equipment that is becoming available and with devices using thinner active layers The target for 2016 is an efficiency increase to above 11%, with production costs below 0.7 €/W on rigid substrates. The corresponding targets for flexible substrates are 10% efficiency and 0.6 €/W respectively. The targets assume production lines of 100-200 MW/yr for glass substrates and 50 MW/yr for flexible substrates. To meet these goals, cost-effective deposition of microcrystalline Si on large area (>1 m^2) must be achieved and the availability of suitable production equipment for high quality large area TCOs or TCO stacks must be ensured. Thirdly, improvement across the manufacturing chain is required (achievable through minimising interconnection losses, improving homogeneity and using in-line process control). The value of 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 of 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, low-cost substrates and equipment specific to roll-to-roll production.

4.3.5. Copper-indium/gallium-diselenide/disulphide and related I-III-VI compounds (CIGSS)

CIGSS technology currently exhibits the highest cell and module efficiencies of all thin-film flat plate technologies (cells of 20.3%; commercial modules of 14%; prototype modules of >14-17% for areas of 0.3-1.0 m^2). The main challenge facing CIGSS technology is to reduce the difference between efficiencies in the laboratory and in production.

Large-scale manufacturing of CIGSS modules has begun with different deposition techniques for the absorber layer and substrates depending on the company. Nevertheless, further research into production processes, such as absorber deposition equipment and in-line characterisation tools, is still essential for increasing module and process performance. New non-vacuum techniques for the deposition of device layers (like nanoparticle printing and electrodeposition) 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. At present, both non-glass substrates and encapsulants are still more expensive compared to the glass standard.

The reduction of material cost is an important issue. High-cost materials like In and Ga could be replaced with other group III elements (e.g. Al), process yield should be increased, active layer thicknesses should be reduced, and tolerance to impurity in the materials should be investigated in view of maximising module performance. The replacement of the CdS buffer layer and the optimisation of the TCO layers in these devices are key to reducing cost in 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 in the longer term.

4.3.5.1. Materials and components

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

- Improved understanding of interface and grain boundary chemistry, diffusion behaviour and defect chemistry of the complete device to enable cell efficiencies above 22%
- Improved understanding and control of nucleation and growth morphology of thin-films on foreign substrates
- Improved understanding of the influence of the deposition process on film characteristics and device behaviour under both accelerated lifetime testing and after long-term outdoor exposure
- Material cost minimisation through thinner films, maximising material yield and optimising material purity
- Replacement of the Cd-containing buffer layer with higher band gap material for enhancing absorption in the blue region of the spectrum
- Screening and synthesis of chalcopyrites and related compounds that offer potential for improved efficiency, higher stability, reduced costs and that contain fewer scarce materials
- Simulation and development of optical confinement to reduce reflection losses and improve optical coupling of incoming photons
- New device concepts (spectrum conversion, quantum effects, multi-gap cells).

4.3.5.2. Performance and devices

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

- 'Proof of concept' modules with efficiencies above 17% in the medium term
- Alternative substrates for glass, such as polymer or metal foils and micro- or macroscopically rough substrates (e.g. glass fibre mat), and design of the full production chain
- Further evaluation of deposition concepts like electrodeposition, nanoparticle printing and associated module design
- Reduction of sensitivity to moisture for all layers; sealing materials and concepts for lifetime beyond 30 years
- Adaption and design of modules for special applications in buildings (operating temperature, humidity and low light intensity, suboptimal alignment to the sun).

4.3.5.3. Manufacturing and installation

Industrial development is required in the following areas:

- Standardisation of prototype production equipment including supply chain management
- Reduction of cycle times and material usage, increase of throughput (including deposition width), high temperature processing (600 °C)
- Equipment designed for very-large-area in-line deposition on glass substrates of up to several square meters and cost-effective roll-to-roll substrates
- Reduction of film thickness, use of lower cost and abundant materials
- Quality control methods and quality management systems
- Recycling techniques for the re-use of material during production and for products at the end of their lifes

Table 6. Research priorities for **thin-film CIGSS** – time horizons for first expected use of research results in (pilot) manufacturing and products.
Targets to be achieved in those time horizons are also shown.

	2011 – 2016	2016 – 2025	2025 – 2035 and beyond
Industry manufacturing aspects	■ Production equipment optimised for production yield, high throughput, reduced investment cost and material consumption ■ Commercial equipment for CIGSS modules at a 15% level ■ Recycling processes for modules and waste material from production Target: ■ line demonstration ■ < 0.7 € / W for >200 MW / yr, η = 15%	■ Production equipment for CIGSS modules at 16 to 17% efficiency level ■ Equipment optimised for low energy, low material consumption and alternative buffer layers ■ Demonstrate low-cost packaging for flexible modules ■ Demonstrate equipment for CIGSS modules at 16% efficiency at absorber deposition times of < 5 min. ■ Concepts for reduced In and Ga consumption at high efficiency ■ demonstrate highly efficient roll-to-roll processes for module production Target: < 0.5 € / W, η = 16-17 %	■ Manufacturing issues for very large scale production ■ Transfer of modified interconnect structures and processing ■ Transfer of ultra-light and low-cost packaging ■ Minimisation of energy needs, material costs, waste ■ Non-vacuum processing of the absorber and TCO layers ■ Standardised processing and equipment for high efficiency modules Target: < 0.35 € / W, η = 18-21 %
Applied / advanced technology aspects	■ Monitor CIGSS modules in outdoor operation ■ Processes for high speed deposition of functional layers ■ Processes for large area CIGSS modules at 16% efficiency level ■ Inline / online quality control techniques ■ Reduction of scarce and expensive matarials ■ Significantly reduced layer thickness ■ Roll-to-roll processes for module production ■ Alternative buffer layers ■ Basic research for optical confinement	■ Processes for large area CIGSS modules at η >17% ■ Low-cost deposition methods for CIGSS absorber ■ Novel interconnects and cell structures ■ Alternative processes for patterning ■ Flexible modules with matching efficiencies compared to rigid substrates ■ Demonstrate concepts for light trapping in CIGSS cells ■ Concepts for the replacement of expensive raw materials (In and Ga) by less expensive and more abundant elements	■ Concepts for modules at η >18% and demonstrate at the cell level e.g. tandem / triple structures with modified chalcopyrites, silicon or dyes as partners
Basic research / fundamentals	■ Understanding of the influence of deposition parameters on all layer and cell qualities, influence of substrate ■ Extrinsic doping of CIGSS ■ Material screening, reducing the use of expensive materials (high efficiency + low-cost) ■ Qualitative and quantitative understanding of defects, impurities, metastabilities, layer structures ■ Understand electronic band structure in relation to buffer layer chemistry and increased cell efficiency	■ Concepts for cells with full spectrum utilisation other than multiple absorber cells e.g. up / down conversion, quantum dot structures ■ Concepts for the use of CIGSS nanoparticles in organic cell structures ■ p-type TCOs for use in multi-layer structures	■ Concept for monolithic multijunction devices, η >30%

4.3.6. 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 the cells easy and cheap to manufacture, with 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 choice of substrate. There is a large gap between the theoretically achievable efficiency (>25%) and the efficiencies reached in the laboratory (16.5% on glass and 13.8% on flexible foil). Data reported to EU PV TP put the highest module efficiency at industrial scale at 12.5% and the average production efficiency at 11.5%. 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 simultaneously to develop processes that are simple and compatible with high throughput in-line manufacture.

The "electrical back contact" on CdTe is still an important R&D challenge because of the high electron affinity and energy band-gap of CdTe. Though several methods have been used to develop 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 glass or polymer substrate forms the upper surface of the completed module. 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 materials such as tellurium.

CdTe thin-film modules are already being produced in Europe, USA and southern Asia at capacities of >1GW / yr. Their manufacturing costs are the lowest of all current PV technologies. Fast and simple deposition of absorber and contact materials allow for high-throughput production and promise further scope for cost reduction.

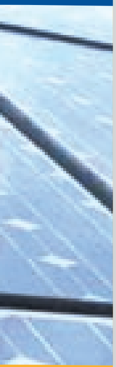
CdTe has the potential to reach 15% efficiency at a specific cost of <0.4 € / W in the medium to long term, but for this to happen further R&D work on understanding the fundamental physical properties of this material is needed. Once transparent and temperature-resistant substrates (e.g. transparent polyimide) have become commercially available, CdTe modules may be produced by roll-to-roll methods. This is expected in the short to medium term.

In the short term, it is also 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 solutions for module end-of-life return and closed material cycles, especially when production volumes increase.

Some of the key areas for study include:

- Fundamental understanding of the physics of CdTe solar cells



- Fundamental understanding of interface and interdiffusion processes, grain boundary effects and materials for advanced devices with high efficiencies (over 20% at laboratory scale)
- Extrinsic doping and simple activation processes
- Development of electron deflectors for the rear side of the cell
- Ohmic contacts and multi-functional materials that increase overall performance and reduce production cost
- Further improvement of single layer or bi-layer TCO materials and processes
- New substrate materials (including foils) 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

4.3.6.1. Performance and devices

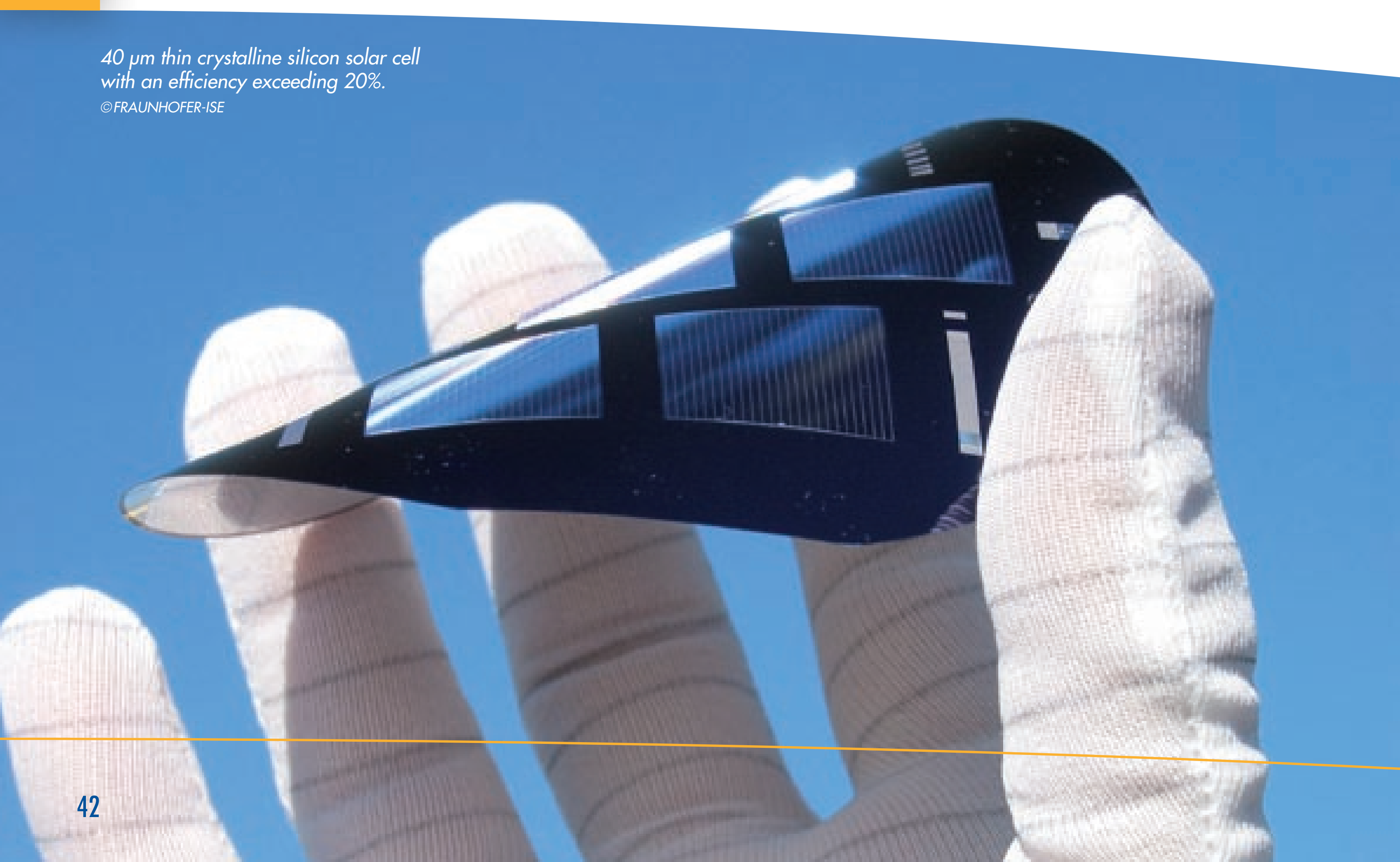
The following performance- and device-related topics need to be addressed to reach the targets outlined earlier.

- Improvements in activation / annealing and back contact formation
- Device structures employing enhanced optical confinements in thinner CdTe layers, significicantly reduced layer thickness
- Designs for high performance (efficiency and stability) cell structures on glass and foils
- Interconnection schemes for reducing interconnect-related losses

4.3.6.2. Manufacturing and installation

Industrial development is required in the following areas:

- High 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



40 µm thin crystalline silicon solar cell with an efficiency exceeding 20%.
©FRAUNHOFER-ISE

Table 7. Research priorities for **thin-film CdTe modules** – time horizons for first expected use of research results in (pilot) manufacturing and products.
Targets to be achieved in those time horizons are also shown.

	2011 – 2016	2016 – 2025	2025 – 2035 and beyond
Industry manufacturing aspects	Advanced cell production technology: ■ Advanced activation / annealing suited to in-line production, dry processes, use of alternative chlorine-containing precursors ■ Ohmic back-contacts by vacuum processes, avoidance of wet chemical etching processes ■ Advanced TCOs, new interconnection processes for modules Target: 14% efficiency module with production cost of <0.6 € / W	Optimised cell production technology: ■ Devices with reduced film thickness ■ Control of nucleation and film morphology during deposition ■ Simple and robust deposition and processing sequences Target: 16% efficiency module with production cost of <0.4 € / W	Optimised cell production technology: ■ Modified device structures (inverted film sequence, p–n cells) ■ Device structures and conversion efficiencies that approach the physical limits of a cell Target: Module production cost of <0.35 € / W
Applied / advanced technology aspects	■ Advanced control of homogeneous deposition ■ Improved doping / activation processes ■ Elaboration of controlled film interdiffusion across the heterojunction ■ Simplified back contact materials and processes ■ Determination and elimination of pinhole and weak diodes Target: knowledge improvement of cells and modules (improvement of efficiency and stability)	■ Alternative TCOs with low-cost processes ■ Reduction of process temperatures ■ Modified deposition techniques (high-speed, low-temperature, large-area, low material consumption) ■ Non-vacuum deposited absorbers ■ Increase of efficiency for flexible modules Target: Development of technology needs for implementation of improved cells	■ Alternative window layers ■ Testing and development of advanced alternative devices in pilot lines: ■ >14% efficiency flexible modules ■ >14% efficiency solar modules on glass with CdTe physical thickness <1 μm ■ New design concepts including tandem junctions
Basic research / fundamentals	■ Understanding of interface interdiffusion processes ■ Understanding of inhomogeneities and grain boundary effects Target: Fundamental understanding of the physics of standard CdTe cells	■ New cell concepts such as p-i-n structures ■ Material and processing approaches for high efficiency and stability ■ Development of structured cells for light trapping in thinner layers ■ Alternative II-VI semiconductors avoiding Cd Target: Development of new cell concepts for the CdTe cell	■ Concepts for full spectrum utilisation ■ Tandem / triple cells, ■ Composite dye/II-VI hybrid cells Target: Fundamental understanding of the physics of full spectrum II-VI cells

4.3.7. Organic PV

Organic solar cells are photovoltaic devices in which at least part of the active layer consists of an organic compound. They have been the subject of R&D efforts for a long time because of the potentially very low-cost of the active layer material, the low-cost substrates on which they can be realised and the potential for production throughput of cells and modules 10 to 100 times higher in terms of area than for present solar cell technologies (by using film casting and printing technologies). The required amounts of active material are typically 10 times lower thanks to the high absorption coefficient of these materials. This has led to claims for the potential cost of polymer solar cells to be under 0.3 € / W.

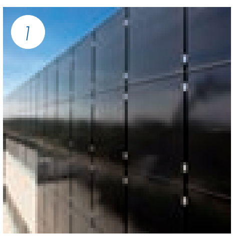
Originally, most attempts to realise organic solar cell devices were based on essentially the same concepts as thin-film p-n or p-i-n devices. This resulted in energy conversion efficiencies of about 1% with the main limitation being the short exciton diffusion length and insufficient exciton dissociation in organic materials. The breakthrough for solar cells incorporating an organic part in the active layer came with the advent of concepts which deviated radically from the planar hetero- or homojunction solar cells.The generic idea behind these concepts is the existence of a bulk-distributed interface to collect the excited carrier and to increase the exciton dissociation rate.

Organic solar cells have been extensively investigated over the last decade with impressive efficiency increases and progress in relation to stability as a result. It is clear however that it will take time to scale up the technology and to build sufficient confidence in it. Application roadmaps for organic solar cells with associated objectives have been worked out in numerous road-mapping exercises, as shown in Table 8.

Table 8. Roadmap for market applications of organic solar cells as proposed by OrgaPVNET.

APPLICATION	EFFICIENCY	LIFETIME	COSTS	TIME FRAME
Mobile electronics	Sufficient according to product	1-3 years product	Competitive with flexible inorganic PV	Short term <2010
Outdoor recreational remote	Suitable for function	3-5 years product	Competitive with flexible inorganic PV	>2010
Building Integrated PV (BIPV)	5-12 % depending on application	>10 years	100 € / m^2	>2013
Grid-connected, high power	>10 %	>10 years	■ Grid parity ■ Energy generation cost competitive with inorganic PV	>2020

Traditionally a distinction is made between dye solar cells and full-organic solar cells. The dye solar cell is based on ultra-fast electron transfer and charge separation on the nanometer scale from an organic sensitiser to an inorganic acceptor material. A monolayer of a metal-organic sensitiser is adsorbed onto the pore walls of a nanoporous TiO_2-layer. After absorption of a photon, the excited electron within the sensitiser molecule is immediately transferred to the conduction band of TiO_2, after which the electron diffuses through the porous network to the contact. The oxidised sensitiser molecule is reduced to the original state by supply of electrons through a liquid redox electrolyte or hole conductor within the pores. Cells based on this concept show certified AM1.5 solar efficiencies of up to 11.5 % on small-area cells, whereas efficiencies of up to nearly 10 % have been reached for up-scaled moduel prototypes under outdoor conditions have been reached by various groups. The stability of dye solar modules will likely be sufficient for first outdoor applications on the short- to mid-term, which take advantage of specific features of dye solar modules, like decorative design and semitransparency. A typical dye solar cell configuration possesses an intrinsic property not present in other photovoltaic devices. Being a photoelectrochemical device, it can include features of energy storage, allowing the PV module additional functionality.



1. 119 kW PV plant on façade, using thin-film modules, (Terlizzi, Bari, Italy) ©ENEL

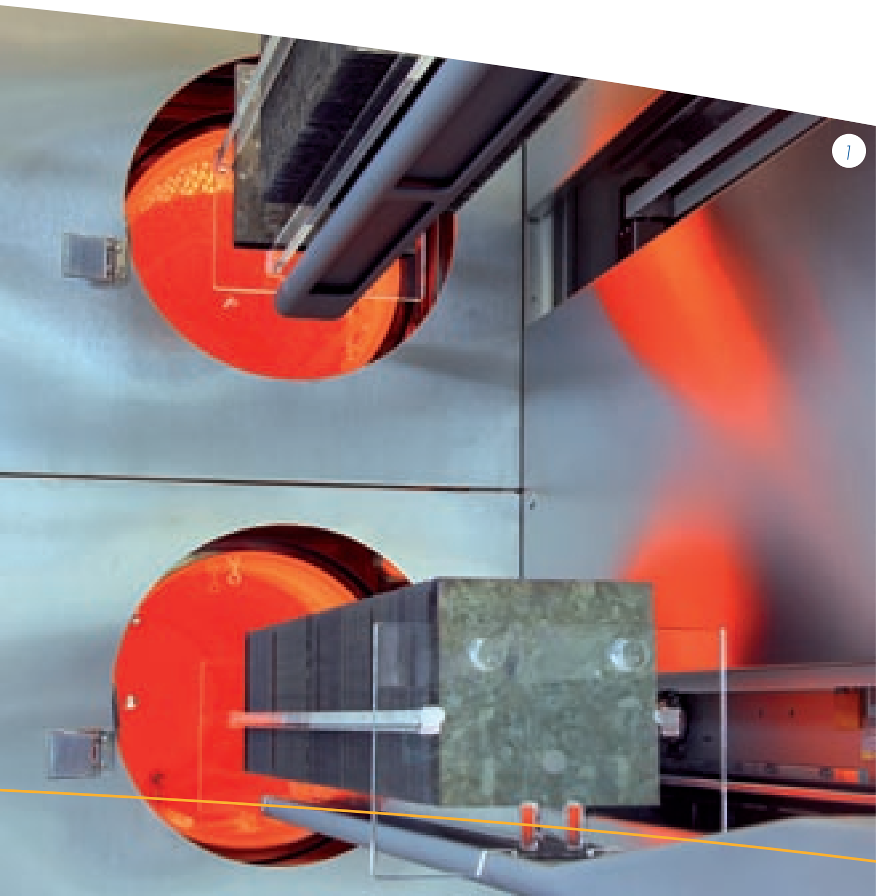
2. Inline processing equipment for light-induced plating of silver for silicon solar cells ©FRAUNHOFER-ISE

The full-organic counterpart of the dye cell is the bulk donor-acceptor heterojunction concept which is based on blends of two organic compounds, one with donor and one with acceptor properties. The excitons dissociate very efficiently at the interfaces between donor- and acceptor phases and flow through the percolated donor- and acceptor subnetworks to the contacts that are carrier selective. Film application technologies, such as film coating and film printing processes, would allow very high throughput rates for industrial production. Solar cells based on small molecules (generally evaporated) are also full-organic devices. But their design is generally based on a p-i-n structure (with layers in the tens to few hundreds of nm in thickness) rather than on a bulk heterojunction.

4.3.7.1. Materials and components

Dye Solar Cells

An important focus of R&D activities in the domain of dye solar cells is the extension of the spectral sensitivity of the cell towards longer wavelengths by the use of alternative dyes. The present results are mainly based on Ru-based dyes (the so-called "red" and "black" dyes). This objective is not only pursued by the development and inclusion of novel dyes but also by including quantum dots in the structure. The development of porous photoanodes with improved structural order to enhance electron transport is another important issue. This comprises templated growth of TiO_2 and ZnO-nanowires, or combinations of both, to realise vertical "brush-like" nanowire configurations. The cathode is also a subject of attention, through attempts to increase its electrochemical reactivity by increasing the surface area, while decreasing its cost by reducing platinum usage. Alternative cathodes based on graphenes or graphene nanoplatelets that do not rely on platinum are still at an early phase of development.



1. Phosphorus diffusion furnace for crystalline silicon solar cells.
©FRAUNHOFER-ISE

2. Long-term module testing of fixed position modules at ENEL's labs in Catania, Italy
©ENEL

Finally, alternative electrolytes and ionic liquids are being developed and tested to replace liquid electrolytes. Liquid electrolytes are liable to leak, so avoiding them entirely is one strategy to improve the reliability of dye solar cells. The replacement of the electrolyte by infiltrating organic hole conductors into the porous network is also an area of research. Based on these efforts, it is reasonable to assume that efficiencies of up to 15% can be achieved for cells produced in the laboratory, which could translate to 10% for scaled-up modules. Using roll-to-roll manufacturing, a cost of 0.3 €/W should be achievable.

Full organic solar cells

The best laboratory efficiencies reported for organic solar cells have increased substantially over the last decade, with an average increase per year of about 0.5% (absolute). This is due to the development of better donor materials (higher mobilities, lower band gap, reduced voltage losses as a result of better aligned LUMO-levels between donor and acceptor materials), better control over the nanomorphology of the layer and improvement of the contacting systems. Concerning acceptor materials, C_{60} (or C_{70}) and its soluble derivatives remain the best discovered so far. In combination with the increased understanding of the opto-electrical behaviour of these devices and the advent of multijunction approaches, a solid base exists for reaching efficiencies up to 15%, in turn allowing costs to reach 0.3 €/W for these technologies, too.

The key areas for R&D are

- Fundamental understanding of the physics of dye and full-organic solar cells
- Fundamental understanding of the effect of nanomorphology and order on the electrical transport and exciton transport and dissociation
- Factors affecting the effect and stability of the nanomorphology and how to improve stability
- Extrinsic doping of organic materials
- Behaviour and time evolution of the contact-organic semiconductor interface
- Development of new materials (sensitisers, donor and acceptor materials) and *ab initio* modelling of properties. Further improvement of single layer or bi-layer TCO materials and processes
- Photon management and optical confinement
- Materials and processes for multiple band gap approaches

4.3.7.2. Performance and devices

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

- Development of 2- and n-terminal multijunction devices to go to high-efficiency devices
- Methods to improve stability by extrinsic means like low-cost encapsulation layers
- Optical optimisation in thin layers taking into account interference effects
- Optimisation of glass (flexible thin glass) and foil substrates

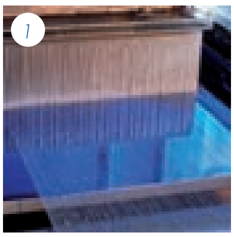
4.3.7.3. Manufacturing and installation

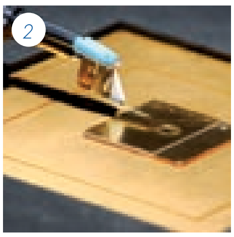
Industrial development is required in the following areas:

- Development of high-throughput sheet-to-sheet (S2S) and roll-to-roll (R2R) equipment
- Assessment of energy yield (including unfavourable locations like façades)

Table 9. Research priorities for **dye solar cells** – time horizons for first expected use of research results in (pilot) manufacturing and products.
Targets to be achieved in those time horizons are also shown.

<table>
<tr><th></th><th>2011 – 2016</th><th>2016 – 2025</th><th>2025 – 2035
and beyond</th></tr>
<tr><td>Industry manufacturing aspects</td><td>■ S2S and R2R-processing
■ Encapsulation and reliability
■ Energy yield assessment
■ Low illumination level behaviour
■ Standard characterisation tools and procedures for efficiency, energy yield and ageing
Target:
5% efficiency module with production cost of <1 € / W for consumer and outdoor recreational market</td><td>■ R2R-processing
■ Encapsulation and reliability
■ Energy yield assessment
■ Low illumination level behaviour
■ Standard characterisation tools and procedures for efficiency, energy yield and ageing
Target:
10% efficiency module with production cost of 0.5 € / W for outdoor recreational and BIPV</td><td>■ R2R-processing
■ Encapsulation and reliability
■ Low illumination level behaviour
■ Standard characterisation tools and procedures for efficiency, energy yield and ageing
■ Multijunction processing
Target:
>10% efficiency module with production cost of 0.3 € / W for BIPV and large-scale power generation</td></tr>
<tr><td>Applied / advanced technology aspects</td><td>■ IR-sensitive dyes
■ Inclusion of quantum dots for extension of spectral sensitivity
■ Porous photoanode templates with reduced degree of disorder
■ Alternative photocathodes with reduced Pt-loading
■ Solid state electrolytes with good mobility
Target:
Development of next generation improved dye solar cells</td><td colspan="2">■ Alternative acceptor materials
■ IR-sensitive dyes
■ Inclusion of quantum dots for extension of spectral sensitivity
■ Porous photoanode templates with lower degree of disorder
■ Alternative photocathodes with lower Pt-loading
■ Solid state electrolytes with good mobility
■ Multijunction devices
■ Inclusion of up- and down-convertors adapted to the spectral absorbance of the sensitiser
Target:
Development of technology required for large-scale production</td></tr>
<tr><td>Basic research / fundamentals</td><td>■ Ab initio material modelling to predict behaviour and required structures for sensitiser and inorganic acceptor
■ Opto-electrical modelling and simulation
■ Photon management
■ Fundamental studies of degradation
■ Fundamental studies of electrochemical reaction rates
Target:
Fundamental understanding of the physics of dye solar cells</td><td colspan="2">■ Ab initio material modelling to predict behaviour and required structures for sensitiser and inorganic acceptor
■ Opto-electrical simulation
■ Fundamental studies of degradation
■ Fundamental studies of electrochemical reaction rates
Target:
Fundamental understanding of the physics of dye solar cells</td></tr>
</table>





1. Cutting of silicon wafers with multi wire slurry saw. *©FRAUNHOFER-ISE*

2. Experimental characterisation of a concentrator solar cell *©FRAUNHOFER-ISE*

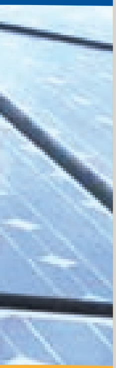


Table 10. Research priorities for **full-organic solar cells** – time horizons for first expected use of research results in (pilot) manufacturing and products.
Targets to be achieved in those time horizons are also shown.

<table>
<tr><th></th><th>2011 – 2016</th><th>2016 – 2025</th><th>2025 – 2035
and beyond</th></tr>
<tr><td>Industry manufacturing aspects</td><td>■ S2S and R2R processing
■ Encapsulation and reliability testing
■ Energy yield assessment
■ Low illumination level behaviour
■ Standard characterisation tools and procedures for efficiency, energy yield and ageing
Target:
5% efficiency module with production cost of <1 € / W for consumer and outdoor recreational market</td><td>■ R2R processing
■ High-throughput coating
■ Encapsulation and reliability
■ Energy yield assessment
■ Low illumination level behaviour
■ Standard characterisation tools and procedures for efficiency, energy yield and ageing
Target:
10% efficiency module with production cost of 0.5 € / W for outdoor recreational and BIPV</td><td>■ R2R processing
■ Encapsulation and reliability
■ Energy yield assessment
■ Low illumination level behaviour
■ Standard characterisation tools and procedures for efficiency, energy yield and ageing
■ Multijunction processing
Target:
>10% efficiency module with production cost of 0.3 € / W for BIPV and large-scale power generation</td></tr>
<tr><td>Applied / advanced technology aspects</td><td>■ New donor and acceptor materials
■ Doping materials for small-molecule organic solar cells
■ Improving intrinsic stability of donor and acceptor materials
■ Fully solution-processed devices
■ Multijunction solar cells
■ Plasmonic effects
Target:
Development of next generation improved full-organic solar cells</td><td colspan="2">■ Development of new donor and acceptor materials
■ Development of doping materials for small-molecule organic solar cells
■ Boosting intrinsic stability of donor and acceptor materials
■ Improving the stability of the nanomorphology of the active film
■ Fully solution-processed devices including active layers and contacts
■ Multijunction solar cells
■ Plasmonic effects
Target:
Development of technology required for large-scale production based on multijunction-like approaches</td></tr>
<tr><td>Basic research / fundamentals</td><td>■ Ab initio material modelling to predict behaviour and required structures for donor and acceptor materials Opto-electrical modelling and simulation for bulk heterojunction solar cells and p-i-n-like configurations enabled by small-molecule approaches
■ Photon management
■ Fundamental studies of degradation
Target:
Fundamental understanding of the physics of organic solar cells</td><td colspan="2">■ Ab initio material modelling to predict behaviour and required structures for sensitiser and inorganic acceptor
■ Opto-electrical simulation
■ Fundamental studies of degradation
■ Fundamental studies of electrochemical reaction rates
Target:
Fundamental understanding of the physics of organic solar cells</td></tr>
</table>

4.3.8. Thin-film PV technologies: summary

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 fundamental science and production technology. The R&D topics with highest priorities are:

Common aspects for existing thin-film technologies:

- 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 end-of-life modules
- Alternatives for scarce chemical elements such as indium, gallium, tellurium

TFSi

- Processes and equipment for low-cost, large-area plasma deposition of micro / nanocrystalline silicon solar cells
- Development of high-quality low-cost TCOs suitable for large-area, high-performance (>12% efficiency) modules
- Demonstration of higher efficiency TFSi devices (above 15% on laboratory scale), improved understanding of interface and material properties, light trapping, and the fundamental limits faced by TFSi-based materials and devices

CIGSS

- Improvement of throughput, yield and degree of standardisation for processes and production equipment
- Module efficiency >16% (or >20% at prototype scale) through improved TCO / heterojunctions, absorber quality, contact passivation, deeper understanding of the fundamental physics of these devices
- Alternative / modified material combinations and processing (roll-to-roll coating, combined or non-vacuum deposition methods); highly reliable and low-cost packaging to reduce material costs
- Device concepts for high efficiency

CdTe

- Activation / annealing treatments to control the electronic properties of the CdTe layer
- Improved and simplified back-contacting for enhanced yield and throughput
- Enhanced fundamental knowledge of materials and interfaces for advanced devices with efficiencies up to 20% at laboratory scale
- Device concepts for reduction of CdTe layer thickness
- Device concepts for high efficiency

OPV

- Fundamental understanding of the physics of dye and full-organic solar cells including the effect of nanomorphology and order on the electrical transport and exciton transport and dissociation
- Improvement of stability, including low-cost encapsulation layers
- Extrinsic doping of organic materials
- Behaviour and time evolution of contact-organic semiconductor interface
- Development of new materials (sensitisers, donor and acceptor materials) and *ab initio* modelling of properties
- Materials and processes for multiple band gap approaches
- Optical optimisation in thin layers taking into account interference effects
- Development of high-throughput S2S and R2R equipment

4.4. Concentrator Photovoltaics (CPV)

4.4.1. Introduction

The idea of concentrating sunlight to generate photovoltaic electricity is almost as old as the science of photovoltaics itself. The basic principle is shown in Figure 7. Concentrating the sunlight by optical devices such as lenses (F_o) or mirrors reduces the area of expensive solar cells (F_c) and / or of the modules that house them, and increases their efficiency. CPV's reliance on beam irradiation and the necessity to track the sun's motion across the sky by moving the system is partly compensated by longer exposure of the cells to sunlight during the day. The most important benefit of this technology is the possibility to use multijunction solar cells enabling system efficiencies beyond 30%, which cannot be achieved by single-junction 1-sun (i.e. non-concentrating) photovoltaic technology.

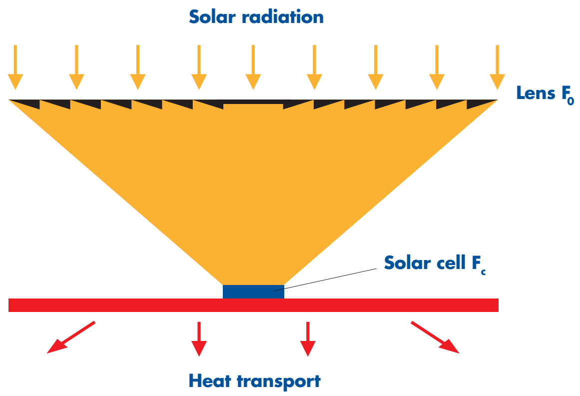
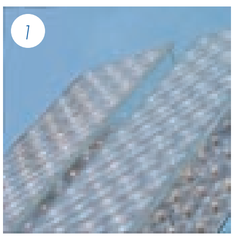
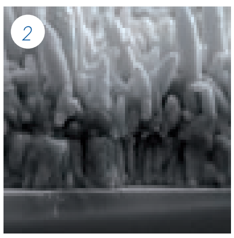


Figure 7. Schematic of a PV-concentrator. Here a Fresnel lens is used to concentrate the sunlight onto a small solar cell. The tracking part of the CPV system is not shown.

CPV technologies have played a minor role in PV industry and R&D for more than 25 years but, over the last few years, the CPV manufacturing capacity has grown significantly (to more than 150 MW / yr) as companies have entered the market. The main reasons for this increased interest in CPV technology are:

- PV applications have grown to scales that bring large PV power plants within sight. The PV power plant market is beginning at sites with high Direct Normal Irradiance (DNI), such as the south west of the USA as well as Mediterranean areas, where water scarcity may be a difficulty for Concentrated Solar Power (CSP).
- Solar cells made of III-V semiconductor compounds have already reached efficiencies above 40%, CPV modules have reached 29% and full-scale systems 25% AC operating efficiencies. Very efficient CPV systems with efficiencies of 35% to 40% can be expected (Figure 8). The high efficiencies are key to achieving low costs on the kWh-level.





1. FLATCON® module equipped with reflective secondary optics
©FRAUNHOFER-ISE

2. 20000x scanning electron microscopic of ZnO films with nanorods prepared by electrochemical deposition for application in nanostructured thin-films solar cells
©D. DIMOVA-MALINOVSKA, ET AL

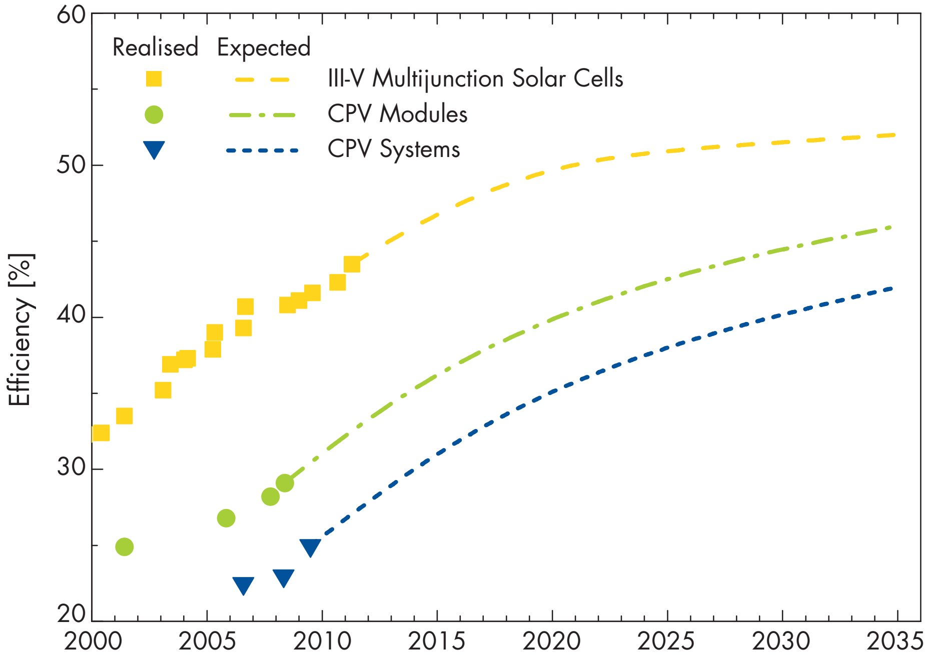


Figure 8. Achieved and expected efficiencies for III-V multijunction solar cells, CPV modules and systems. Indicated cell efficiencies before 2011 refer to calibrated measurements. For CPV modules and systems efficiencies from outdoor measurement are shown. Source: Fraunhofer ISE

4.4.2. What has happened since 2007?

The evolution in CPV technology has been more rapid than foreseen in the first edition of the SRA. Concentrator solar cells in production have already surpassed the efficiency target of 35% for concentration ratios around 500 suns and the efficiency targets for laboratory solar cells have also exceeded expectations at higher concentration ratios. Moreover multijunction III-V based cells are now the baseline technology for the majority of satellite power systems, leading to synergistic benefits to both space and terrestrial applications. New approaches for higher efficiencies and / or cost reduction, including the use of more junctions, III-V on silicon and inverted metamorphic concepts show good progress. Concentrator module efficiencies have reached 29%, easily surpassing the targeted value of 25%.

Today the CPV technology can be classified into two sectors: low-concentrating PV (LCPV) with concentration factors below 100 and high-concentrating PV (HCPV) with concentration factors from 300 up to 1000. Medium concentration range modules with concentration factors between 100 and 300 have disappeared. The majority of concentrator modules are realised with secondary optics. Results on accelerated ageing and long-term real-time outdoor testing are now available for different types of concentrator modules. Outdoor durability tests give promising results (<4% difference in comparison with predicted energy yields) and demonstrate reliability as CEC-listing, UL-listing and IEC-62108 have been achieved. There is a trend towards larger modules. For processing MW-level capacity, fully automated processes offering rapid and precise placement are available. The industry has demonstrated installations of tens of MW and the capacity to produce hundreds of MW.

In the field of tracking and supporting systems it is noteworthy that very good tracking accuracy has been achieved under outdoor conditions in different climates. Also, inverters specific to CPV systems have been developed.

Despite the strong technological advancements and the increase in production capacities, deployment has been slower than hoped due to perceived technological risks that stem from the limited availability of long term reliability information and the rapid reduction in cost of other PV technologies. Although the cost and prices of CPV systems have decreased significantly, further cost reduction should remain the central goal for the future.

In summary, CPV has moved from a prototype development phase into manufacturing since the time that the last SRA was produced. The main aims are now further cost reduction, improvement of efficiencies, standardisation and reduction of risks to investors, e.g. concerning reliability and the energy output forecast. It is expected that the required confidence can be acquired by arranging pilot schemes with shared R&D funding.

4.4.3. Materials and components

R&D in CPV should obey the following principles if it is to be successful:

- CPV is suited to medium or large PV installations rather than small ones
- CPV should be sited in open areas or on large flat roofs

CPV systems that adhere to these principles can follow a variety of designs. The concentration factor may be low or high. The concentrating elements may be based on reflection, refraction or other forms of optical manipulation. The tracking system may be 1-axis, 2-axis or based on another system. In spite of the diversity of system layouts, R&D in CPV may be divided into the following activities:

- Concentrator solar cell manufacturing
- Optical systems
- Module assembly and fabrication methods of concentrator modules and systems
- System aspects: tracking, inverter and installation issues

Research in the field of CPV must address the whole system. Only if the interfaces 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:

1. High-efficiency silicon cells or III-V compound multijunction **solar cells** should be used in concentrator systems. The environment to create these cells must be ultra-clean. For all solar cell concepts, procedures to test reliability under CPV operating conditions should be developed and assessed.

2. A great variety of **optical systems** have been introduced and tested, using plane and concave mirrors, lenses, Fresnel lenses and secondary concentrators. The task here is not 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. Especially in the high-concentration

range, optical systems must be precise with good surfaces and / or surface coatings. Fresnel lens-type elements must be produced with sharp ring segment borders in order to exhibit transmittance of over 90%. Refracting elements must have low absorbance and good anti-reflective coatings. Reflecting elements must have long-lasting coatings able to reflect more than 90% of incident light. Production of these elements should minimise material usage and be automated to reduce costs. Also, new concepts such as spectrum splitting approaches should be investigated as these could minimise the impact of daily spectral variations on the CPV system efficiency. Accelerated ageing tests and long-term, real-time outdoor testing are also necessary for the development of optical components.

3. Module assembly. The optical elements work in a geometry fixed with respect to the concentrator solar cells. This mounting must be made in a fully automated process, with rapid and precise placement of the cells, a task that can be made easier by borrowing from the expertise of micro-electronic 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. An advanced solution could be the integration of point-sensitive detector (PSD) and maximum power point (MPPT) devices into the module. In some cases optical elements and solar cells are enclosed in a weatherproof module box, in which they are interconnected in serial or parallel strings. Concentrator modules must be mechanically stable and resistant to humidity, condensation and rain water ingress over long periods. Module size must maximise long-term stability, but minimise fabrication and mounting costs. Standardised durability tests need to be developed. Recycling aspects should also be investigated.

4. System aspects. A considerable part of the cost of a CPV system may be attributed to the tracker and the largest cost of its manufacture is the cost of steel. Tracker designs must find the best compromise between size, load capacity, stability, stiffness and material consumption. This implies co-operation between the PV community and the designers of load bearing structures.

   A second important issue is the tracking accuracy under outdoor conditions, where temperatures vary and wind puts a strain on the structure. The need for accuracy depends on the concentration factor required of the system. High-concentration systems must track to accuracies better than 0.1 degrees requiring advanced mechanical construction and electronic control systems. The electronic control of CPV systems should include routines to analyse faults quickly and automatically. Tracking accuracy has already reached a good level, but requires further optimisation and development of failure correction algorithms.

   A third aspect is the total cost of installation, which should be further reduced to below 0.10 € / W by optimising the system installation (tracker & CPV modules) and reducing the time for installation. A large range of tracker constructions have already been demonstrated and convergence towards cost–effective, standardised layouts is expected.

   Most of the inverters on the market today have been designed to work with crystalline silicon or thin-film flat-plate modules. Recently, several inverters optimised for CPV systems have also been developed but further optimisation is necessary. The integration of tracking control electronics and the inverter into one device could result in large savings. Tracking strategies that foresee the use of smart modules are also of interest.

4.4.4. Solar cell devices and efficiency

There are good reasons to use the most efficient solar cells in CPV applications. For low concentrations **crystalline silicon** is a good choice. Small monocrystalline Si solar cells have reached 25% efficiency under 1 sun illumination. Under concentrations of 92 suns a silicon point contact cell has shown 27.6% efficiency. This efficiency is close to the theoretical limit, so there is not much room for improvement. However, it is important to achieve these results in large industrial production with high yield and reduced costs. New materials and solar cell concepts for cost-effective and high-efficiency applications with low concentration levels should also be investigated.

A shift towards higher concentration (500 suns or more) and towards **multijunction cells consisting of III-V semiconductor compounds** is observable. These cells are composed of fairly complex layer systems that are epitaxially grown by metal organic vapour phase epitaxy (MOVPE) in a computer-controlled semi-automatic process.

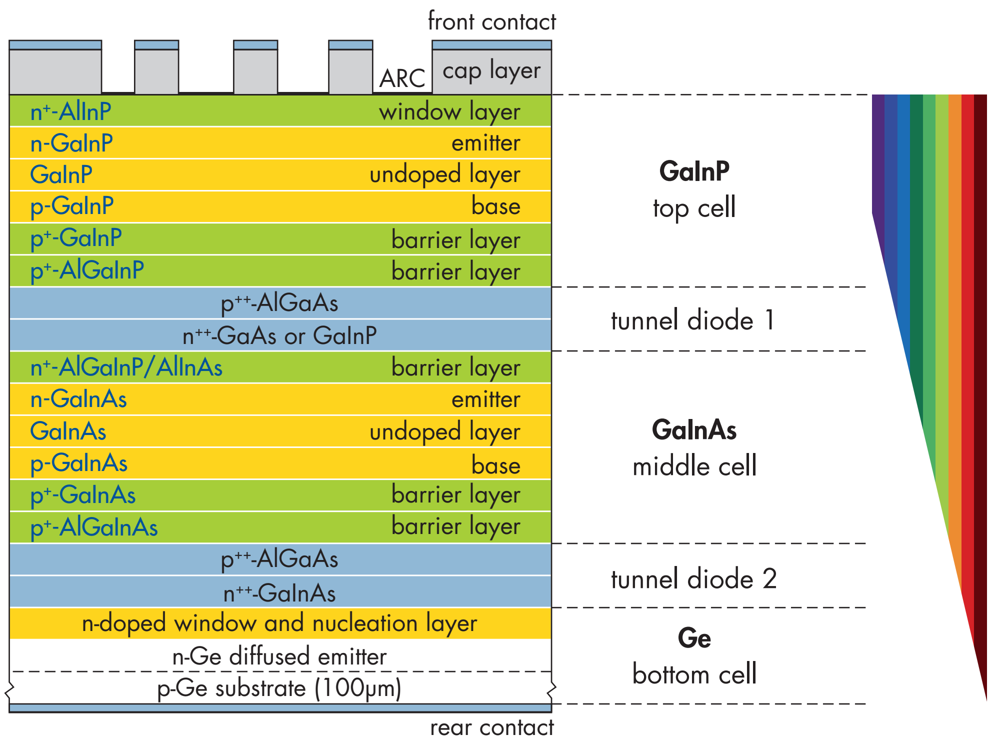


Figure 9. Left: Schematic layer system of a GaInP / GaInAs / Ge triple solar cell on Ge substrate. ARC: Anti-reflective coating. Source: Fraunhofer ISE

Recently III-V triple-junction solar cells have shown efficiencies of 41.1% at 450 suns (made GaInP / GaInAs / Ge, Fraunhofer ISE, Europe) and of 43.5% at around 500 suns (GaInP / GaAs / GaInNAs, Solar Junction, USA). It should be possible to push the efficiencies of these multijunction cells higher, perhaps by adding further junctions to the cells. This is R&D that can be expected to be commercialised in the medium to long term.

Short-term R&D in technologies close to the market should focus on producing large quantities of multijunction cells with a minimum average efficiency of 45% (depending on concentration factor) at high yield and reduced costs. 42.3% has already been achieved with MOVPE and 43.5% with molecular-beam epitaxy (MBE) and the strong increase in performance seen in the last decade is expected to continue. High yield can be achieved by adopting robust solar cell structures, investigating new growth processes and improving the MOVPE and process technology. A further medium- to long-term goal is to replace the Ge substrate by a Si substrate, which would reduce costs. Another option under investigation is inverted or bi-facial growth, which might allow reuse of the substrate in the future. In addition, new solar cell concepts for spectrum splitting approaches should be developed. These approaches take the spectral sensitivity of CPV systems into account.

4.4.5. Manufacturing and installation

The scale of the CPV industry lags that of flat-plate PV by one or two decades. It is expected, however, to make up this delay to the point where, in 2014, cumulative installed capacity will surpass 1 GW. R&D work has to be undertaken in the area of high-throughput production to realise this ambition. Material consumption must also be reduced. A projection for future turn-key CPV system prices extrapolated from current prices is shown in Figure 10.

The most important R&D in CPV manufacturing will aim at:

- Improving the efficiency of mass-produced cells to the levels currently seen in the laboratory (over 26% for low-concentration-Si solar cells and up to 45% efficiency for III-V multijunction solar cells)
- Improving optical elements (optical efficiency, lifetime and product engineering)
- Further progress in automated industrial module assembly (adjustment of elements, packaging and sealing), high-throughput manufacturing with high yield, resulting in products with long lifetimes
- Construction of light, robust and precise trackers for all outdoor climate conditions
- Assembly and monitoring of large plants, in the range of several MW (short term) to over hundred MW (medium term) as well as direct comparison with other PV technologies
- Techniques for guaranteeing the quality of products with intended lifetimes of over 30 years, development of standards, in-line testing and recycling methods for the modules

Parabolic mirror concentrating systems of Zenith Solar in Israel with PV central receivers
©FRAUNHOFER-ISE

This list encompasses an immense quantity of work, which is broken down into tasks with short-term and medium-term relevance in the Tables 12-14.

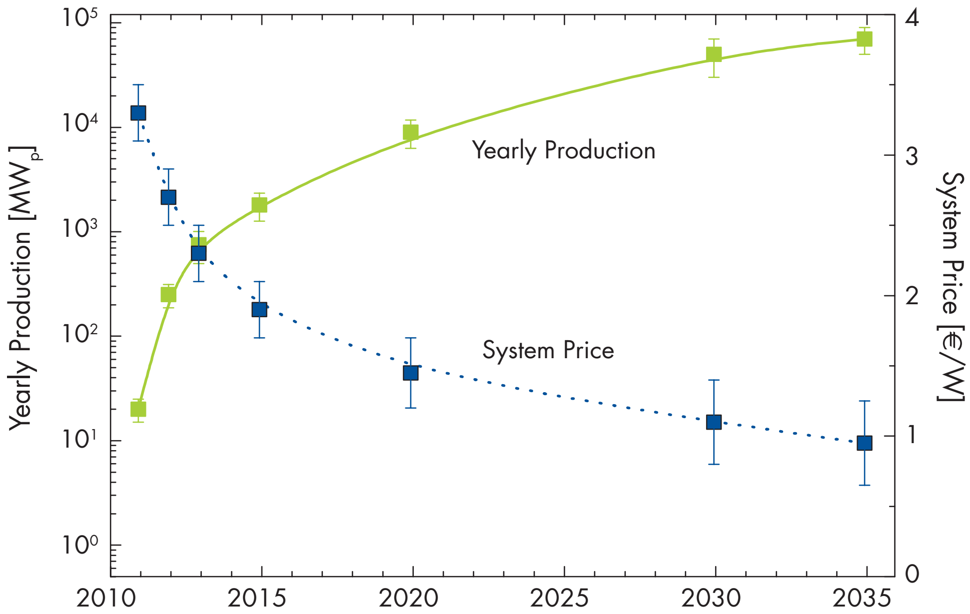


Figure 10. The expected yearly production of CPV systems (dotted) and the price of turn key installed CPV systems in € / W (solid).

4.4.6. Summary

Although CPV technology, out of all PV technologies, has the highest conversion efficiencies, experience with manufacturing CPV systems is still lacking in comparison with other PV technologies. However, experience in manufacturing CPV technology is being built up, as is a track record in the operation of CPV systems, helping to increase investor confidence.

A large number of R&D tasks have to be undertaken to meet the common targets across all PV technologies for the short term (up to 2016) and medium term (up to 2025):

- Materials and components:
  - Optical systems: find reliable, long-term stable and low-cost plane and concave mirrors, lenses and Fresnel lenses as well as secondary concentrators.
  - Module assembly: Develop materials and mounting techniques for assembling concentrator cells and optical elements into highly precise modules, stable over long periods using low-cost fully automated methods.
  - Tracking: Identify constructions that are optimised for size, load capacity, stability, stiffness and material consumption.

- Devices and efficiency: Develop materials and industrial production technologies for very high efficiency concentrator solar cells: Si cells with efficiencies of 26%; multijunction III-V-compound cells with efficiencies above 45% (48% in the laboratory). Identify the optimum concentration factor for each technology.

- **Manufacturing and installation:** Optimise design, production and testing routines for the integration of all system components. Scale-up production with fully automated production lines for high volumes. Optimise methods for installing CPV systems, testing them in outdoor environments and evaluating their cost.

Table 11. Research priorities for **concentrator photovoltaic solar cell manufacturing** – time horizons for first expected application of research results in (pilot) manufacturing and products. Targets to be achieved in those time horizons are also shown.

CONCENTRATOR CELL	2011 – 2016	2016 – 2025	2025 – 2035 and beyond
Industry manufacturing aspects	■ Improve high-yield industrial manufacturing processes for Si and III-V concentrator solar cells Target: ■ η Si: 22% @10-30 suns ■ η Si: 26% @100-300 suns ■ η III-V: 45% @ >500 suns ■ Cell production costs <0.15 €/W by 2013	■ Manufacturing processes for III-V multijunction solar cells with efficiency of >45% at >1000 suns ■ Low-cost design concepts and manufacturing processes for silicon cells for moderate concentration and moderate climates (thin-films with light-trapping) Target: ■ Cell production costs: <0.10 €/W	■ Manufacturing concepts for 4- to 6-junction cells
Applied / advanced technology aspects	■ For low concentration factors: use, adapt and improve standard Si technology ■ For high concentration factors: Improve III-V triple-junction solar cells ■ Improve MOVPE growth processes, equipment and source materials ■ Layer transfer and bonding technologies for new cell concepts	■ Application of manufacturing techniques derived from microelectronic technology for mass production	■ Fully automated, high-throughput processes for large-scale cell production
Basic research, fundamentals	■ Materials research for improved understanding of properties and behaviour ■ Efficiency increase (triple-junction cell, with 44% average production efficiency at 1000 suns) ■ Increase stability and lifetime ■ Encapsulation technologies ■ Characterisation techniques ■ Solar cell modelling ■ Multijunction solar cells with low spectral sensitivity ■ CIS and other alternatives as concentrator cells ■ Novel cell concepts for efficiencies exceeding 50% ■ Develop reliability test procedures and standards for cells	■ Research for 4- to -6-junction cell applications ■ III-V material studies and solar cell modelling ■ Growth of III-V semiconductors on Si ■ Solar cells with lower material usage, e.g. through substrate reuse ■ New materials like GaInN and III-V-IV superlattices ■ Research on new concepts for cells with η >25% for application in LCPV modules	■ Research for detailed understanding of material, properties, behaviour

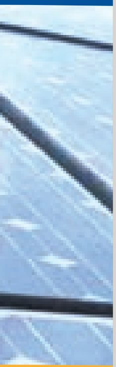
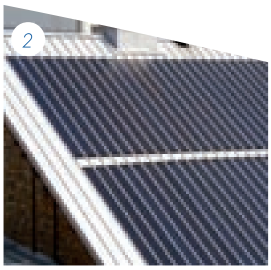


Table 12. Research priorities for **concentrator photovoltaic optical systems** – time horizons for first expected application of research results in (pilot) manufacturing and products. Targets to be achieved in those time horizons are also shown.

OPTICAL SYSTEM	2011 – 2016	2016 – 2025	2025 – 2035 and beyond
Industry manufacturing aspects	■ Cost reduction (lens or mirror) ■ Process automation, high-volume production at 200 W / minute ■ Process control, quality checks, standardised CPV module test ■ Low-cost materials with high optical efficiency, reproducible anti-reflective treatment Target: ■ primary optics <0.2 € / W, secondary optics: <0.05 € / W by 2013	■ Systems design and materials able to reach 90% optical efficiency in mass production Target: ■ Optics <0.1 € / W	Target: ■ Optics: <0.08 € / W ■ Optical efficiency >90%
Applied / advanced technology aspects	■ Ongoing improvement of primary and secondary optics for high-concentration with wider acceptance angle ■ Technologies for improved alignment of optical parts and cell assembly ■ Optimisation of production process for primary and secondary optics ■ Inline quality control during manufacturing of optics	■ Films and coatings on plastic or glass ■ Spectrum splitting optical system ■ Highly automated production concepts for optical mirror and lenses ■ Highly transparent anti-soiling layers on optical elements	■ New technologies for large-area coating
Basic research, fundamentals	■ Increase optical efficiency (>85% average / yr), stability (>30 years) and acceptance angle of the optical systems ■ Develop stability testing procedures for lifetime guarantees ■ Develop long-term test sequences for foils and coatings ■ New optical concepts for very high concentration (>1000 suns) ■ Hydrophobic and hydrophilic surfaces to reduce soiling effect ■ New optical system to minimise the spectral sensitivity of the CPV system (i.e. spectrum splitting)	■ Ultra-high concentration (>2500 suns) ■ Improved heat dissipation ■ Development of optical systems for hybrid (thermal and electrical) applications	■ Optics with high acceptance angle at high concentration level ■ Advanced optical systems that reduce the tracking requirements

Table 13. Research priorities for **concentrator photovoltaic module and system assembly and fabrication** – time horizons for first expected application of research results in (pilot) manufacturing and products. Targets to be achieved in those time horizons are also shown.

MODULE ASSEMBLY	2011 – 2016	2016 – 2025	2025 – 2035 and beyond
Industry manufacturing aspects	■ Target guaranteed module lifetime: η 30 years) ■ Manufacturing concepts for module fabrication ■ Implementation of process control measures and quality checks Target: ■ LCPV / HCPV module efficiencies: >19% / >35% ■ Target assembly costs 0.5-0.8 € / W	■ Very large scale (GW range) CPV module production Target: ■ LCPV / HCPV module efficiency >21% / >40% ■ assembly costs: <0.5 € / W	Targets: ■ LCPV / HCPV module efficiency >23% / >45% ■ Assembly costs <0.35 € / W
Applied / advanced technology aspects	■ Low-cost concepts and process automation for the single parts, solar receiver assembly, housing, cabling, etc) and the whole module ■ Approaches for high throughput assembly ■ Concepts for fully automated production, e.g. for automated mounting and sealing of modules ■ Recycling concepts ■ Manage constraints associated with concentration levels >1000 suns	■ Procedures for easy mounting and replacement ■ Lifetime performance-models	■ Concepts for fully automated production
Basic research, fundamentals	■ New sealing techniques for stable long-term field performance ■ The long-term stability of materials like glues, solder and silicones ■ The interaction between the materials used for module fabrication ■ Smart modules with integrated detectors and tracking control ■ Adapted tests for reliability	■ Designs for larger modules ■ New materials for effective passive cooling ■ Combined use of CPV and thermal solar energy ■ Direct electrolysis in the CPV module to produce hydrogen	■ New materials for lower cost and a higher degree of integration on the module level



1. *CPV systems produced by Soitec Solar. These modules with Concentrix™ technology use Fresnel lenses to concentrate sunlight 500 times onto cells of 2 mm diameter.*
   ©SOITEC SOLAR

2. *Roof-integrated PV on a historical building (amorphous silicon module on metal sheet)*
   ©UNIVERSITY OSNABRÜCK

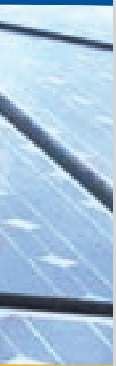


Table 14. Research priorities for **concentrator photovoltaics system aspects – tracking, inverter and installation –** time horizons for first expected application of research results in (pilot) manufacturing and products. Targets to be achieved in those time horizons are also shown.

TRACKING / INSTALLATION	2011 – 2016	2016 – 2025	2025 – 2035 and beyond
Industry manufacturing aspects	■ Production technology for trackers ■ Inverters with increased efficiency and lifetime Target: ■ Tracker cost 80-150 € / m² ■ Tracking accuracy <0.2° ■ Inverter cost <0.15 € / W	■ Automated mass production of trackers Target: ■ Tracker cost: 50-80 € / m² ■ Tracker lifetime >30 years ■ Inverter cost <0.1 € / W	
Applied / advanced technology aspects	■ Designs optimised for ease of transportation and utility-scale installation ■ Fast detection of tracker failure ■ Optimisation of material utilisation (lightweight construction) ■ Power plant engineering ■ Grid connection of power plants ■ Dedicated inverters for CPV ■ Standards for trackers and CPV inverters defined	■ Trackers for larger systems ■ Maintenance-free, low energy consumption, high reliability and performance stability ■ Inverters with power quality functions and active grid stabilisation ■ Integration of short-term storage ■ Development of automated-cleaning techniques	■ Inverter-based grids ■ Standardised village grids powered by CPV ■ Integration of long-term storage
Basic research, fundamentals	■ Combination of inverter and tracker electronics ■ Smart tracking control ■ Increased tracking accuracy ■ Effects of wind loading ■ New tracker drivers ■ Combined maximum power point and tracking algorithms	■ New tracker design concepts ■ Alternatives for steel in the tracking construction ■ Sensorless tracking methods ■ Advanced control algorithms for grid stabilisation	■ Control algorithms for distributed inverter-based grids

4.5. Novel PV technologies

4.5.1. Rationale for inclusion within the Strategic Research Agenda

Reduction in cost per watt is an aim of crystalline silicon technology and of the thin-film technologies that are challenging crystalline silicon's dominance of the PV market. Cost reduction in these technologies is largely driven by the know-how accumulated from many years of industrial manufacture and system operating time, allowing robust extrapolations to future costs to be made.

However, limiting R&D to this set of PV technologies has two obvious risks. Firstly, given the Shockley-Queisser limit, the existing technologies saturate at <25% efficiency on flat-plate modules unless novel features are included. Secondly, the European PV industry would miss opportunities related to "beyond evolutionary" technology developments. Therefore, there should be sufficient openness towards developments taking place in material and device science (nanomaterials, self-assembly, nanotechnology, plastic electronics, photonics, etc.) to allow these opportunities to be detected at an early stage.

4.5.2. Definition and classification of novel PV technologies

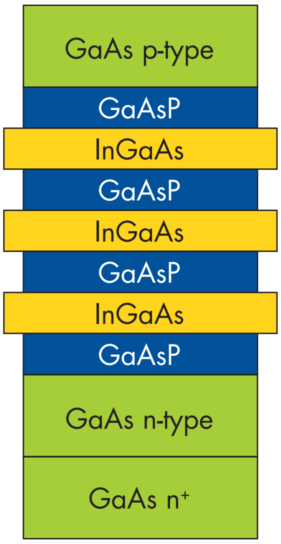
The term "novel" relates to the maturity of different approaches. It is used here for developments and ideas that can lead to potentially disruptive technologies, but where there is not yet clarity on practically achievable conversion efficiencies or future costs. Most of these novel PV technologies can be categorised as high-efficiency approaches and are often grouped under the misleading term "third-generation concepts" (misleading because of the suggestion of evolution from existing technologies). Rather, "novel" and "third-generation" should be understood to mean approaches that try to defy the Shockley-Queisser limit.

In this respect, an essential distinction is made between approaches which modify and tailor the properties of the active layer to match it better to the solar spectrum and approaches which modify the incoming solar spectrum and are applied at the periphery of the active layer without fundamentally modifying its properties. In both cases, nanotechnology and nanomaterials are expected to provide the necessary toolbox to enable these effects. Given the nature of these developments and the flux dependence of many of the targeted phenomena, it is expected that these developments will probably first be adopted in concentrator photovoltaics (CPV - see Section 4.5). Application in 1-sun flat-plate modules is foreseen only at a later stage.

4.5.2.1. Novel active layers

Nanotechnology allows the introduction of features with reduced dimensionality (quantum wells (QW), quantum wires and quantum dots (QD)) in the active layer. There are three basic ideas behind the use of structures with reduced dimensionality in the active layer. The first aims at decoupling the basic relationship between output current and output voltage of the device. By introducing quantum wells or quantum dots consisting of a low-band gap semiconductor within a host semiconductor with wider band gap, the current may be increased while retaining (part of) the higher output voltage of the host semiconductor. A second approach aims at using the quantum confinement effect to obtain a material with a higher band gap. The third approach aims at using the excess energy of excited carriers before they thermalise to the bottom of the energy band (e.g. hot carrier cells, multiple exciton generation). The reduced dimensionality of the QD material tends to reduce the allowable phonon modes by which this thermalisation process takes place and increases the probability of harvesting the full energy of the excited carrier. Several groups in Europe have built a strong position in the growth, characterisation and application of these nanostructures in various materials (III-V, Si, Ge) and groundbreaking R&D is also being performed at the conceptual level.

The purpose of using quantum wells in the active part of the device is to extend the cell spectral response beyond the limits imposed by the band gap of the host semiconductor. This technology is being applied mainly in III-V PV cells by companies like QuantaSol, a new independent designer and manufacturer of strain-balanced quantum-well solar cells, who have obtained excellent efficiencies. The efficiency of QuantaSol's single-junction device has been verified by the research centre Fraunhofer ISE to be 28.3% at >500-sun concentration. More recently, InGaN-based materials have been under investigation since the band gap can be varied over a wide range by alloying with In. The best efficiencies to date are in the range of 2-3%. This material system is potentially interesting because of its relative insensitivity to crystal defects (at least for LEDs), resulting in high radiation hardness which would also make these cells attractive for application in space.



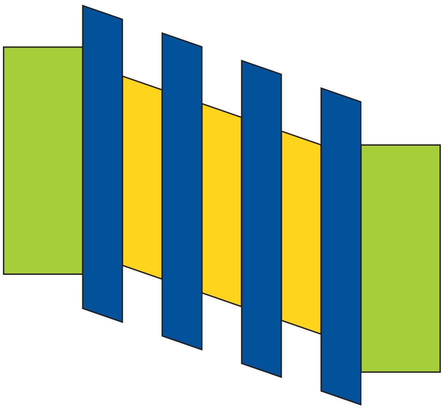


Figure 11. (courtesy: K. Barnham) Left: Illustration of QW-based approach to extend the spectral response towards longer wavelengths. Right: Schematic band gap diagram of quantum well solar cell

Most of the work on quantum wires and dots for active layers deals with systems based on InGaAs or InAs QDs, which are included in GaAs solar cells to improve the response towards longer wavelengths. The level of maturity and the amount of information for Si-QDs and QWs is less than for III-V QDs. They are used to realise a Si-based material with a higher bandgap than crystalline silicon or to obtain energy-selective resonant tunneling contacts for hot carrier cells. The final objective is to investigate the feasibility of a Si-based multijunction approach and implement this in a thin-film configuration with a crystalline Si bottom cell. For the quantum confinement effects to occur, the size of the Si-QDs and Si-nanowires has to be below 5 nm.

In recent years, QDs and QWs based on II-VI materials have been investigated. The aim is to include II-VI QDs as absorbers in bulk donor-acceptor heterojunction solar cells of various types. The concept is simple: the added QDs should improve the cell response at longer wavelengths relative to cells without QDs. QD-containing cells are often called "hybrid solar cells" as the active layer consists of organic and inorganic compounds. Most attempts have successfully demonstrated the enhancement, but no approach has yet led to higher results than the best bulk donor-acceptor heterojunction solar cells (8%) and dye solar cells (11.5%). The efficiencies obtained are typically around 2-3%. In recent years, however, there has been renewed interest in another area: multiple exciton generation to harvest more than 1 electron-hole pair per incident photon. The process has been demonstrated in several II-VI materials, including selenides and lead salts.

A specific approach which often relies on QDs is the so-called Metallic Intermediate Band (MIB) approach. This approach aims to increase absorbance towards longer wavelengths by allowing 2-photon absorption processes using a half-filled metallic band positioned within the band gap of a host semiconductor. InAs QDs have been most intensely investigated in this regard. Nevertheless interest is increasing in bulk-like MIB-materials like Ti-implanted Si or ZnTe doped with O. Detailed calculations indicate that the limiting efficiency of the MIB solar cell is 63% for non-concentrated sunlight and up to 70% for concentrated light.

4.5.2.2. Tailoring the solar spectrum to boost existing cell technologies

Up and down-conversion

The basic principle of up and down-conversion is shown in Figure 12. The application to photovoltaics is still at a very early stage, but the fact that these effects can be tailored to boost existing solar cell technologies by introducing modifications outside the active layer represents an appreciable advantage which could reduce their "time to market" considerably.

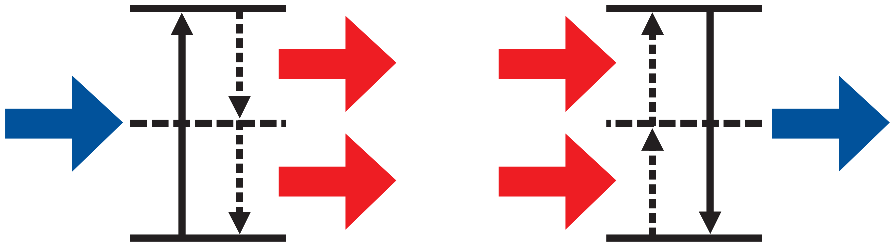


Figure 12. In down-conversion systems a high-energy photon is converted to two low-energy photons allowing more efficient harvesting of the energy of the high-energy photon; in up-conversion, two low-energy photons are converted to a high-energy photon. Down-conversion systems should be applied at the front of the cell, while up-conversion systems should be incorporated at the rear of bifacial solar cells.

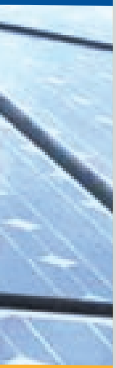
Generally-speaking, two types of wavelength-converting materials can be distinguished. The first is based on lanthanides and the second on organic materials. The lanthanides feature characteristic luminescence properties due to energy levels arising from interaction between the 4f-electrons in the partly filled 4f-shell. The desired absorption and emission spectra are achieved by choosing the right atom. Proofs-of-concept were realised on a-Si:H and GaAs solar cells (based on the Yb^{+}-Er^{+} combination) as well as on c-Si and dye cells (based on Er^{+}). In all cases the required injection levels were equivalent to about 500 suns which points to CPV as the first domain to apply these concepts. Potentially, combination with plasmonic effects might lower this threshold.

Photonic structures

Photonic structures can be realised in several ways to enhance the performance of the solar cell device. The most straightforward approach uses periodic front- and rearside structures to improve the coupling of light into the cell or for increasing the rearside reflectance. This approach might be quite beneficial at the rearside of the cell as the spectrum of the non-absorbed light is narrower at the rear than at the frontside of the cell. This category also includes the use of Bragg reflectors.

A second approach relies on surface plasmons which are generated upon interaction between light and metallic nanoparticles. This has been proposed as a means to increase photoconversion efficiency by wavelength-shifting photons in the incoming solar spectrum towards the wavelength region where the collection efficiency is maximal, by increasing the absorbance by enhancing the local field intensity or by increasing the forward or backward scattering of light. The effect has been demonstrated in crystalline Si, a-Si:H and organic solar cells.

Lastly, the use of nanoscale structuring can be applied to obtain in-plane spectral splitting and concentration of light. This approach might be very interesting when combined with concentrator microcells to which the different parts of the spectrum are guided, thereby realising an in-plane multijunction solar cell without the need for current matching between the subcells. Companies like Hypersolar are pursuing this combination of photovoltaic and photonic structures.



4.5.3. R&D Topics

The following tables describe priority topics only. For novel PV technologies the emphasis in the coming years should be on modelling, on nanotechnology (nanoparticles, and methods to grow and synthesise them) and on the first demonstration of concepts based on the use of such nanoparticles within functional solar cells. These developments will require adapted tools allowing morphological and opto-electrical characterisation on the nano-scale. Beyond 2025, the most promising concepts will be selected and implemented with increased emphasis on aspects like cost, upscaling, manufacturing and sustainability when moving to very large >10 GW/yr production scenarios. The successful development of these novel PV technologies requires timely selection and rapid take-up of promising developments.

Table 15. R&D roadmap for novel PV technologies.

BASIC CATEGORY	TECHNOLOGY	ASPECTS	2011 – 2016	2016 – 2025	2025 – 2035 and beyond
Novel active layers	■ Quantum wells ■ Quantum wires ■ Quantum dots ■ Nanoparticle inclusion in host semi-conductor ■ Multiple exciton generation	Material	■ *Ab initio* material modelling ■ Deposition technology ■ Nanoparticle synthesis ■ Metallic intermediate band bulk materials ■ Morphological and opto-electronic characterisation		Upscaling of most promising approaches requiring low-cost approaches for deposition technology, synthesis, cell and module technology compatible with module costs < 0.3 €/W
		Device	■ Opto-electrical simulation and modelling ■ First functional cells under 1 sun or concentration ■ Lab-type cells ■ Selection		
		Performance	N.A.	>30%	
		Cost	N.A.	N. A.	
Boosting structures at the periphery of the device	Up-down converters	Material	■ *Ab initio* material modelling ■ Basic material development ■ Stability of boosting layer materials		Upscaling of most promising approaches requiring low-cost approaches for synthesis of required materials, deposition or application technology of peripheral layers with module costs <0.3 €/W. Cost of these layers and applying them should therefore be <0.05 €/W.
		Device	■ Opto-electrical simulation and modelling ■ First demonstration on existing solar cell types under 1 sun or concentration ■ Lab-type cells ■ Selection		
		Performance	N.A	>10% improvement relative to baseline without spectrum conversion	
		Cost	N.A.	N.A.	
	Exploitation of photonic structures	Material	■ *Ab initio* material modelling ■ Metallic nanoparticle synthesis with control over size, geometry and functionalisation ■ Stability of boosting layer materials		
		Device	■ Opto-electrical simulation and modelling ■ First demonstration on existing solar cell types under concentration ■ Lab-type cells ■ Selection of most promising apprahces		
		Performance	N.A.	>10% improvement relative to baseline without spectrum conversion	
		Cost	N.A.	N.A.	

4.6. PV components and systems: integration with the electricity grid and buildings

4.6.1. Introduction

Photovoltaic systems can be implemented in a range of applications, sizes and situations, meeting a wide range of power needs. The user encounters PV technology at the system level and requires it to be reliable, cost-effective and look attractive. This research agenda concentrates on topics that will achieve one or more of the following:

- reduce costs
- increase overall performance, efficiency and component lifetimes, reduce losses and maintain performance levels throughout system life
- improve functionality, so adding value to the electricity produced
- implement innovative approaches in the grid-connected system design (e.g. storage), inverter design and technical standards in order to broaden the hosting capacity of the grid
- improve the integration of systems in the built environment (BIPV) to reduce overall costs and environmental impact and ensure public support for large-scale deployment
- enlarge the range of BIPV elements available to facilitate innovative architectural approaches, including enhancement of multifunctionality

Traditionally, PV systems are divided into two main categories depending on whether or not they are connected to the electricity grid system. The first, grid-connected systems, can be further sub-divided into central systems, which feed all the electricity generated into the grid, or distributed systems, where the electricity goes to meet local loads first with only the excess fed into the grid. Most large ground-based systems fall into the first category. Building-integrated systems of all sizes can be operated in either mode, but are most often utilised as distributed systems.

"Off-grid", or "stand-alone", systems (the second category of system) can also be further divided into two sub-categories: commercial applications (e.g. telecommunications, remote sensing) and rural development applications (e.g. irrigation, lighting, health centres, schools).

The wide variation in system applications means that there is necessarily a variation in system costs. The module has for a long time been the most costly component, typically accounting for 50-60% of the costs at system level, but this share varies considerably with application and system size, since balance of systems (BoS) components and installation costs do not scale linearly with system size. The module will remain the highest single cost item for some time to come. Nevertheless, in order to meet the cost targets required for high PV penetration, substantial and consistent system-level cost reductions must be made alongside those for the PV module. The system costs can broadly be divided into those for BoS components (whether part of the energy generation and storage system or components used for control and monitoring) and installation (including labour, design costs and administrative costs). For BIPV, the cost for structural elements can be reduced if the array has multifunctional features. Significant scope exists for cost reduction at the component level, but it is equally important to address installation issues by harmonising, simplifying and integrating components to reduce site-specific overheads.

The reduction of BoS costs is fundamental to reaching these goals for all grid-connected systems. For large system sizes and therefore component quantities, 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.

With very high penetration levels the value of PV power will be more time-dependent. Therefore PV system-related energy management including decentralised load management, generation peak shaving and electricity storage will gain importance. This requires higher controllability of PV systems and loads.

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

4.6.2. Components

At the component level, highest priority is given to the development of inverters, storage devices and new designs for specific applications, especially BIPV systems.

The main objectives for the inverter are the extension of lifetime to 20 years and cost reduction. Research for the medium term focuses on the possibility of using functionality built-in to the inverter to improve the quality of grid electricity, by controlling reactive power, filtering harmonics etc. Another emerging topic is the development of micro-inverters and DC/DC solar optimisers, both for retrofitting traditional modules and embedding in new "smart" PV modules. In the short term, research should address the reliability assessment of such components. A recent development has been devices to disconnect the PV modules in case of damage or fire, by means of circuit breakers or short-circuit switches in order to prevent hazardous voltages on the DC side of PV systems. Since these devices are safety-relevant components, the reliability and proof of function is of utmost importance and requires research on reliability, test specifications and failure analysis.

Storage of electricity has grown in importance due to the increasing input of stochastic renewable sources into electricity grids. Research into new storage devices was neglected in the past decade but is an important aspect of the use of all variable-output renewable energies. The SRA does not include development of the storage devices themselves, but supports their development within an overall European research agenda. PV-related research for storage devices is necessary for off-grid systems but is now also needed for grid-connected systems. Some recommendations for storage research are made below relating mainly to batteries:

- Adaptation of battery management systems (BMS) for new battery technologies (e.g. Li-ion and Ni-MH) for PV applications
- Field testing of new battery technologies developed for other applications (e.g. automotive, consumer market) and with the potential to reduce lifecycle costs in PV applications, to assess lifetime, performance, added value and cost (target of less than 3 c€/kWh of energy throughput)
- Innovative approaches for the short-term storage of small amounts of electricity (1-10 kWh), including materials and processes for cost reduction, lifetime, flexible operation and modularity that comply with requirements for recycling and low lifecycle emissions
- Approaches for the integration of the storage component into the module, to provide a single product that is both low-cost and straightforward to use in stand-alone and remote applications (including considerations of operating temperature)
- Devices for i) storing large amounts of electricity (>1 MWh) ii) storing electricity for long periods (several weeks)

Most of the research on PV modules has been discussed in previous sections. However, issues such as multifunctionality, the use of PV modules as construction elements and the integration of modules with other system components relate to the system and are included here. The principal R&D objectives for BIPV are to improve functionality and create new designs of BIPV elements for general and specific use. Approaches to R&D that combine such disciplines as architecture, energy-efficient building design and PV technology improvements (efficiency, module size, appearance, etc.) are becoming increasingly important.

A major objective of BoS development is to extend the lifetime of BoS components to match as closely as possible that of the PV modules. The short- to medium-term target for grid-connected and stand-alone systems is to increase BoS component lifetime to 20 years. For systems installed in isolated, off-grid areas, component lifetime should be increased, particularly that of the battery, to around 10 years. Components for these systems need to be designed so that they require little or no maintenance.

4.6.3. Systems and system use

System-level research targets cost reduction, reliability and utility. This includes concepts of storage in grid-connected systems or using inverters that are able to operate in island mode to increase the reliability of supply in case of disturbances on the main grid.

The monetary value for end-consumers of electricity from grid-connected PV systems depends on where they are situated. In countries that offer feed-in tariffs, it is equal to that tariff. In countries where net-metering is practised it equals the avoided purchase cost of electricity. In the case of a time-dependent electricity tariff and a demand curve that follows the power output of PV modules, the value of PV electricity can be very high especially if the marginal cost of grid electricity generation capacity is high. Technologies to capture this value need to develop in parallel to PV systems.

In the longer term, PV systems will become key components in low-voltage sub-grids (or microgrids). A detailed and ongoing assessment of the value of PV electricity in various grid configurations in Europe both with and without storage is very important, especially in the context of the development of smart grids and the increasing use of renewable energy sources of all kinds in the electrical delivery network.

The research agenda focuses on harmonisation, including of component lifetime, module specifications (to reduce initial design costs and to simplify replacement and modification of systems in the future), grid codes and modularity (to reduce costs for large installations). It includes the development of control and monitoring strategies to maximise system performance, whilst retaining simplicity of operation, and considers the interaction of PV systems with the grid at high PV penetrations. Performance assessment is important for the "on-line" analysis of PV systems (e.g. for early fault detection) and for "off-line" analysis of PV systems (e.g. to determine and address loss mechanisms). The knowledge gathered can be used to validate and improve yield prediction models. This work needs to be revisited as new module types and system designs are adopted. Intelligent inverter functions and the way in which PV systems interact with other distributed generation technologies are relevant here.

The rapid growth of grid-connected applications over the last decade seems to have overshadowed stand-alone systems in research programmes, including those of the EU. The Platform's working group on developing countries has identified the following topics as particularly important in BoS research:

- Low-cost and highly reliable components for island PV systems and island PV-hybrid systems
- techniques to manage island microgrids with a high share of PV generation
- cost-effective instruments for performance monitoring of large numbers of distributed PV systems (e.g. satellite communications)
- efficient and sustainable incentives for the use of PV systems
- financial mechanisms that make off-grid PV systems more affordable

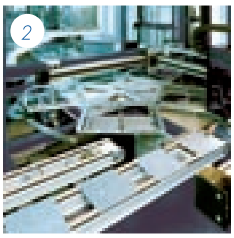
In the main, the research priorities above describe activities that should be implemented in the short- and medium-term. As new module technologies emerge, some of the ideas relating to BoS may need to be revised to accommodate them.

4.6.4. Interaction of PV systems with the electricity grid

Ever more interest is being taken in Europe and in developed countries in general in the impact of electricity generated by PV systems on electricity grids. The main challenge facing PV integration is its daily and seasonal variation in output. The wider use of smart grids, smart meters and smart inverters will help to overcome this challenge. Storage, electric vehicles and coordination with other renewable energy generation (wind especially) are other areas to which short- and medium-term research efforts should be directed.

In the past PV systems had a negligible influence on the operation of interconnected grids, but today in some regions, this situation has changed. In Germany in early 2011, it happened that PV's penetration reached 17 GW of about 40 GW minimum load. It is necessary to make PV systems more compatible with smart grids. This mainly concerns parameterisation of frequency limits but also controllability in terms of active and reactive power. This is required in order to avoid unnecessarily high costs for adapting their behaviour in the field.

With such measures, the allowable penetration PV power could be considerably increased and the related grid reinforcements could be realised more efficiently. The smaller and the weaker the grid, the more attention has to be given to these issues. For large scale systems in the multimegawatt range, even more sophisticated control systems have to be developed in order to enable very high penetration levels that will be cost efficient in future. Here improved dynamic behaviour of PV systems, perhaps in combination with other sources, storage units and controllable loads is needed.



1. Ground-mounted PV plant in Rodenäs (northern Germany)
©SHARP ELECTRONICS (EUROPE) GMBH 2010

2. Automatic loading station of an in-line PE-CVD deposition system for anti reflective and passivation coatings on c-Si solar cells
©SINGULUS TECHNOLOGIES AG

The share of PV in the grid can be boosted by measures that tune load management to the fluctuating PV source. Decentralised load management systems should therefore be a topic for research. The system design should be improved to support a holistic energy management approach, including load management, energy storage and, as a last resort, active power limitation.

R&D should therefore focus on these general topics:

- Linking PV systems to grid communication systems, energy management and building automation
- Pre-standardisation including development of smart grid integration
- Development of advanced and harmonised grid connection rules for high PV penetration levels
- Development of (decentralised) energy management systems that support the efficient use of fluctuating power sources
- Improvement of controllability and forecasting of PV system output concerning active and reactive power, frequency behaviour and decentralised voltage regulation

More specifically, the areas of research can be divided into two groups, grid-side measures and PV system- and consumer-side measures.

On the grid side (both distribution and transmission grid), many initiatives can be undertaken both "hard" (such as grid reinforcement, new voltage control and monitoring systems, smart meters) and "soft" (e.g. standards and regulations for frequency control, tools for energy output forecasting). These are not the subject of this SRA, but rather fall under the remit of the development of smart grids in general. In that regard, the integration of PV into the grid is part of a continuing dialogue with the European Technology Platform for Electricity Networks of the Future.

On the PV system- and consumer-side, many research fields can be defined, for example:

1. **Voltage control.** Inverters can cause overvoltages during their normal operation, particularly for long distribution lines with high impedance (rural lines). Enhanced inverters with reactive power control should be studied to avoid this voltage rise.

2. **Temporary voltage drop immunity.** Voltage drops cause immediate disconnection of PV systems from the grid with consequent production loss and potential problems with grid balancing. Research should focus on finding the right compromise between safety rules, protection device sensitivity and grid connection solidity.

3. **Frequency-dependent power control.** Current inverters disconnect themselves from the grid during frequency fluctuations. This can cause severe grid instabilities and limit the deployability of PV systems. New smart and self-adaptative inverters should be developed in order to react correctly to these conditions (e.g. with a proportional reduction of the power output).

4. **Stepwise power reduction through remote control.** In the case of grid overloads, an automatic reduction of power output may be demanded by sending a signal to all inverters in a specified area. Many short-term research topics are involved in this measure, such as standards for communication systems and power electronics controls.

5. **Storage.** For grid-connected PV systems the use of batteries to store energy may not be economic. Nevertheless, because with the right incentives, it can be in both the system owner's and grid operator's interests for the system owner to consume the PV electricity (s)he needs before exporting it to the grid, and because the costs of batteries are coming down, storage will play an important role for PV deployment in Europe. Some pilot tests are being carried out but more in-depth research is required to identify the best interface between state-of-art batteries and PV systems.

6. **Smart appliances.** There are benefits to consumers if they are able, in real time, to switch on and off electrical devices according to their production of PV electricity. Functionality to link smart inverters to electricity-consuming devices in homes or commercial premises must be developed.

7. **PV production forecasting.** An important research topic, both for grid operators and consumers, is the ability to predict the output of PV plants. Output forecasting will have a strong impact on the near-term development of smart grids. The R&D priorities in this field span many issues including cloud cover prediction, the analysis of the optical properties of clouds, solar radiation prediction models and statistical methods for predicting the behaviour of PV plants (including artificial intelligence techniques). The ability to predict the optical transparency of the atmosphere could be of great importance to the development of methods for separating the diffuse and direct components of solar radiation for PV production forecasting. Further R&D efforts must be directed towards the use of satellites for characterising atmospheric conditions (clouds, aerosols, water content, pollution etc.). This is done already for weather forecasting models, but very different spatial and temporal resolutions are needed for PV plant output forecasting.

4.6.5. PV integrated in the built environment

The EU "20-20-20" climate and energy goals require European Member States to reduce CO_2 emissions (by 20%) to deploy renewable energy to meet 20% of demand by 2020 and to increase energy efficiency by 20%. Moreover, the European Energy Performance of Building Directive [EPBD 2010] requires all new buildings to be "nearly zero-energy buildings" by 2020.

For the next decade, special attention must be paid to material improvements and whole-system approaches for buildings. BIPV is one of the best techniques for achieving these goals. By incorporation of PV modules into structural building products, cost compensation can be achieved for other functions performed (such as thermal insulation, noise protection, solar control, etc.) since conventional building materials for the realisation of these functions can be omitted. The extent to which cost compensation occurs depends on the functions served and the electricity output of the system (note that BIPV arrays are liable to have higher operating temperatures than ground-mounted modules, reducing their efficiency). Likewise, multifunctionality can enable lifecycle CO_2 emissions to be reduced compared to components fulfilling each of the functions separately. New BIPV design approaches and a wider choice of BIPV products will stimulate new architectural designs. Collaboration between building designers and constructors and PV technology developers is required.

European companies and workers are well-placed to capture a significant share of the value of BIPV installations since:

- The system integration and installation works (such as the interconnection between different components and buildings) represent a significant part of the cost of a BIPV system and cannot be delocalised

- Europe has a wealth of experience in the BIPV sector
- There is a strong "local fit" component in BIPV (e.g., adapting design to local architecture)

The following **research topics** should be addressed.

- Standards & Regulation
  - BIPV standards and individual building regulations
  - Testing of BIPV for compliance with building codes
  - Effects of BIPV on relevant building functions
  - BIPV on non-glass materials
  - Improvement of the multifunctional aspects of BIPV elements
- Effects of BIPV on relevant building functions.
  - Methodology for calculating CO_2-footprint of BIPV
  - Contribution of BIPV to energy efficiency requirements
- BIPV performance
  - Energy yields (monthly, yearly, etc.)
  - Issues relating to ease of installation
- BIPV economics
  - Added value of BIPV as a multifunctional building component
  - Comparisons of total cost of ownership with conventional building products
- The "Smart building"
  - Combination of BIPV with ICT to promote own-consumption
  - Combination with building services

1. See-through thin-film silicon PV modules used as skylights in the Suzuka City Hall (Mie Prefecture, Japan)
©SHARP CORPORATION 2009

2. Installers setting up a roof-top residential PV system in Germany
© SHARP ELECTRONICS (EUROPE) GMBH 2010


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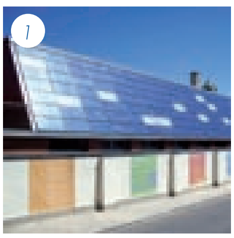
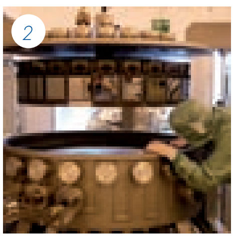
Table 16. Research priorities for **Balance of System at the component level** – time horizons for first expected application of research results in (pilot) manufacturing and products.

	2011 – 2016	2016 – 2025	2025 – 2035 and beyond
Industry manufacturing aspects	■ Increased inverter reliability and lifetime to achieve >20 years of full operation ■ Low-cost electronic components including new design strategies and new materials ■ Microinverters and DC / DC solar optimisers for both retrofit use and embedded in PV modules. Assessment of lifetime of these components ■ New storage technologies in pilot units for large field trials and assessment of lifetime and cost ■ General purpose tracking platforms for high efficiency module options of all kinds ■ Low-cost support structures, cabling and electrical connections for domestic and large ground based PV systems	■ Increased inverter reliability and lifetime to achieve >30 years of full operation	Too soon to be determined
Applied / advanced technology and installation (incl. O&M) aspects	■ Adaptation of battery management systems for new generations of batteries ■ Highly reliable, low-maintenance components for stand-alone systems ■ Component development for minimisation of system losses (e.g. modules with tolerance to partial shading, modules for operation at a system voltage >1000V) ■ Low-cost control and monitoring of system output, including using appropriate measurement protocols	■ Innovative storage technologies for small storage capacities (1-10 kWh) ■ Advanced modules for BIPV applications – multi-functional, self-cleaning, construction elements, new design solutions ■ Strategies for centralised system monitoring (e.g. web based) ■ Interaction of PV with other decentralised generation	■ Modules with integrated storage, providing extended service lifetimes (40 years)
Basic research / fundamentals	■ PV inverters optimised for different PV module technologies	■ Power electronics and control strategies for improving the quality of grid electricity at high PV penetrations	■ Technologies for high capacity storage (>1MWh) ■ Alternative storage technologies





1. 29 kW PV façade on workshop studio (Hellerau, Germany) ©SOLARWATT

2. CIGS evaporation pilot system at the Angström Solar Center (CIGS) lab (Uppsala, Sweden) ©LUKAS PLESSING

Table 17. Research priorities for **Balance of System at the system level and or interactions between PV system and the grid** – time horizons for first expected application of research results in products and applications. This table only contains research priorities that deliver results that can be applied before 2025. It is too soon to determine research priorities that will be applied in longer time horizons.

	2011 – 2016	2016 – 2025
Industry manufacturing aspects	■ Standardisation of system components to facilitate economies of scale in manufacture and simplify replacement ■ Prefabricated ready-to-install units, particularly for large grid-connected systems	Too soon to be determined
Applied / advanced technology and installation (incl. O&M) aspects	■ Assessment of value of PV electricity, including for meeting peak demand, and as an uninterruptible power supply when combined with a storage device ■ Tools for early fault detection ■ Assessment of long term average local radiation potentials and forecasts of solar insolation ■ New protection criteria for inverters due to the high density of PV systems in the European grids (voltage and frequency controls, voltage dips immunity, output power control, etc.) ■ Short term PV production forecasts both on single plant side and on portions of the electric grid based on satellite meteorological data	■ Management of island microgrids with high share of PV generators ■ Development of efficient incentive management for PV systems ■ Billing and metering schemes for PV in off-grid PV systems ■ Bringing the lifetimes of different components into line with each other above 25 years ■ Updating fault-detection tools for advanced system designs ■ Active inverters able to control the insertion of electric loads according with PV production
Basic research / fundamentals	■ Development of technology for high voltage systems ■ (>1000 V)	■ New concepts for stability and control of electrical grids at high PV penetrations

4.6.6. Summary

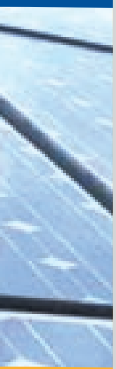
Research into PV components aims at reducing costs at the component and/or system level, increasing the overall performance of the system and capturing the full value of electricity produced by the system and/or by the system's use as a building component. The research priorities are:

- Increasing inverter lifetime and reliability
- New storage technologies for small and large applications and the management and control systems required for their efficient and reliable operation
- Harmonising components, including lifetimes, dimensions and options for modularity to decrease site-specific costs at installation and replacement costs during system life
- Assessing and optimising the added value of PV systems for different system configurations
- Innovative BIPV components that enhance multifunctionality
- Components and system designs for island PV and PV-hybrid systems

On the PV systems side, the expected high penetration of PV into the grid will require research with several approaches:

- Grid codes with appropriate requirements on distributed generation devices in terms of reactive and active power control, fault-ride-through capabilities, etc
- Consumption of electrical energy at the point of generation in order to reduce the grid loads
- Implementation of smart-metering concepts in order for system operators and end-consumers to visualise local energy generation and consumption
- In order to increase the utilisation of PV, the potential storage capability of electric vehicles should be taken into account

In particular, research on ICT-based systems for the above mentioned approaches should be addressed.



4.7. Standards, quality assurance, safety and environmental aspects

4.7.1. Introduction

Defined standards are as important for PV as for any other industry, because they impose non-negotiable specifications on the technology, for instance on its manufacture or its installation. Approved quality assurance (QA) procedures enable reliable comparisons to be made between products. Standards and QA procedures together foster investor confidence by giving investors a sound basis for judging the viability of their investment.

To minimise the cost of PV electricity, it is essential for the systems to work well for long periods. This implies that the quality of the system needs to be assured and that it needs to be adequately maintained according to defined standards, guidelines and procedures. Continuing quality assurance development is needed as new PV technologies and system configurations are brought to market.

System design and installation should include appropriate safety measures, including minimisation of electrical hazards in normal operation and under extreme conditions (e.g. protection of firefighters from electrical shock). This should be addressed both in terms of safety standards for components and best practice guidelines.

Any negative environmental impact associated with the production, operation and dismantling of PV systems must also be minimised. This implies that the energy payback time of systems needs to be short, that the use of hazardous materials needs to be avoided and that systems and system components need to be designed in a way that encourages recycling.

4.7.2. Standardisation, harmonisation, testing and assessment

Government legislation and rules imposed by utilities oblige PV systems to meet building standards, fire safety standards and electrical safety standards. There remain some cases where the development of the PV market is hindered by differences in local standards (inverter requirements / settings, grid connection regulations, building standards). Inconsistencies in standards that affect PV should be addressed along with any gaps in standards that inhibit the growth of the sector.

Sometimes guidelines are more appropriate than standards. Guidelines are required for the quality of manufacturing materials, wafers, cells, modules, components for concentrator systems and BoS components and also for system design, system installation and system testing. These should be updated and developed to reflect changes in system configuration and application.

4.7.3. Quality assurance

In-line production control is a good way to characterise PV components and make the implementation of QA procedures easier. Production control should be embedded in the development of production equipment. Component certification schemes should be updated as necessary to reflect developments in technology and applications.

4.7.4. Environmental aspects

EU research on strategies for PV module disposal when modules reach the end of their lives has mainly focused on the recycling of crystalline silicon modules and some thin-film technologies. The recycling of concentrator modules and BoS components, as well as of new photovoltaic materials as they approach commercial applications, requires further attention. Recycling infrastructure should take account of the needs of end-users and of the PV industry. Research is needed into the best ways to make low cost, easy-to-access recycling infrastructure available to all.

Lifecycle Analyses (LCAs) have become an important tool for evaluating the environmental profile of energy technologies, particularly CO_2 emission per kWh and energy payback time. The results of LCAs can be used in the design of new processes and equipment for cell and module production lines. LCA will be needed as long as new module technologies and system configurations are developed.

4.7.5. Summary

- Further develop performance, energy rating and safety standards for PV modules, PV building elements and PV inverters and AC modules
- Harmonise conditions for grid-connection across Europe, including in relation to smart grids
- Develop quality assurance guidelines for the whole manufacturing chain
- Develop recycling processes for thin-film modules and BoS components.
- Conduct LCAs on thin-film and concentrator PV modules and BoS components, and in the longer term, on novel cell / module technologies

Douneika PV 2 MW project, Greece, in which 'balance-of-system' costs were minimised by designing the plant so it followed the contours of the hillside. This approach helps the system to blend in to the surrounding landscape.
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Table 18. Research priorities for **standards, quality assurance, safety and environmental aspects** – time horizons for first expected application of research results. This table and table 19 contain only research priorities that deliver results that can be applied before 2025. It is too soon to determine research priorities that will be applied in longer time horizons.

	2011 – 2016	2016 – 2025
Industry manufacturing aspects	■ Performance, energy rating, qualification and safety standards for new developments in – PV modules – PV building elements – concentrator systems incl. trackers – PV inverters / AC modules – system operation under normal and extreme conditions ■ In-line process and production control techniques and procedures ■ Guidelines for specifications and quality assurance of new developments in – materials, wafers and cells – modules (including sizes and mounting techniques) – components for concentrator systems – BoS components ■ Materials availability for very large-scale deployment, safety and closed loop recycling ■ Harmonisation of conditions for grid-connection	■ Guidelines for new designs of production equipment ■ Develop further in-line process and production control techniques and procedures as necessary ■ Improved certification schemes for systems ■ Harmonise standards and guidelines applied to components
Applied / advanced technology and installation (incl. O&M) aspects	■ Guidelines for new system configurations in – design, installation and system test – monitoring / evaluation ■ Recycling processes for new module designs ■ Lifecycle analyses for all new module and component designs ■ Lifecycle analysis at system level	■ Recycling processes (new components) ■ Lifecycle analyses on novel cell / module technologies

4.8. Socio-economic aspects and enabling research

4.8.1. Introduction

Scientific and technological excellence play a critical role in innovation, but successful exploitation of innovation also depends on other factors, including:

- Aligning the priorities for technological development with important market needs, including those relating to consumer acceptance of specific products
- Increasing access to funding and capital, both public and private
- Ensuring availability of trained personnel for the different parts of the value chain from basic research to sales and marketing
- Increasing public and political awareness and providing information to the public
- Responding quickly to societal concerns and preferences for technology development
- Maintaining an appropriate and effective regulatory balance throughout the process

This section makes recommendations for socio-economic and other enabling research that addresses the non-technical influences on the development and uptake of PV across Europe and in the markets addressed by European companies. Some of the recommendations are specific to PV, whilst others relate to the more general concept of decentralised energy generation and may be more logically carried out within a project looking at a range of energy supply solutions, e.g. the development of smart grids.

4.8.2. Socio-economic aspects of large-scale PV use

The successful introduction of a technology such as PV is dependent on an effective public dialogue encompassing the total costs, risks and benefits. Despite rapid growth in the last decade, the absolute production volumes of PV are still small compared with the installed conventional generation capacity and the benefits of economies of scale may not yet be clearly visible to the general public. Media attention is too often focused on the high upfront investment costs of PV systems rather than on the advantages it brings to society in the long term. Popular misperceptions of PV cost, energy production and environmental performance are long-lived and correcting these misperceptions is difficult. In the near future, PV is expected to reach generation costs comparable with conventional electricity supply in several countries in southern Europe heralding a transition period for PV in which it is important that accurate information is conveyed to potential users and society more generally.

Ways of exploiting the added value of the PV electricity have already been discussed (Section 4.6), along with the merits of using PV in smart grids. Both require optimisation of supply patterns, which in turn requires market research. The increased distribution of energy technologies brings more participants to the energy market and empowers individual consumers. Socio-economic research in this area should consider the optimum procedures for introducing PV up to target levels for a wide range of users. This should include research into interfaces that allow end-users to interrogate the PV system.

Research into the macro- and micro-economic effects of implementing a new source of electricity production, such as on employment and regional development are still required. Consideration should be given to the affordability of PV systems for lower income households, even as system price is reduced.

4.8.3. Enabling research

Public awareness of photovoltaic technology has increased significantly in recent years and the technology overall enjoys popular support. However, it is important to ensure that this situation persists as ever more PV systems are installed. This requires studies on market acceptability (i.e. on making sure the product fits the requirements of the market place), perhaps by the appropriate use of focus groups and publicity campaigns.

The growing PV industry and the evolving electricity supply industry create a demand for appropriately trained personnel at all levels, from cell development to system installation and sales and marketing. The skills base required over the next two decades should be defined. Alongside the technical challenges outlined in the SRA, ensuring a sufficient supply of well-trained personnel for the fast-growing PV industry is a serious challenge. In addition to academic education in universities and research institutes, more centres offering practical training have to be established. A major benefit of the research outlined here will be the training of skilled personnel for the industry, and so it is important that the research should include training provision at master's or doctoral level wherever possible. It is also important to ensure the training provided is well aligned with industry needs, including all aspects of system development.

Since PV implementation is related to a number of other sectors, including electricity supply, construction, nanotechnology and flat panel displays, information transfer to and from these sectors is also very important and should be promoted.

Table 19. Research priorities for **socio-economic and enabling research** – time horizons for first expected application of research results.

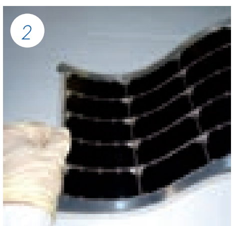
	2011 – 2016	2016 – 2025
Market and industrial aspects	■ Market development research, including in the efficiency of financial schemes for promoting PV in different markets ■ Regulatory aspects of market development – insurance, contracts, planning issues ■ Understanding of industry training needs for short and medium term ■ Optimisation of technology transfer to construction and electricity supply sectors ■ Economic and logistical aspects of PV module and component reuse and recycling	■ Reassessment of training needs for medium and long term
User aspects	■ Identification and quantification of non-technical costs and benefits of PV technology ■ User interaction with PV systems – optimisation of the user interface ■ Public awareness and information dissemination relating to widespread deployment of PV technology	■ Continuing public awareness and information dissemination relating to widespread deployment of PV technology

4.8.4. Summary

It is important to address proactively any societal concerns and other barriers that might set back the progress of PV.

The main priorities are to:

- Identify and quantify the non-technical (i.e. societal, economic and environmental) costs and benefits of PV
- Address regulatory requirements and barriers to the use of PV on a large scale
- Build up the skills base that will be required by the PV and associated industries in the short- and medium-term and develop a plan for its provision
- Address the administrative and public relations aspects of a cost-effective and workable infrastructure for reusing and recycling of PV components
- Develop campaigns for improved awareness in the general public and targeted commercial sectors



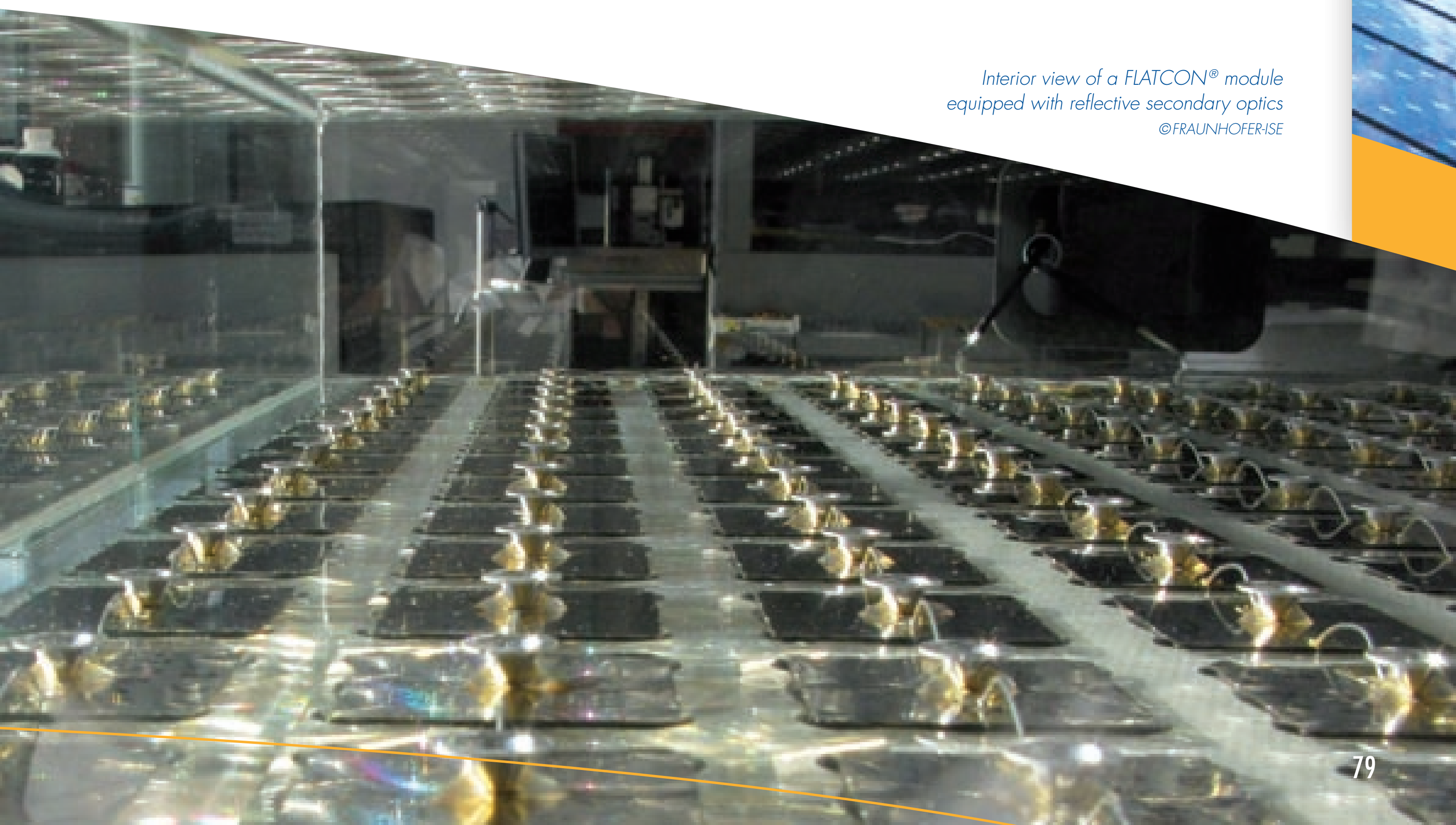
1. Long-term module testing of a sun-tracking module at ENEL's labs in Catania, Italy ©ENEL

2. Ultra-light, flexible mini-module made of high-efficiency, multijunction III-V compound solar cells ©SHARP CORPORATION 2009

5 Concluding remarks

This second edition of the Strategic Research Agenda of the European Photovoltaic Technology Platform has updated the cost and performance targets of this rapidly growing technology. This reflects the progress in the PV market in recent years and the increased ambition for the contribution of PV to Europe's electrical energy supply in the period to 2020. In particular, the cost and energy payback targets up to 2020 have been harmonised with those of the Solar Europe Industry Initiative and are reflected in the short-term research priorities.

The SRA identifies a wide range of research topics to be undertaken to realise the full potential of PV technologies, but it is gratifying to see that much progress has already been made since the first edition was published. Further editions of the SRA will be developed as necessary to reflect the technological progress of PV and its contribution to European electrical energy supply.



Interior view of a FLATCON® module equipped with reflective secondary optics
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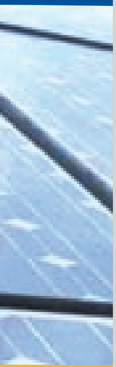

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