A STRATEGIC RESEARCH AGENDA FOR PHOTOVOLTAIC SOLAR ENERGY TECHNOLOGY

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ABSTRACT: The EU PV Technology Platform [1] aims at joining forces on a European level to contribute to the further development of photovoltaic solar energy into a competitive technology that can be applied on a large scale and to the strengthening of the position of the European PV industry on the global market. The Platform mobilises a wide range of stakeholders from all European countries and mainly operates through its four Working Groups, addressing distinctly different fields of activity: 1. Policy and Instruments, 2. Market Deployment, 3. Science, Technology & Applications, and 4. Developing Countries. A key result of the Platform activities over the first two years of its existence is the Strategic Research Agenda (SRA), which was prepared by the Working Group on Science, Technology & Applications and published in June 2007. The SRA defines broadly supported overall development targets for PV technology and outlines research fields and topics to be addressed to reach these targets. In this context cost reduction of PV electricity generation is a crucial, although not the only, issue. This paper provides a brief summary of the SRA. The full document can be downloaded from the Platform website.

Keywords: Strategy, Cost Reduction, R&D and Demonstration Programmes.

1 INTRODUCTION

Although reliable PV systems are commercially available and widely deployed, further development of PV technology is crucial to enable PV to become a major source of electricity. The current price of PV systems is low enough for PV electricity to compete with the price of peak power in grid-connected application and with alternatives like diesel generators in stand-alone applications, but cannot yet rival consumer or wholesale electricity prices. A drastic further reduction of turn-key system prices is therefore needed and fortunately possible. This was emphasised in the document A Vision for Photovoltaic Technology, published by the Photovoltaic Technology Research Advisory Council (PV TRAC) in 2005, see [1]. Further development is also required to enable the European PV industry to maintain and strengthen its position on the global market, which is highly competitive and characterised by rapid innovation. Research, or rather, research and development, is crucial for the advancement of PV. Performing *joint research* addressing *well-chosen issues* can play an important role to achieve the critical mass and effectiveness required to meet the sector's ambitions for technology implementation and industry competitiveness. This led the PV Technology Platform to produce a Strategic Research Agenda (SRA), summarized in this paper, to realise the "Vision" referred to above. The SRA may be used as input for defining the EU's Seventh Framework Programme for Research (the main source of funding for collaborative research between European countries), but also to facilitate a further coordination of research programmes in and between Member States.

2 DRIVERS AND ENABLERS FOR PV DEVELOPMENT

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

The evolution of turn-key PV system prices outlined in A Vision for Photovoltaic Technology [1] provides an excellent starting point to define underlying cost targets to be addressed in this SRA. It is noted that research and technology transfer to industry directly influences manufacturing and installation costs (as well as some other parameters), but not directly turn-key prices. The latter are also determined by market forces. Cost reduction targets are nevertheless essential to enable price reduction.

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

2008 ~ 2013:	short term
2013 ~ 2020:	medium term
2020 ~ 2030 and beyond:	long term

The year 2013 has been chosen because it coincides with the end of the European Commission's current programme for funding research, FP7. The start of 'short term' does not coincide with the start of FP7 (2007) because no significant results are expected from FP7 in its first year. The convention used in the SRA is to refer research priorities to the time horizons in which they are first expected to be used in commercial products or applications, not to the year by which widespread use is expected.

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

Generally, cost and performance of PV technology are the foci of research efforts, but the importance of other drivers should be emphasised.

First of all R&D also needs to address the value of PV electricity. For example, if the PV supply pattern could be fully matched with the electricity demand rather than following the availability of sunlight, its value at these times would be higher. This may imply a need for low-cost, small storage systems. Note that PV supply and electricity demand also match to a certain extent with storage, especially in the case of peak demand due to air conditioning and cooling.

Secondly, the lifetime of system components must be considered. Long technical lifetimes not only help to reach cost targets, they 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 pay-back time of systems will add to the advantages of PV as an energy source and, in the longer term, its ability to avoid carbon dioxide emissions. Avoiding the use of scarce or hazardous materials, or if that is not possible, closing material-use cycles, is an important topic with great R&D challenges.

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

In addition to the technical issues described above, the SRA 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

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

Environmental quality

- Energy pay-back time:
  - modules
  - BOS
- Substitution of hazardous materials
- Options for recycling

Applicability

- Method and ease of mounting, cabling, etc. (also for maintenance and repair)
- Flexibility / modularity
- Aesthetics
- Lifetime

Socio-economic aspects

- Public and political awareness
- User acceptance
- Training and education
- Financing

3 PV DEVELOPMENT TARGETS

The preparation of the SRA started by discussing and defining overall development targets for PV technology. This process involved a broad consultation of stakeholders and "bottom-up" (e.g. cost build-up of PV module manufacturing) as well as "top-down" (e.g. learning curve) analyses of what can be achieved under the condition of high ambition combined with scientific and technological realism. As mentioned in the previous section, a clear distinction has always been made between *cost* and *price*, the former having a direct relation with manufacturing & installation and thus with R&D, the latter being a crucial parameter for application and market development. The consultation and analyses led to the definition of –broadly supported- targets for PV technology as summarized in Table I below. The underlying figures and breakdowns can be found in the SRA; a selection is also included in the next section. The quantitative targets have been compared with those contained in related Japanese and US documents (see [2] and [3]) and were found to be roughly consistent where a direct comparison was possible.

Table I: Summary of key targets contained in the Strategic Research Agenda. Figures are rounded and indicative (see text below for further details).

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

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

Current turn-key system prices may vary from ~4 to ~8 €/Wp, depending on system type (roof-top retro-fit, building-integrated, ground-based, ...), size, country, and other factors. The figure of 5 €/Wp, however, is considered representative. Similarly, prices in 2015 may range between ~2 and ~4 €/Wp. All prices are expressed as constant 2007 values.

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

- an average performance ratio of 75%, i.e. a system yield of 750 kWh/kWp·yr at an insolation level of 1000 kWh/m^2·yr. In southern Europe, where insolation is typically 1700 kWh/m^2·yr, a performance ratio of 75% translates into 1275 kWh/kWp·yr;
- 1% of the system's price will be spent each year on operation & maintenance;
- the system's economic value depreciates to zero after 25 years;
- a 4% discount rate.

<u>The overall aim of short-term research is for the price of PV electricity to be comparable to the retail price of electricity for small consumers in southern Europe by 2015.</u> Specifically, this means reaching PV generation costs of 0.15 €/kWh, or a turn-key system price of 2.5 €/Wp (Table I). This system *price* arises from typical manufacturing and installation *costs* of <2.0 €/Wp. <u>Continued price reduction after 2015 implies that this situation will apply to most of Europe by 2020.</u> This state, where prices are comparable, is known as 'grid parity'. Larger systems and ground-based PV power plants that are not connected directly to end-consumers will generally need to produce electricity at lower prices before they can be said to have reached 'grid parity'. On the other hand, they may also involve a somewhat lower specific investment (expressed in €/Wp).

4 GOVERNING PRINCIPLES OF THE SRA

The EU PV Technology Platform has discussed and adopted a few "governing principles", which underlie the SRA development process. They are described hereafter.

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

<u>No exclusivity.</u>
PV comes and will come in different formats. The SRA does not exclude technologies but sets overall targets that each PV format must reach and describes the research priorities for each format in order for it to succeed in meeting the targets.

<u>There is a need for public money to fund short-, medium- and long-term research into all parts of the value chain(s), as well as research into socio-economic issues.</u>
Since drastic cost reductions are needed for all elements of the PV system, research should address all parts of the value chain, from raw materials up to the complete system, and even beyond. In addition, public funding agencies should make a strategic top-down decision on how to allocate funding between short-, medium- and long-term research. Industry will push for short-term research to be the main beneficiary of funding and as the PV industry grows, this pressure may become stronger. Governments must, however, look ahead to the medium and long term and set aside fixed budgets for research applicable to these time-frames. The SRA recommends that the combined research spending of the public and private sector should be distributed between

topics with commercial relevance in the short, medium and long term in the typical ratio 6:3:1 in the short term, moving to the ratio 10:5:1 as private sector funding increases. See the full-length document for background and details.

Based on a detailed analysis of cost reduction potentials, the working group decided that the same cost targets shall be used for all flat-plate PV module technologies considered, i.e. 0.8-1.0 €/Wp in 2013 (implemented in large-scale production in 2015), 0.60-0.75 €/Wp in 2020, and 0.3-0.4 €/Wp in 2030. The targets are expressed as a range in order to reflect the efficiencies of different types of module. To meet the overall, cross-technology cost target, lower efficiency modules need to be cheaper than higher efficiency modules, due to the area-related component of the BoS costs. These targets should not be interpreted as predictions. It is possible that some technologies will even exceed them. The efficiency targets as detailed in the SRA for each technology are to be considered as performance targets that should be met in order to meet the cost target. System costs and prices, it should be noted, are dependent on the specific application that the system is put to. Therefore the costs and prices mentioned in the SRA are only approximate.

The Balance-of-System (BoS) costs are strongly dependent on, among other factors, the type of system (e.g. roof-top, building-integrated, ground-based), the efficiency of the modules used, and the country where it is sited. This makes it difficult to formulate general targets. Indicative targets for the BoS costs for roof-top systems are: 0.9-1.1 €/Wp in 2013, 0.75-0.9 €/Wp in 2020, and <0.5 €/Wp in 2030. The ranges in system cost targets mainly correspond to the range in module efficiencies mentioned in the previous bullet, reflecting the fact that part of the BoS cost is system area-related and thus affected by module efficiency (a given system power requires a smaller area when using higher efficiency modules).

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

For concentrator systems target costs it is not meaningful to distinguish between modules and BoS. Therefore indicative targets for the turn-key cost (not price) of full systems have been identified: 1.2-1.9 €/Wp in 2013, 0.8-1.2 €/Wp in 2020 and 0.5-0.8 €/Wp in 2030. Considerable uncertainty exists for these numbers because, with little industrial production at present, extrapolation from what does exist carries high uncertainty. Furthermore, no clear definition so far exists of the watt peak (Wp) power rating of concentrator technology, because, unlike other technologies, they function only under direct sunlight. Some attempts to define a Wp rating have, however, been made and are the basis for the cost targets above.

5 SCOPE OF THE SRA

To reach the targets outlined in the previous sections, the SRA details the R&D issues related to:

- PV cells and modules:
  - materials;
  - conversion principles and devices;
  - processing and assembly (incl. equipment);
- Balance of System:
  - system components and installation materials;
  - installation;
  - operation and maintenance;
- 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 evinced by the investments being made worldwide in production capacity based around many different technologies, and in the numerous concepts developed in laboratories that have large commercial potential. Therefore it is important to support the development of a broad portfolio of options and technologies rather than a limited set. The development of PV is best served by testing the different options and selecting on the basis of the following criteria:

- the extent to which the proposed research is expected to contribute to reaching the overall targets set;
- the quality of the research proposal and the strength of consortium or research group(s) involved.

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

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

The main R&D topics per technology area that need to be addressed to realise the Vision are summarised in the following section. The detailed descriptions can be found in the SRA [1].

6 R&D TOPICS TO BE ADDRESSED

The SRA contains a range of tables outlining short- medium- and long-term research priorities for the categories ”Industry manufacturing aspects”, “Applied/advanced technology aspects”, and “Basic research and fundamentals”. In this paper, this distinction is not made and only a brief summary of priorities per research area is given.

6.1 Cells and Modules

6.1.1 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 (€/Wp), but also on the energy yield (kWh/Wp) over the economic or technical lifetime.
- High productivity manufacturing, including in-process monitoring & control.
- Throughput and yield are important parameters in low-cost manufacturing and essential to achieve the cost targets.
- Environmental sustainability.
- The energy and materials requirements in manufacturing as well as the possibilities for recycling are important for the overall environmental quality of the product.
- Applicability.
- Achieving a degree of standardisation and harmonisation in the physical and electrical characteristics of PV modules are important to bring down the costs of installing PV. Ease of installation as well as the aesthetic quality of modules (and systems) are important if they are to be used on a large scale in the built environment.

6.1.2 Wafer-Based Crystalline Silicon Technology

- Reduced specific consumption (g/Wp) of silicon and materials in the final module.
- New and improved silicon feedstock and wafer (or wafer equivalent) manufacturing technologies, with careful consideration of cost and quality aspects.
- Devices (cells and modules) with increased efficiency.
- New and improved materials for all parts of the value chain, including encapsulation.
- High throughput, high yield, integrated industrial processing.
- Safe, low-environmental-impact processing.
- Novel and integrated (cells/modules) device concepts for the longer term.

6.1.3 Existing Thin-film Technologies

6.1.3.1 Common Aspects
- Reliable, cost-effective production equipment for all technologies.
- Low cost packaging solutions both for rigid and flexible modules.
- Low cost transparent conductive oxides.
- Reliability of products. Advanced module testing, and improved module performance assessment.
- Handling scrap modules, including re-use of materials.
- Developing replacements for scarce substances such as indium.

6.1.3.1 Thin-Film Silicon (TFSi)
- Processes and equipment for low cost large area plasma deposition of micro/nanocrystalline silicon solar cells. The interplay between the effects of plasma, devices and upscaling should be fully mastered.
- Specific high-quality low cost transparent conductive oxides suitable for large, high performance modules (greater than 12% efficiency).
- Demonstration of higher efficiency TFSi devices (meaning greater than 15% at laboratory-scale), improved understanding of interface and material properties, of light trapping, and of the theoretical performance limits of TFSi based materials and devices.

6.1.3.2 Copper-Indium/Gallium-diSelenide/diSulphide (CIGSS)
- Improvement of throughput and yield in the whole production chain and standardisation of equipment.
- Modules with efficiencies greater than 15%, developed through a deeper understanding of device physics and the successful demonstration of devices with efficiencies greater than 20% at laboratory-scale.
- Alternative or modified material combinations, of process alternatives like roll-to-roll coating and of combined or non-vacuum deposition methods.
- Highly reliable and low cost packaging to reduce material costs.

6.1.3.3 Cadmium Telluride (CdTe)
- Alternative activation/annealing and back contacts for simpler, quicker and greater yield and throughput.
- New device concepts for thinner CdTe layers.
- Enhanced fundamental knowledge of materials and interfaces for advanced devices with high efficiencies (up to 20% at laboratory scale).

6.1.4 Emerging and Novel Technologies

6.1.4.1 Emerging Technologies
- Improvement of cell and module efficiencies and stability to the level needed for first commercial application.
- Encapsulation materials and processes specific to this family of cell technologies.
- Product concepts and first generation manufacturing technologies.

6.1.4.2 Novel Technologies
- Demonstration of new conversion principles and basic operation of new device concepts.
- Processing, characterisation and modelling of (especially) nanostructured materials and devices; understanding of the morphological and opto-electrical properties (including development of theoretical and experimental tools).
- Experimental demonstration of the (potential) effectiveness of add-on efficiency boosters (spectrum converters).

6.2 Concentrator Technologies

6.2.1 Materials and Components

- Optical systems - Find reliable, long-term, stable and low-cost solutions for flat and concave mirrors, lenses and Fresnel lenses and their combination with secondary concentrators.
- Module assembly - Materials and mounting techniques for the assembly of concentrator cells and optical elements into highly precise modules that are

stable over the long-term using low-cost fully automated methods.

- Tracking - Find constructions which are optimised with respect to size, load-capacity, stability, stiffness and material consumption.

6.2.2 Devices and Efficiency

- Develop materials and production technologies for concentrator solar cells with very high efficiencies, i.e. Si cells with efficiencies greater than 26 % and multi-junction III-V-compound cells with efficiencies greater than 35 % in industrial production and 45 % in the laboratory. Find the optimum concentration factor for each technology.

6.2.3 Manufacturing and Installation

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

6.3 Balance-of-System Components and PV Systems

It is important to understand better the effect of Balance-of-System (BoS) components on turn-key system costs and prices. BoS costs vary according to system type and – at least at present – the country where the system is installed, which impacts on whether the cost targets for BoS may be deemed to have been reached or not. The SRA recommends that a study of these aspects be undertaken to quantify in detail the cost reduction potential of PV technology beyond 2030 (see Table I). Key factors include:

- Increase 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.
- Harmonise the dimensions and lifetimes of components.
- Increase modularity in order to decrease site-specific costs at installation and replacement costs during system life.
- Assess and optimise the added value of PV systems for different system configurations.
- Produce workable concepts for maintaining the stability of electrical grids at high PV penetrations.
- Devise system components that enhance multifunctionality and/or minimise losses.
- Develop components and system concepts for island PV and PV-hybrid systems.

6.4 Standards, Quality Assurance, Safety and Environmental Aspects

- Identification of performance, energy rating and safety standards for PV modules, PV building elements and PV inverters and AC modules.
- Common rules for grid-connection across Europe.
- Quality assurance guidelines for the entire value chain.
- A cost-effective and workable infrastructure for the reuse and recycling of PV components, especially thin-film modules and BoS components.
- Analysis of lifetime costs especially of thin-film and concentrator PV and BoS components over the short term and for emerging cell/module technology over the longer term.

6.5 Socio-Economic Aspects and Enabling Research

- Identifying and quantifying the non-technical (i.e. societal, economic and environmental) costs and benefits of PV.
- Addressing regulatory requirements and barriers to the use of PV on a large scale.
- Establishing the skills base that will be required by PV and associated industries in the period to 2030 and developing a plan for its provision.
- Developing schemes for improved awareness in the general public and targeted commercial sectors.

7 SRA UTILIZATION AND IMPLEMENTATION

The SRA has been prepared to serve as a *reference document* when developing or fine-tuning EC and national R&D programmes. By interpreting the research priorities described in the SRA in their own national contexts (national R&D strengths, presence of industry, etc.), countries can align their publicly-(co)funded R&D with the SRA's recommendations, to the benefit of PV in Europe. The SRA implementation process will be carried out in close cooperation with Platform's Mirror Group.

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