European Commission

LOW CARBON ENERGY OBSERVATORY

PHOTOVOLTAICS
Technology development report

Joint Research Centre

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Contact information

Name: Nigel TAYLOR
Address: European Commission, Joint Research Centre, Ispra, Italy
Email: Nigel.TAYLOR@ec.europa.eu

Name: Maria GETSIOU
Address: European Commission DG Research and Innovation, Brussels, Belgium
Email: Maria.GETSIOU@ec.europa.eu

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FOREWORD ON THE LOW CARBON ENERGY OBSERVATORY

The LCEO is an internal European Commission Administrative Arrangement being executed by the Joint Research Centre for Directorate General Research and Innovation. It aims to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

Which technologies are covered?

- Wind energy
- Photovoltaics
- Solar thermal electricity
- Solar thermal heating and cooling
- Ocean energy
- Geothermal energy
- Hydropower
- Heat and power from biomass
- Carbon capture, utilisation and storage
- Sustainable advanced biofuels
- Battery storage
- Advanced alternative fuels

How is the analysis done?

JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patents filings. External experts may also be contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

What are the main outputs?

The project produces the following report series:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Future and Emerging Technology Reports (as well as the FET Database).

How to access the reports

Commission staff can access all the internal LCEO reports on the Connected LCEO page. Public reports are available from the Publications Office, the EU Science Hub and the SETIS website.

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- Data on patent statistics and R&I investments at EU, national and corporate level have been provided by the C.7 SETIS R&I team: Alessandro Fiorini, Francesco Pasimeni and Aliki Georgakaki.

ABBREVIATIONS AND DEFINITIONS

General

CAPEX	Capital expenses
EC	European Commission
EERA	European Energy Research Alliance
EIT	European Institute of Innovation and Technology
EPBT	Energy Pay Back Time
EPC	Engineering, Procurement and Construction
ETIP PV	European Technology innovation Platform for Photovoltaics
ETS	Emissions Trading Scheme
EU	European Union
EUPVSEC	European Photovoltaic Solar Energy Conference
FIOM	Fixed installation, operating and maintenance [costs]
FP4/5/6/7	Fourth/Fifth/Sixth/Seventh Framework Programme (EU R&D programmes)
H2020	2013-2020 EU R&D Framework Programme
KPI	Key Performance Indicator
LCA	Life-Cycle Analysis
LCoE	Levelised Cost of Electricity
NER	New entrant Reserve
NREAP	National Renewable Energy Action Plan
O&M	Operation and Maintenance
OPEX	Operational expenses (running costs)
R&D	Research and Development
R&I	Research and Innovation
SETIS	Strategic Energy Technologies Information System
SET-Plan	European Strategic Energy Technology Plan
SPE	Solar Power Europe

Technical and Theme-Related:

a-Si	Amorphous silicon
AZO	Aluminum-doped zinc oxide
CdTe	Cadmium telluride
CIGS	Copper Indium Gallium Diselenide
CPV	Concentration Photovoltaics
c-Si	Crystalline silicon
CVD	Chemical Vapour Deposition
CZTS/Se	Copper Zinc Tin Sulphide/Selenide (kesterites)
DSC	Dye-Sensitized Cell

ED	Electro-Deposition
HJT	Heterojunction Technology
ITO	Indium tin oxide (used as a TCO on cells)
ITRPV	International Technology Roadmap for Photovoltaics
LID	Light-Induced Degradation
LeTID	Light and elevated Temperature-Induced Degradation
Mo	Molybdenum
OPV	Organic solar cell
PERC	Passivated Emitter Rear Contact
PERT	Passivated Emitter Rear-Totally Diffused
PID	Potential-Induced Degradation
PK	Perovskite (solar cell)
PV	Photovoltaic(s)
PSC	Perovskite solar cell
R2R	Roll-to-roll (production process)
SPC	Solid Phase Crystallisation
SPS	Spark Plasma Sintering
TCO	Transparent Conductive Oxide
TF	Thin-film

1 INTRODUCTION

Over the past decade PV electricity has become a significant player in energy supply and a truly global industry. It is characterised by rapid innovation and increasing cost-competitiveness. As such it is uniquely positioned to help achieve the EU's energy transition [1], to support EU jobs and economic growth, and to contribute to meeting the commitments made in the COP-21 Paris Agreement of December 2015 [2].

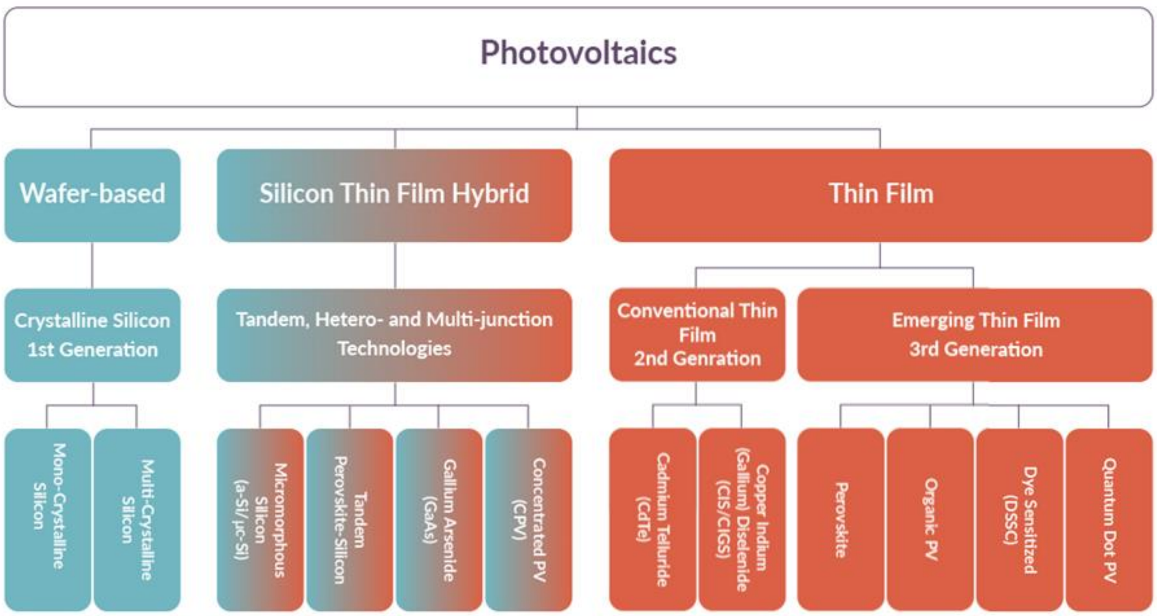
This LCEO Technology Development Report aims to provide unbiased assessments of the state of the art, development trends, targets and needs, technological barriers, as well as techno-economic projections until 2050. Particular attention is paid to how EC funded projects contributed to technology advancements. It follows the structure and methodology set out in LCEO Work Programme, as revised in 2017. A companion LCEO Technology Market Report is due in the second half of 2018. Both reports build on previous editions, released in 2016.

1.1 Main Characteristics of the Technology

Photovoltaics is a solar-power technology for generating electricity using semiconductor devices called solar cells. Connected together, a number of solar cells form a solar ‘module’ or ‘panel’, which can then be combined in a solar power system. These range in power from a few watts of electricity output to multi-megawatt power stations.

PV devices can be broadly classified as "commercial", i.e. in mass production, "emerging" i.e., small production volumes and "novel", i.e. concept or early laboratory stage. Commercial technologies include wafer-based crystalline silicon (c-Si) PV, as well as the thin-film technologies of copper indium/gallium disulfide/diselenide (CIGS) and cadmium telluride (CdTe) (see Figure 1). Thin-film silicon PV (amorphous and microcrystalline silicon) and high concentrating photovoltaics (multijunction technology using III-V semiconductors, e.g., GaAs and InGaP) have lost market shares due to their lack of efficiency improvements or problems with overall system cost reductions respectively. Some organic and dye-sensitized solar PV devices have been commercialised up to now, but for the most part this sub-technology remains in the novel and emerging categories. In terms of current market share, silicon wafer based photovoltaics are by far the dominant technology on the global market, with a 2018 share of about 95 %. This report focuses on the commercial and emerging technologies, while the novel approaches (technology readiness level < 4) are addressed in the LCEO future and emerging technologies reports.

Figure 1 Overview of photovoltaic technologies (source: http://pvthin.org/).



1.2 Current Market Status

At the end of 2018 global installed capacity stood at 518 GW, after an annual growth of over 100 GW. This reflected booming demand in Chinese, India and the Americas [3]. Although PV provided just a 2.5 % share of total electricity generation, its importance for our future energy mix is now acknowledged. .

An annual market at the hundred GW level makes reaching the IEA's [4] Sustainable Development Scenario of 3 246 GW by 2040 look very feasible. Taking a more ambitious view (arguably needed to meet the 2015 Paris Climate Agreement goals), the new IRENA roadmap for 2050 [5] foresees 7 122 GW of solar PV. Both scenarios assume that the cost of PV electricity will continue to decrease. For this to happen, R&D is needed on a broad spectrum of issues relating to the energy conversion technology itself, production processes and a range of other factors including operation, integration and sustainability.

The EU reached a cumulative capacity of 117 GW at the end of 2018. This represented a welcome rebound after several years stagnation - new installations in 2017 amounted to just 5.2 GW[1] [3, 6]. There is guarded optimism that the annual market can continue to grow Indeed to reach the EU's proposed 2030 target of 32 % renewables, installed PV should reach 300- 320 GW implying an annual market of at least 15 GW.

There two main PV market segments:

a) Ground-mounted PV power plants (utility-scale or industrial) that feed their entire electricity generation into the grid. The plant itself is either owned or contracted by a utility company or large consumer. The electricity price is mainly determined either by direct power purchase agreements (PPAs) between the PV plant owner and the electricity off-taker, or by public auctions or tenders.

b) Rooftop PV systems (commercial or residential), in which part or all of the electricity produced is used directly on site, and part is feed into the grid.

In the EU utility-scale ground mounted plants accounted for one third of the market and rooftop for two thirds of the total installed solar PV power, according to the European industry association Solar Power Europe. The business models are distinct for both cases. Nonetheless, storage (on-site or as a virtual service) is expected play an increasing role in the development of both segments.

1.3 Methodology and data sources

The methodology for the technology development reports is based on three main pillars:

- JRC peer review and expert judgement;
- Monitoring, data compilation; definition and use of indicators;
- Modelling relevant to long-term deployment trends, using the JRC-EU-TIMES model.

The data sources are divided as follows:

i) R&D projects: the analysis includes:

  - most relevant EU-funded projects in H2020;
  - recently completed FP7 projects;
  - SOLAER-ERA-NET projects;
  - EIT InnoEnergy projects;
  - COST programme;
  - NER-300;
  - InnovFin Energy Demo Projects;
  - Member States' activities based on information from the respective SET Plan Temporary Working Groups (with the proviso that reports that are public and in English);

[1] Note that IEA PVPS reports a value of 6.5 GW for "Europe" in 2017, while SolarPowerEurope claims over 7 GW (including Turkey). The overall message remains that substantial market growth is needed to deliver on EU 2030 targets.

- major international projects, in particular from IEA PVPS;
- national projects and programmes from major non-EU countries.

ii) Patents statistics, for patents filed on technologies/sub-technologies

iii) Scientific publishing statistics, as analysed with the JRC's TIM (tools for information monitoring) software, which makes use of text mining and computational linguistic techniques to treat and enrich individual data items with useful information.

iv) Existing scientific overviews and compilations, for instance: proceedings of the European Photovoltaic Solar Energy Conference (EU PVSEC); publications of the European Technology and Innovation Platform for Photovoltaics, the Fraunhofer ISE Photovoltaics Reports 2018 [7] and the SEMI 2017 International Technology Roadmap for Photovoltaics [8].

Concerning technology performance and cost targets, the 2015 SET-Plan Declaration of Intent on Strategic Targets in the context of Global Leadership on Photovoltaics [9] provides the main benchmark; Table 1 below summarises the relevant parameters and values. Since several of these are indicated as percentage increases, for the purpose of the present document Table 2 shows indicative absolute values.

Concerning the indicators, the main focus is on the technology readiness level parameter, using the technology-specific guidance developed in the 2017 study contract for DG-RTD [10].

Table 1: Technical Goals in the SET-Plan PV Implementation Plan, October 2017.

Aspect	Targets
PV module efficiency	2020: increase by at least 20 % compared to 2015 levels
	2030: increase by at least 35 % compared to 2015
Reduction of turn-key system costs	2020: reduce by at least 20 % compared to 2015[2]
	2030: reduce by at least 50 % compared to 2015
Enhancement of lifetime	2020: increase module lifetime (at 80 % of initial power) to 30 years
	2025: increase module lifetime (at 80 % of initial power) to 35 years
Life cycle impact	Minimise; no criteria specified up to now
Recyclability	Increase; no criteria specified up to now
Building integrated products for roofs or facades	2020: reduce additional BIPV cost/m^2 by 50 % compared to 2015 levels[3]
	2030: reduce additional BIPV cost/m^2 by 75 % compared to 2015 levels
Manufacturing and installation	Production capabilities of at least 20 m^2 per minute by 2020[4]
	Concepts for highly automated installation

[2] In February 2016 world-wide prices for residential systems ranged from EUR 1.25/Wp to EUR 2.40/Wp for systems with installation, but without permitting or connection costs. For commercial systems the range was EUR 0.92/Wp to EUR 1.80/Wp.

[3] For BIPV the end-2015 reference values are EUR 80-120/m^2 for roof integrated modules, EUR 130-200/m^2 for roof tiles & membranes, EUR 150-350/m^2 for semi-transparent façade integration and EUR 130-250/m^2 for opaque roof integration. These are additional to PV module costs).

[4] This production volume implies a factory with a nominal production capacity of up to 2 GW per year.

Table 2 Module efficiency values calculated from the percentage increases stated in the 2017 SET-Plan PV Implementation Plan.

PV technology		**Ref. year 2015*)**	**2020**	**2030**	*Current cell records June 2018*
	Target increase	-	+20 %	+35 %	
Wafer-silicon	mc-Si	16.2	19.4	21.9	*21.25*
	mono-Si	17.0	20.4	23.0	-
	HJT	19.0	22.8	25.7	*25.6*
Thin-film	CI(G)S	13.8	16.6	18.6	*22.0*
	CdTe	14.6	17.5	19.7	*22.0*

*) 2015 reference data for commercial modules as reported in the Fraunhofer ISE Photovoltaics Report, November 2015.

2 STATE OF THE ART

2.1 PV Technologies

2.1.1 Wafer-based crystalline silicon

Wafer-based crystalline silicon is the mainstream PV technology. The production process starts with silica sand (SiO_2), which is smelted to produce metallurgical silicon. This is then refined and cast in the form of long ingots with either mono- or multi-crystalline microstructure. These are then sliced into wafers, which are processed into solar cells (doping, antireflective layers, electrical contacts) and finally interconnected in weatherproof packages designed to last for at least 25 years.

Silicon PV is a complex field in its own right, and Figure 2 gives an overview of the technologies variants available. These are distinguished broadly by the type of silicon processing and doping (p- or n-type), whether cast in multi-crystalline or monocrystalline form, and the type of contacting used to extract current (**Table 3**).

Figure 3 shows the current and projected market shares of the main commercial technologies, as reported by the ITRPV in 2017 [8]. The cell (and therefore module) efficiency plays an increasing role in determining the balance of systems costs, which for large-scale systems (> 100 kW) are estimated at 55 % of the total.

Currently just over 70 % of the market is taken by "p-type" silicon devices in either multi-crystalline or mono-crystalline. P-type multi-crystalline cells with aluminium diffused back-surface field (Al-BSF) have traditionally been the market mainstay and have led the dramatic cost reduction seen over the last 10 years together with the emergence of GW scale production. Many analysts presumed that energy conversion efficiency would limit growth of this area, but this has not been the case up to now. Trina Solar hold the record efficiency of 19.9 % for a polycrystalline module [11], while Jinko Solar recently announced that they'd reached 22.0 % efficiency for a full-size cell (156 x 156 mm^2).

Recently PERC (passivated rear emitter and rear cell[5]) technology has emerged to challenge the standard aluminium back surface field approach. PERC has helped push production-line cell efficiencies above 20 %. In February 2018 Longi (China) announced a record efficiency of 23.6 % on for mono -Si cells. Indeed a major shift to PERC cell production is now underway, with the ITRPV roadmap (Figure 3) showing a market share of already 10 %, and expected to rise to over 50 % over the next decade. A further driver is that the PERC cell design can be adapted to make bi-facial cells i.e. they can capture light coming from both sides of the cell. In this way a relatively small (and hence low cost) modification to the cell processing equipment can give a significant increase in output (typically 10 % or more depending on the mounting and environment, although manufacturers often claim much higher values). On the down side, the industry has had to develop ways to cope with specific degradation processes: light induced degradation (LID) can cause modules to lose a percentage of power after first exposure to light; potential induced degradation (PID) can lead to significant power losses in longer term operation, depending on the system configuration.

Cells using n-type silicon offer superior performance for several fundamental physical reasons, but up to now the production price differential has favoured the p-type. Market share is currently about 5 % [8]. Sunpower have traditionally dominated this segment with its mono-crystalline cell with interdigitated back-contacts. They still hold the cell efficiency record in this class (25.3 %), although Trina Solar have recently made big advances and announced a cell with 25.2 % efficiency. Other technology options include PERC architectures, full-area passivated designs and increasingly also heterojunction (HJT) cells that include thin layers of amorphous silicon deposited on the n-type mono wafer substrate. Although the market share for HJT modules is still relatively small (only a few % in 2017), the ITRPV report forecasts it to reach 14 % by 2027. Indeed the efficiency record for silicon wafer solar cells is held by Kaneka's IBC/HJT cell, which established a record of 26.7 % in 2017. Kaneka maintain that this value could be increased up to 27.1 % (the theoretical limit for this type of junction is 29.3 %). Modules using these cells have reached 24 % efficiency, but at present the associated production process is not considered commercially viable.

[5] PERC covers a family of cell concepts, of which the PERL (Passivated Emitter, Rear Locally-doped) and PERT (Passivated Emitter, Rear Totally-diffused) are the most widely implemented. The concept was first realised in the 1980s, but has taken off commercially in the last 3 years with the introduction of cost effective laser processing equipment, among other factors.

Figure 2 Schematic of the silicon wafer sub-technologies, indicated also the mid-2018 efficiency records for each class.

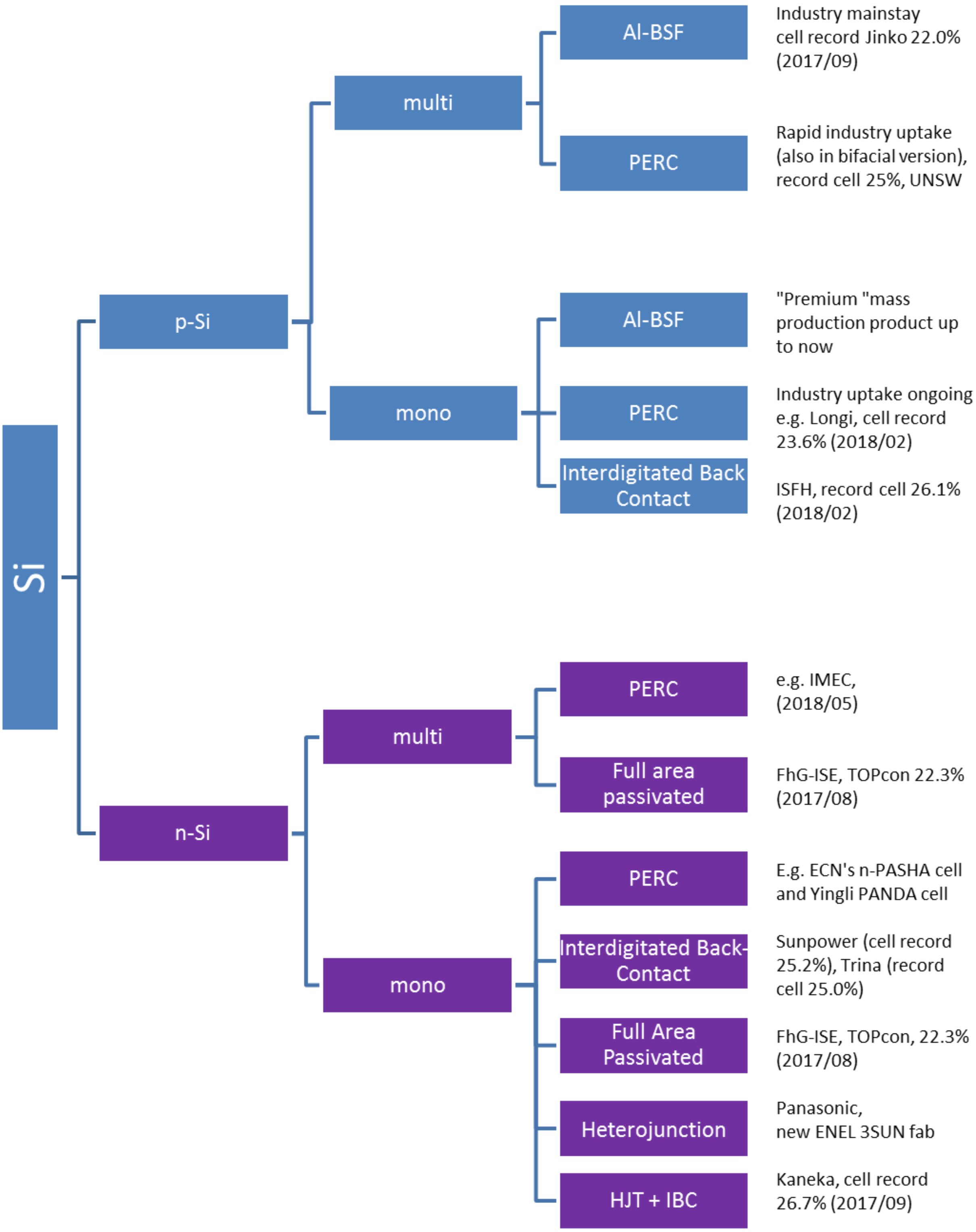


Table 3 Overview of PV cell designs and contacting options

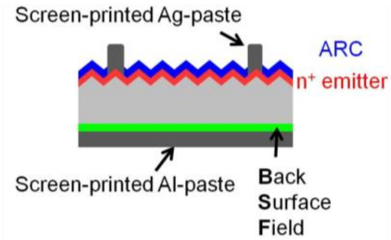
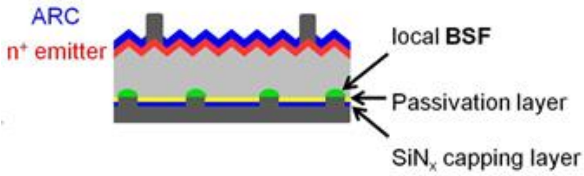
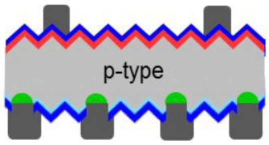
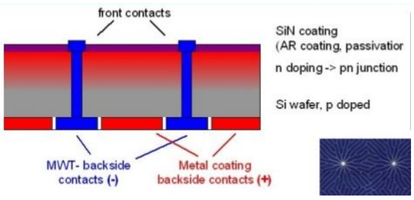
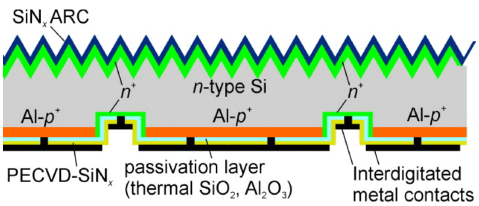
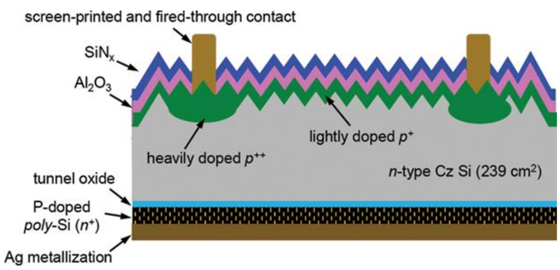
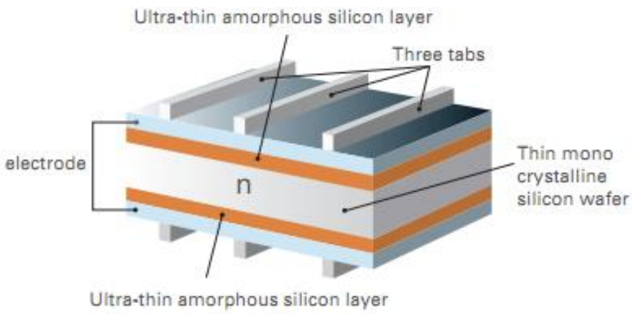
	**Aluminium Diffused Back Surface Field Cell (AL-BSF)** This is "standard" technology and can be used on p- or n-type, multi- or mon-crystalline wafers. It currently represents almost 80 % of the market.
	**Passivated Emitter Rear contact Cell** (PERC): two extra steps are added to the AL-BSF process.: a rear surface passivation film is applied and then lasers or chemicals are used to open the rear passivation stack and create tiny pockets in the film to absorb more light.
	**Bifacial cell design**, in this case adapted from PERC. A screen-printed rear aluminium finger grid is used instead of a full-area rear layer to allow light to access.
	**Metal Wrap Through Technology (MWT)** Back contact option with lower silver paste consumption as the rear contact architecture leads to smaller shaded area
	**Interdigitated back contact (IBC)** Both the positive and negative contacts are on the rear of the device. This eliminates shading from front contacts, and increases efficiency. Its however relatively expensive to produce.
	**Full Area Passivated Cell:** the bottom of the wafer is given a thin-film structure that passivates and serves as a conductive contact to the cell. This eliminates (i) the need for diffusion or implantation doping of the wafer and (ii) complicated patterning of selective emitter/BSF
	**Heterojunction (HJT) Cells**: An ultra-thin layer of amorphous silicon is deposited on the front and back surfaces of a mono, n-type wafer. This can also be combined with IBC contacting for the very highest efficiency Si cells.

Figure 3 Current and projected global market shares of c-Si cell concepts (ITRPV Roadmap 2017 [8]).

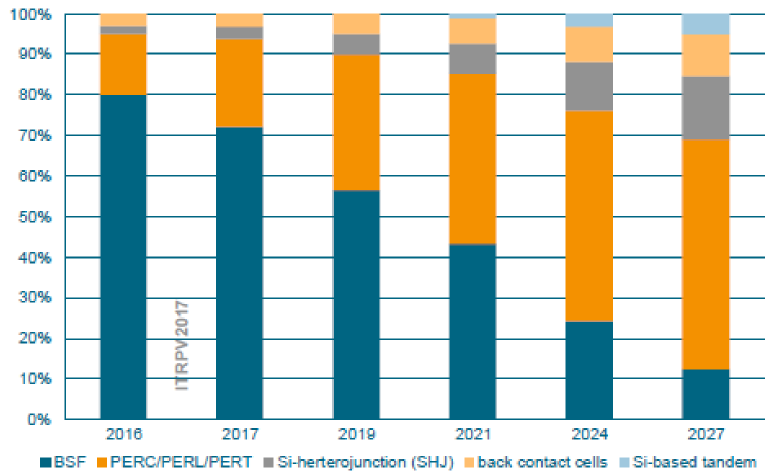
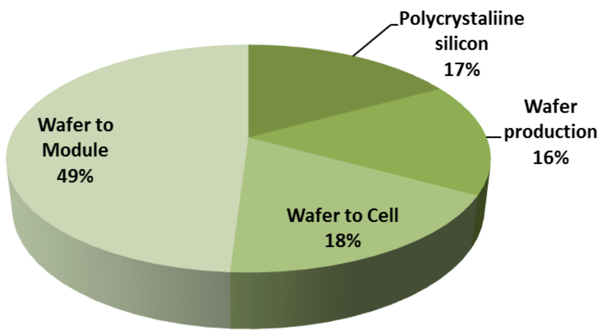


Figure 4 Breakdown of cost elements in c-Si PV module production (from data in the ITRPV Roadmap, 2017).



It's worth noting that value chain for c-Si modules consists in several stages, all of which need to be addressed by R&D in order to reduce costs (**Figure 4**). Issues include:

- Silicon feedstock: fluidised bed reactors can offer significant energy (and hence cost) savings compared to the conventional Siemens process, but the product quality is not yet at the same level.
- Silicon wafers: the industry currently relies mainly on 160-180 µm wafers, and with silicon prices at an historic low (currently about USD 12/kg, down from USD 70/kg in 2010), the pressure to move to thinner cells is not as strong as it was a few years ago. The ITRPV roadmap foresees a modest reduction in thickness up to 2025, however not going below 100 µm. Overall, silicon material usage for cells has reduced over the last 10 years from 16 g/W to less than 6 g/W now. Moving to thinner wafers is also a challenge for the production process. The EU FP7 Cheetah projects demonstrated the feasibility of handling 90 µm wafers on pilot production equipment with some adaptions, but lower thicknesses would require significant modification of the processing equipment.
- Contacting: the use of passivated contacts (deposited as a thin-film on the wafer surface) offers a step beyond PERC in terms of efficiency which can be incorporated in high volume production.
- Kerfless wafer technologies are being developed that eliminate the sawing process entirely. So-called epitaxial wafers/foils are fabricated by chemical vapour deposition of Si layers either p- or n-type in the thickness range between 40 and 150 µm on re-usable seed substrates. The ITRPV roadmap [8] predicts a modest 10 % market share for kerfless wafers in the 2025 timeframe. However there are issues to be solved regarding automated handling of large area thin wafers in the production environment.
- Metallisation: efforts to reduce silver usage and bring in substitutes e.g. copper.
- Anti-reflective glass: need to extend service life

- Cell interconnection: move to lead-free materials, use of half-cells or shingled cells, conducting adhesives, compatibility with thinner wafers etc.
- Encapsulants and backsheet development for longer service life and for cost reduction.

Research efforts in the EU are largely focussed in Germany (Fraunhofer ISE, ISC Konstanz, IFSH), Belgium (IMEC), the Netherlands (TNO[6]), France (CEA-INES) and Switzerland (EPFL). Institutes in many other countries also contribute significantly. These activities are largely funded by national programmes and by industry collaborations (in many cases now with Asian companies).

2.1.2 Thin-film Photovoltaics

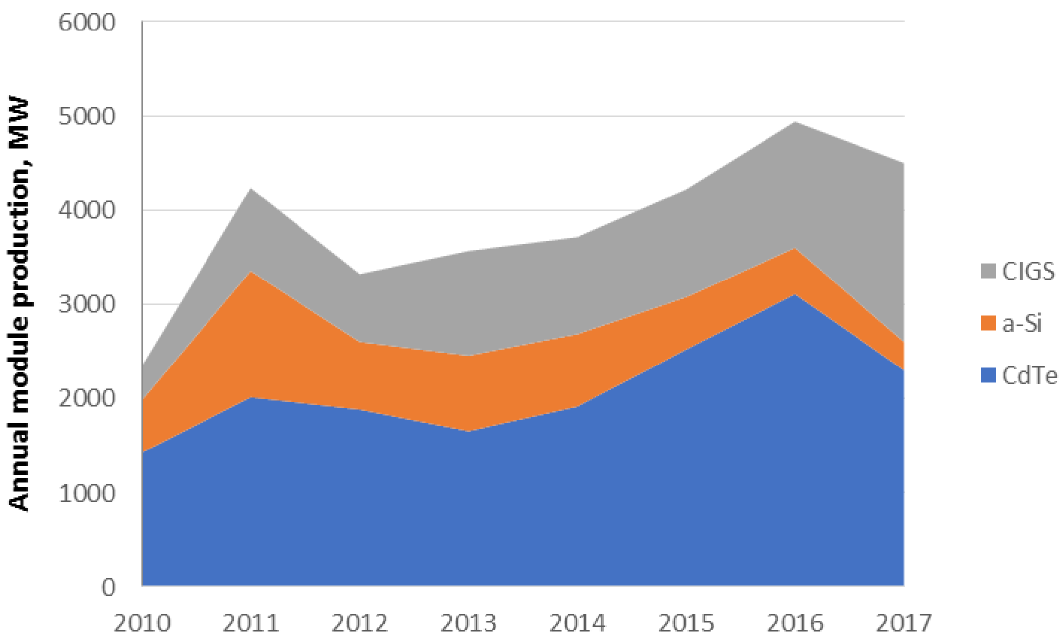
The term "thin-film" refers to devices with active layers of a few microns thickness (i.e. about 100x thinner than silicon wafers) deposited on a suitable substrate These technologies emerged some decades ago as a consequence of new deposition methods and concepts. They offer:

- low manufacturing costs
- low energy payback time
- low CO_2 footprint

Thin-film modules using cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), amorphous and other thin-film silicon have been commercially available since the 1980s. Production in 2017 was reported as 4.5 GW (Figure 5), a slight decrease on 2016 [7]. Overall the market share has decreased on account of the booming silicon wafer market and thin-film is now below 5 % of total annual PV module production. Only CdTe is being produced at multi-GW scale and from one producer (First Solar, USA).

The 2016 White Paper on CIGS by an industry/research consortium [12] claims that the technology can be competitive in many applications (including as building integrated products) and that advanced processing can yield a cost of ownership of USD 0.40/Wp. ZSW, Europe's leading lab on this technology, has boosted the efficiency of its CIGS solar cells to 22.0 %, and estimate that values could reach 25 %. Table 4 summarises the state of the art of the main technologies and of several emerging concepts such as: organic, dye-sensitized, and polymer-based solar cells, perovskite solar cells and copper zinc tin sulphide/selenide (kesterites).

Figure 5 Production trends for the main thin-film PV technologies (source: own elaboration of data from Fraunhofer ISE PV Report 2018 [7])



6 Now includes the former ECN activities

Table 4 Characteristics of the principal thin-film photovoltaic technologies (based on the scheme presented in [13]).

Technology	Record Efficiencies (mid-2018)		Main Features	Challenges
	Cell	Module		
Cadmium Telluride	22.1 %	18.6 %	- Competes with c-Si for utility scale projects - Potential for efficiency to reach 25 % for cells and 85% of that for modules - High potential for cost reduction - Lowest EPBT (0.6 years) - Low CO_2 impact - Cadmium toxicity: not technically an issue for CdTe as a compound and in the quantities used in PV prodcuts	- Tellurium scarcity is a potential limitation to very large scale deployment - Production dominated by a single company (First Solar USA) - Extend module long-term module lifetime
Copper Indium (Gallium) Diselenide CI(G)S	22.6 %	17.1 %	- Low temperature coefficient and good low light performance give potential for good energy yields - Technological flexibility already demonstrated at industrial scale: production of flexible light weight modules (< 2 kg/m^2) - Claimed that production costs could be reduced to €0.24/W by 2020.	- Need to decrease cell-to-module efficiency gap - Indium and gallium on the EU critical materials list - TCOs with higher carrier mobility and optimal optical transmittance, compatible with temperature process requirements (≤ 150 °C) - Hybrid modularisation schemes including metal grids in combination with thin-film scribing processes for definition of individual cells
Amorphous silicon a-Si	10.2 %		- Early leader in mass produced thin-film products - Dwindling commercial interest	- Low efficiency and no clear route to values closer to crystalline silicon
Organic thin-film devices OPV	13.2 %	6 %	TRL 5-6 - Active material in form of small carbon-based molecules, dendrimers and polymers - Low-cost production[7], form-factor flexibility, customised appearance, transparency. - Excellent sustainability profile. - Commercial module efficiency of 6 % and a life time of 10+ years	- Commercialisation issues with lack of stability and faster degradation rates than for other technologies - Efficiency drop-off from cells to modules can be as high as 50 %
Dye sensitised solar cells (DSSCs)	11.9 %		TRL 5-6 - Use light absorption in dye molecules (the "sensitizers") attached to the very large surface area of a nanoporous oxide semiconductor electrode (e.g. TiO_2), followed by injection of excited electrons from the dye into the oxide to generate electricity. - Interest for use as semi-transparent coloured glass building facades	- Long-term stability, in combination with a reasonable efficiency, - Scientific effort has shifted to perovskites as they promise much high efficiency levels

[7] According to [27], mass production could lead ultimately to costs of 8 USD/m^2, a factor 10 below that projected for c-Si.

Technology	Record Efficiencies (mid-2018)	Main Features	Challenges
Perovskites (hybrid organic-inorganic lead or tin halide-based material)	22.1 %	TRL 4-5 for lead-containing materials; TRL of 2-3 for lead-free perovskites - Uses abundant elements - Low temperature solution-based production processes (aids suitability for tandem applications on silicon wafers) - Tuneable band gap - High efficiency - High potential for flexible light weight and semi-transparent applications	- Lead toxicity, stability, scalability - New cost efficient encapsulation materials and processes - Identification of suitable buffer layers for optimal buffer/absorber front interface
Kesterites CZTS	12.7 % [8]	TRL 3-4 - free of critical raw materials - high stability - high level of technological - compatible with CIGS industrial processes - band gap tuneable in broad IR – UV region	Need to increase efficiency Low open circuit voltage (now only 60 % of the theoretical maximum) e.g. by reducing defects in the structure, use of graded band gap concepts

2.1.3 Tandem PV

A major theme in PV research is how to raise the efficiency of PV devices above the Shockley-Quiesser limit of 29 % for single junction devices[9]. The answer lies in tandem devices, with the rule of thumb that the efficiency of both the top and bottom components needs to be above 20 % to arrive at a combined efficiency above 30 %[10]. Further major challenges include the contacting of the two layers and developing a production process compatible with both components. For the latter, the approaches are either to directly deposit the thin-film on the silicon (monolithic integration) or to create the thin-film layer separately and then physically attach it to the silicon (mechanical stacking).

Table 5 shows recent record results for several tandem concepts, both with silicon + thin-film and thin-film + thin-film. The efficiency record for such multi-junctions is for a silicon cell with a monolithically added III-V material layer, with values now reaching 33.3 %. However the commercialisation of such devices may be restricted by costs of a GW production of such cells and the availability of the III-V materials used.

Another combination attracting strong interest is the perovskite on silicon tandem. There is an area of vibrant research globally. The UK-German firm Oxford PV stands out as one of the most advanced: it is currently developing a pilot production line and have secured over EUR 40 million in funding, including a EUR 15 million grant in 2017 from the European Investment Bank.

Concerning thin-film on thin-film concepts, the CIGS – perovskite device cited in Table 5 is a leader in terms of efficiency. Previous efforts to realise higher efficiencies for thin-film silicon devices looked at tandem devices with a high band gap amorphous silicon top cell and one or two lower band gap microcrystalline silicon cells [14]. However the stabilized efficiencies never got past the 13 % level. Many of the highest efficiency OPV devices are tandems, but the obtained efficiency/lifetime combination hasn't been able to compete with mass production silicon wafer technology. However in early 2018 University of Michigan scientists[11] demonstrated a tandem organic solar cell (2mm² active area) with 15 % efficiency.

[8] IBM device, result certified; reported (but uncertified) efficiency value of 13.9 % from DGIST, Korea
[9] Concepts with optical concentration of the sunlight are discussed in section 2.1.4 below
[10] PV-Magazine interview with Martin Green, 19/05/2018
[11] Xiaozhou Che et al, Nature Energy Vol 3, pages422–427 (2018)

Table 5 Energy conversion efficiencies (2018) of tandem PV cells (active areas of the order of 1 cm²).

Bottom Cell	Top Cell	Efficiency %	Integration	Year/Month
Silicon	III-V	35.9[12]	Stacked	2016
Silicon	III-V	33.3[13]	Monolithic	2017
Silicon	Perovskite	27.3[14]	Monolithic	2018/06
Silicon	Perovskite	27.1[15]	Stacked	2018/08
Silicon	Perovskite	23.9[16]	Stacked	2017
Silicon	Perovskite	23.6[17]	Monolithic	2017
CIGS	Perovskite	22.4[18]	Monolithic	2018
CIGS	Perovskite	20.5[19]	Stacked	2015

2.1.4 Concentrating Photovoltaics (CPV)

This category exploits the fact that some PV materials show much higher energy conversion efficiency when the incident light is concentrated by lenses or mirrors. Within CPV there is a differentiation according to concentration factor: low concentration refers to < 10 suns, whereas high concentration implies a factor of several hundred. The latter require the use of tracking devices. Despite its technical promise, CPV has failed to make an impact in the market, struggling in particular with the intense cost completion from standard silicon wafer products. Fraunhofer ISE and NREL have released a comprehensive review of the technology and market in February 2016 [15].

For HCPV systems the most commonly used cell is a three-junction device based on GaInP/GaAs/Ge, with a record efficiency of 46.0 % [11] for 508x concentrated light. With appropriate optics, module efficiencies of over 35 % have been recorded can be achieved, In February 2016 Fraunhofer ISE announced an efficiency of 43.4 % for a CPV mini-module with quadruple junction solar cells. HCPV systems require a high fraction of direct (vs diffuse) irradiation, and is thus only suited for the sun-belt regions with the optical systems currently available. Approximately 340 MW of CPV systems are installed worldwide.

CPV is at the beginning of an industry learning curve, with considerable potential for technical and cost improvements. The most challenging task is to become cost-competitive with other PV technologies in order to reach substantial production volumes and the associated economies of scale.

2.2 Power conversion equipment

The key interface/integration element is the DC-AC inverter, and its cost makes up approximately 10 % of system CAPEX. Efficiency for branded products currently stands at 98 % and above [7]. Development trends include:

- extension of operational life (manufacturer guarantees are typically for 10 years)
- addition of features for grid stabilization and optimization of self-consumption; inclusion of storage units
- introduction of different semiconductors (SiC or GaN) to allow higher efficiencies and higher voltages.

In regard to the latter point, the uptake of SiC is mainly for large central inverters. In utility applications this can reduce or eliminate the need for transformers, and improve grid support capabilities. For instance, the German HV-SiC project (BMBF) recently announced an inverter using SiC components that can regulate power

[12] Werner, J. et al, ACS Energy Lett., 2016, 1 (2), pp 474–480
[13] J. Benick et al, Monolithic III-V//Si Multi-Junction Solar Cell Exceeding an Efficiency of 31%, presented at EU PVSEC 2017 (not in proceedings)
[14] Oxford PV press release, 1 cm² tandem cell recorded a 27.3% conversion efficiency,
[15] IMEC press release, for 0.13cm² area (for 4cm² the cell efficiency is 25.3%)
[16] Imec press release, August 2017
[17] K.A. Bush et al, Nature Energy 2, 2017, 17009
[18] UCLA, reported in Science 31 Aug 2018: Vol. 361, Issue 6405, pp. 904-908
[19] F. Fu et al, Nature Communications 6, 2015, 8932

of up to 10-15 kV, more than ten times higher than regular silicon inverters. This opens possibilities for new system architectures for utility scale plants. Use in the string inverter market will depend on getting manufacturing costs down.

The market for module level power electronics[20] up has up to now focussed largely on power optimizers (DC-DC converters) and micro-inverters (DC-AC). Fraunhofer ISE [7] estimates that about 3 GWp of DC/DC converters were installed in 2017, and that micro-inverters represent a small fraction (about 1 %) of the inverter market[21]. This area is expected to develop in the future. The ITRPV roadmap [8] foresees a 20 % market share for so-called smart junction boxes by 2027, covering DC-DC optimisers, micro-inverters and integrated safety switches. The long-term durability of such devices is a critical factor as replacing defective components at module level could be expensive.

Figure 6 Overview of inverter characteristics and costs (source [7])

Inverter / Converter	Power	Efficiency	Market Share (Estimated)	Remarks
String Inverters	up to 150 kWp	up to 98%	~ 52%	• 6 - 17 €-cents /Wp • Easy to replace
Central Inverters	More than 80 kWp	up to 98.5%	~ 44%	• ~ 5 €-cents /Wp • High reliability • Often sold only together with service contract
Micro-Inverters	Module Power Range	90%-95%	~ 1%	• ~ 28 €-cents /Wp • Ease-of-replacement concerns
DC / DC Converters (Power Optimizer)	Module Power Range	up to 98.8%	~ 3%	• ~ 9 €-cents /Wp • Ease-of-replacement concerns • Output is DC with optimized current • Still a DC / AC inverter is needed • ~ 3 GWp installed in 2017

Data: IHS 2016. Remarks: Fraunhofer ISE 2018. Design: PSE GmbH 2018

2.3 Cross-Cutting Aspects

2.3.1 Standards

The International Electrotechnical Commission (IEC) Technical Committee 82 deals with solar photovoltaic energy systems and was established 1981. It has published more than 100 standards, which have laid the foundations for the dramatic increase of trade in PV products. In the EU, CENELEC has a mandate for standardization in the field of solar photovoltaic energy systems and components (M/089 EN). This is implemented by its Technical Committee 82: Solar Photovoltaic Systems. Under the terms of the Frankfurt Agreement with IEC, CENELEC transforms IEC standards into European standards, usually in a "fast track" procedure. The JRC annual PV standards report summarises the current status of IEC and CENELEC activities [16].

PV modules are subject to certification (type approval) under the IEC 61215 series, with specific requirements for each of the main technology groups (crystalline silicon, cadmium telluride, amorphous silicon and microcrystalline silicon, copper indium gallium selenide and copper indium selenide). Work is also in progress on a revision to include flexible (non-glass superstrate) products and bifacial designs. Compliance with IEC 61215 is expected to ensure low initial failure rates in the PV products entering service.

[20] Other terms used include "smart modules" and "AC modules".

[21] A requirement in the US building fire safety codes that a PV system can be isolated at or very close to the modules has been a recent driver for the market in module integrated safety switches has been.

In a survey on needs for new or improved standards carried out in 2017 with the EU PV community[22], respondents saw "reliability degradation and lifetime" as key priority for all components and indeed for systems. Standards for building integrated products were also flagged by a significant number of respondents, highlighting issues such as system functionality and performance, compatibility with construction codes and the need to avoid frequent (and expensive) design re-certification.

The International Photovoltaic Quality Assurance Task Force (PVQAT) has been successful in coordinating pre-normative research and promoting new technical standards for verifying PV component and system quality and bankability. PVQAT has a three-pronged approach that seeks to establish:

- a rating system to ensure durable design of PV modules for the climate and application of interest;
- a guideline for factory inspections and quality assurance (QA) during manufacturing;
- a comprehensive system for certification of PV systems, verifying appropriate design, installation, and operation.

The JRC has supported the development of the PVQAT from its inception and is represented on the steering committee together with NREL and AIST[23].

The IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE System) was formed in 2014 to define how certificates can be issued at system level for three energy sectors: wind, solar and marine energy. Conformity assessment can be performed and certificates issued for an individual PV power plant on a specific site at various stages of its design and implementation. It aims to give confidence that a PV plant will safely perform as promised and reduce cost at the same time. It represents a step beyond standards, in that while IEC writes technical standards, IEC does not define how these are used. The IECRE Specific Certificate Categories can include:

- PV Site Qualification certificate;
- PV Power Block design qualification certificate;
- PV Plant Design qualification certificate;
- Conditional PV Project certificate (construction complete / commissioning);
- Annual PV Plant Performance certificate;
- PV Asset Transfer certificate;
- PV Decommissioning certificate.

Finally, in the context of the EU's circular economy policy, EC mandate M/543 is a formal request to the European standardisation organisations as regards Ecodesign requirements on material efficiency aspects for energy-related products. Generic standards are expected in 2019 on aspects such as durability, dismantlability, disassemblability and remanufacturing. Product-specific standards (e.g. for PV modules or inverters) would then need be developed in this framework.

2.3.2 Critical Raw Materials

EU Raw Materials Initiative aims to help ensure their secure, sustainable and affordable supply. Of relevance to PV, the 2017 list critical materials list[24] includes gallium, indium and silicon metal.

2.3.3 Sustainability

Photovoltaic modules have an environmental impact. Areas of potential concern include:

- energy required to produce the PV cells and modules, typically expressed as an energy payback time or energy footprint; these values are strongly influenced by the power source mix used during production;

[22] Cheetah Project, Deliverable D5.9

[23] Fraunhofer ISE and China General Certification Centre will also join PVQAT Steering Committee in 2018.

[24] COM(2017) 490 "Communication on the 2017 list of Critical Raw Materials for the EU"

- water required during production and operation i.e. for cleaning;
- toxic and other potentially harmful materials used or created during manufacturing;
- potential release of toxic and other potentially harmful materials during operation i.e. leeching, fires etc.;
- reduction of use of materials whose availability is or may become critical: silver for crystalline silicon devices; tellurium, indium, gallium for thin-film devices;
- limitation of land use i.e. possible displacement of agricultural activities, visual impact;
- end-of-life management and recycling.

Carbon footprint and energy payback time (EBT) have received particular attention. The world average carbon footprint of PV electricity generation is estimated as 55 g CO_2-eq/kWh – for Europe values range from 38 g CO_2-eq/kWh for Cyprus which has a high irradiation to 89 g CO_2-eq/kWh for Iceland which has a low irradiation[25] [17]. Regarding technologies, thin-film modules have the lowest emissions, followed by poly-crystalline silicon and then mono-crystalline silicon.

At international level the IEA PVPS Task 12 group issued methodology guidelines on PV-specific parameters used as inputs in LCA [18].

The EU initiative on the Single Market for Green Products includes two methods to measure environmental performance throughout the lifecycle: the Product Environmental Footprint (PEF) and the Organisation Environmental Footprint (OEF) [19]. Photovoltaic electricity generation was assessed as a pilot product, and the resulting Product Environmental Footprint Category Rules[26] provide a methodology for assessing the environmental impacts of PV technologies based on life cycle assessment.

PV is included the Ecodesign Working plan 2016-19. A preparatory study[27] is in progress on solar panels, inverters and systems, in order to assess the feasibility or proposing Ecodesign, EU Energy label, EU Ecolabel and Green Public Procurement (GPP) policy instruments. It is expected to be completed in 2019. Should the decision be taken to implement an Ecodesign regulation, this would be expected to require a further two years.

Concerning recycling, PV modules come under the scope of the WEEE Directive[28] since 2012. The industry has set up a pan-European producer scheme called PV CYCLE, which offers WEEE compliance and waste management services for solar energy system products.

2.3.4 Performance, operation, reliability and lifetime

a) PV Performance measures for trade, system design and planning

The rated peak power value remains the key parameter for commerce in photovoltaic products, as well as for regulatory purposes (e.g. in trade cases). An energy yield rating for PV modules is now available under the IEC 61853 (parts 3 and 4 were approved in 2018). This allows calculation of a module's potential energy yield under 6 reference climates (i.e. an annual data set with hourly values of irradiation, spectral content, ambient temperature and wind speed). The approach offers investors and prosumers better information on actual operational performance, and can underpin improved product performance differentiation.

[25] Calculated using an average "world" carbon footprint of 1798 kgCO_2-eq/kWp for PV system manufacturing in 2011, based on market shares of 88% for c-Si and 12% for TF and other technologies. End-of-life processing is not included.

[26] The document "Product Environmental Footprint Category Rules (PEFCR) Photovoltaic Modules Used In Photovoltaic Power Systems For Electricity Generation" is due to be released in November 2018; see also the PEF site https://webgate.ec.europa.eu/fpfis/wikis/display/EUENVFP/PEFCR+Pilot%3A+Photovoltaic+electricity+generation

[27] See http://susproc.jrc.ec.europa.eu/solar_photovoltaics/projectplan.html

[28] 2012/19/EU Waste Electrical and Electronic Equipment Directive regulates the appropriate treatment of end-of-life products and requires that producers comply with national waste management obligations, including the related financing and administration.

b) Reliability and Operational Lifetime

Today's market requires warranties that are decades long (typically 80 % of power after 25 years). However the subject of degradation of PV modules is still under open debate within the PV community. The lack of extended standardisation work on this topic is due mainly to the fact that new and different failure modes of PV modules appear in the field as time passes and as module technologies and packaging are explored. The IEC 61215 series standard for design certification has been demonstrated to be valuable for rapidly uncovering well-known failure mechanisms; however, it is insufficient for assessing long-term risk, evaluating newer or less common materials and designs and establishing field performance degradation.

Field data can be used to give estimates for degradation rates. A recent compilation study [20] found a median degradation rate[29] for c-Si technologies of 0.5 to 0.6 %/year and a mean of 0.8–0.9 %/year. The data for thin film technologies indicate a slightly higher rate of around 1 %/year.

c) Operation performance analysis and monitoring

A range of tools is now available for situations that can range from utility-scale plants of 10 MW with 50 000 modules down to small roof systems of a few kW. Issues include:

- early detection of performance anomalies;

- optimisation of maintenance;

- detecting faulty modules.

d) Forecasting/resource measurement methodologies

Solar irradiance measurements provide essential information at all stages of the PV system life cycle (site selection, system design, certification, operation, maintenance, trouble-shooting, upgrading, expansion) and business decisions rely on accurate solar irradiance data. Most modern sensors used to measure global (or hemispherical) solar irradiance fall into the following categories: thermopiles pyranometers, photodiodes

and photovoltaic reference cells. Spectro-radiometers are used for measuring spectral content. Within these categories are instruments in various price and performance classes.

Data from geostationary satellites is also used to estimate the solar resource. The advantage of this approach is that the data are available uniformly over large geographical areas. Using different satellites, the solar resource can be estimated for the entire world except for the polar areas. In recent years, several data sets have achieved accuracy in the estimate of global horizontal irradiation of close to 5 % (95 % confidence interval for the annual average solar irradiation). The estimate of direct normal irradiance, important for concentrating solar power plants, is less precise, with recent studies giving an uncertainty of about 10 % (95 % confidence interval). The availability of the solar resource data varies. For some areas long-term time series of data are available for free, this is the case for Europe, North America, Africa and most of Asia.

Power forecasting is also necessary for efficient grid integration of fluctuating PV power. The IEA-PVPS Task 14 produced a state of the art report on forecasting in 2013 [21]. They distinguish broadly for forecasting horizons of 0 to 6 hours ahead and from 6 hours to a few days ahead. The requirements also vary with spatial scale. Single-site forecasts may be used for storage management or direct marketing of single PV power plants. Regional forecasts may be relevant for marketing and balancing of PV power.

Many different forecasting methods are available including numerical weather prediction (NWP), model output statistic (MOS) approaches and satellite-based forecast models. IEA) Solar Heating & Cooling (SHC) Task 46 "Solar Resource Assessment and Forecasting" addresses the need for a framework to evaluate and compare different forecast models. Considerable effort is devoted to forecast benchmarking and accuracy metrics. RMSE (and MSE) give more weight to the largest errors. Since these are considered to have a disproportionate impact on costs, RMSE may be better for system operators. Indeed the SET-Plan Integrated Roadmap specifies an RMSE of <8 % of installed power by 2020 for an intra-day single-site power forecast in NW-Europe. The data reported by Lorentz et al in 2015 [22] suggest that this may be already achievable.

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[29] This degradation rate is with respect to the initial nominal power (W_p); the decrease in power is therefore implicitly linear in time.

3 R&D OVERVIEW

3.1 Global and European Trends

3.1.1 Scientific Publications

The JRC Technology innovation Monitoring tool (TIM[30]) provides the functionality to check on scientific publications in its database, which contains documents from the database Scopus (Elsevier) published after 1996. Figure 7 shows the global distribution of scientific articles published in 2017[31]. EU authors were involved in approximately 25 % of the 8057 papers identified in the search. Separate analysis shows that this proportion has been maintained since 2010, underlining the high level scientific excellence in photovoltaics in Europe. It is also significant that Asian countries account for a very significant fraction of scientific output and indeed the Chinese Academy of Sciences is the single largest contributor organisation.

Looking at the recent time trends (Figure 8), EU output of scientific publications on PV almost doubled from 2010 to 2014. However it appears to have then plateaued in the period 2015-2016, and the TIM data search even shows a drop in 2017 (this data may not be complete, as the global figures also show a similar drop for 2017).

Figure 9 the distribution of main research locations for 2017, while Table 6 shows the top 100 ranking of organisations with publications in 2016 involving at least one EU co-author. These data confirm the well-known centre of excellence in PV research in Western Europe, while the low level of publications from organisations in Eastern Europe is also notable.

Figure 7 Distribution of scientific articles published in 2017 (source: JRC TIM tool)

[30] EU, Joint Research Centre, Tools for Innovation Monitoring, http://www.timanalytics.eu/

[31] TIM search string: topic:(photovoltaic OR "solar cell") AND class:(article) AND emm_year:2017.

Figure 8 Time trend for EU scientific publications on photovoltaics (source: JRC TIM tool).

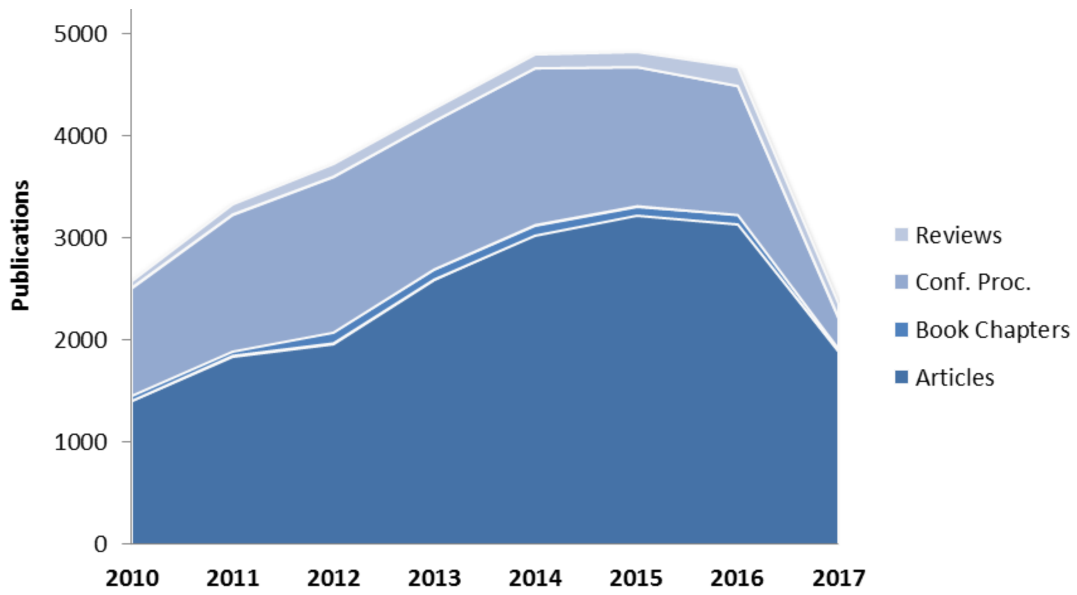

Figure 9 Geographical distribution of authors of PV research publications **(source: JRC TIM tool).**

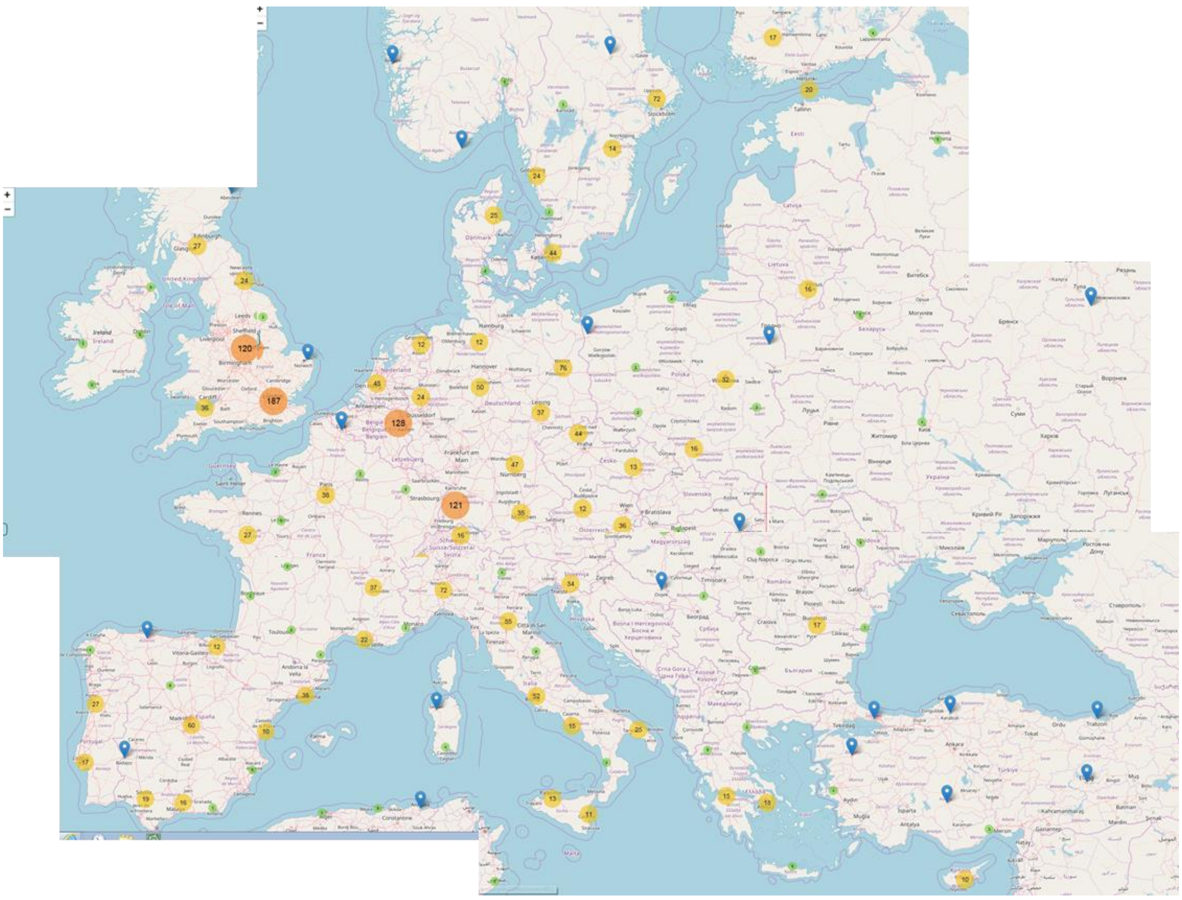

Table 6 Ranking of organisations with publications in 2016 involving at least one EU co-author (source: JRC TIM tool).

Rank	Institution/Organisation	Pubs.
1	CNRS	99
2	Imperial College London	53
3	University of Oxford	48
8	Fraunhofer ISE	45
4	University of Cambridge	39
5	Helmholtz Berlin für Materialien und Energie	38
6	Uppsala University	36
7	Eindhoven University of Technology	35
9	Delft University of Technology	29
10	Lund University	26
	Universidad Politécnica de Madrid	26
	University College London	26
13	Aalto University	25
14	Politecnico di Milano	23
	Technical University of Denmark	23
16	Chalmers University of Technology	22
	Politecnico di Torino	22
18	Aalborg University	21
	Ecole Polytechnique Fédérale de Lausanne	21
	Friedrich-Alexander-Universität Erlangen-Nürnberg	21
20	Swansea University	20
21	University of Manchester	19
23	Bavarian Center for Applied Energy Research	18
	King Abdullah University of Sci & Tech	18
	KU Leuven	18
	University of Rome Tor Vergata	18
	University of Sheffield	18
28	Newcastle University	17
	Technische Universität Dresden	17
	University of Luxembourg	17
36	Ecole Polytechnique	16
	Linköping University	16
	Loughborough University	16
	Polish Academy of Sciences	16
	Universitat Politècnica de Catalunya	16
	University of Aveiro	16
	University of New South Wales	16
39	Stanford University	15
	Tampere University of Technology	15
	University of Nottingham	15
	University of Patras	15
45	Chinese Academy of Sciences	14
	Freie Universität Berlin	14
	KTH Royal Institute of Technology	14
	Massachusetts Institute of Technology	14
	University of Oldenburg	14
	University Politehnica of Bucharest	14
48	Forschungszentrum Jülich	13
	Universidad de Jaén	13
	University of Glasgow	13
	Utrecht University	13
	continued …	
52	Max Planck Institute for Polymer Research	12
	School of Chemical Science and Engineering	12
	Technische Universität München	12
	Universidad Autónoma de Madrid	12
	Universidad de Sevilla	12
	Universitat Jaume I	12
	University of California	12
	University of Groningen	12
60	Humboldt-Universität zu Berlin	11
	Istituto Italiano di Tecnologia	11
	RWTH Aachen University	11
	Tallinn University of Technology	11
	University of Angers	11
	University of Liverpool	11
	University of Ljubljana	11
	University of Palermo	11
	University of Salento	11
	Vilnius University	11
78	Aarhus University	10
	Friedrich-Schiller-University Jena	10
	Hasselt University	10
	Mälardalen University	10
	National Renewable Energy Laboratory	10
	Northwestern University	10
	Queen Mary University of London	10
	Universidad de Castilla-La Mancha	10
	University of Bayreuth	10
	University of Bordeaux	10
	University of Potsdam	10
	University of Science and Technology	10
	University of Southampton	10
90	Catalonia Institute for Energy Research. IREC	9
	Institute for Solar Energy Research Hamelin	9
	Johannes Kepler University Linz	9
	King Abdulaziz University	9
	Leibniz Universität Hannover	9
	National Technical University of Athens	9
	National University of Singapore	9
	PSL Research University	9
	Sheffield Hallam University	9
	Universidade de Lisboa	9
	University of Applied Sciences SUPSI	9
	University of Catania	9
	University of Duisburg-Essen	9
	University of Konstanz	9
	University of Milano-Bicocca	9
	University of Valencia	9

3.1.2 Patents

The data considered is from Patstat (European Patent Office) for the period to 2014[32], with subsequent processing by the JRC [23]. The overall volume of patents (>30 000) precludes a detailed analysis of content. However generic technology–related information is given by the CPC classification codes (Table 7)

Table 7 CPC classification codes relevant to photovoltaics

Grouping	CPC codes
Photovoltaic energy (PV generic)	Y02E 10/50
Material Technologies	Y02E 10/540 Y02E 10/541 $CuInSe_2$ materials Y02E 10/542 Dye sensitized Y02E 10/543 Group II-VI materials (CdTe) Y02E 10/544 Group III-V materials Y02E 10/545 Microcrystalline silicon Y02E 10/546 Polycrystalline silicon Y02E 10/547 Monocrystalline silicon Y02E 10/548 Amorphous silicon Y02E 10/549 Organic[33]
Building applications	Y02B 10/10, Y02B 10/12 PV Roof systems for PV cells Y02B 10/14 PV hubs
System with concentrators	Y02E 10/52
Power conversion	Y02E 10/56 PV - Power conversion electric or electronic aspects Y02E 10/563 Grid connected Y02E 10/566 Power management inside the plant Y02E 10/58 Maximum power point tracking (MPPT) systems
PV-thermal hybrids	Y02E 10/60
Manufacturing processes	

Figure 10 shows the overall trend in counts of patent families[34] per year for three categories: all patent families, so-called "high-value" patent families i.e. application made to two or more patent offices and granted patent families. Overall filings grew strongly from 2000 up to 2012, but have decreased in 2013 and 2014. The reasons for this are not fully clear, but anecdotal evidence suggests that patenting has become less valued as a means to protect IPR in the industry.

In terms of global regional breakdown for 2014, China took the largest share when considering all patent family applications, followed by Japan and Korea. However if just the "high-value" patent families are considered a different picture emerges, with Japan as leader and the EU in second positon.

Figure 13 shows the data analysed in terms of seven main CPC classifications (see Table 7). Patents on materials technologies are the largest single grouping, followed by manufacturing processes. Both of these grew strongly over the period 2000-2012. The increase in power conversion inventions is also note-worthy. Figure 13b shows the regional breakdown for 2013. China has markedly high proportion of patents relating to manufacturing processes, as might be expected for the world's largest producer of PV products. For the EU, patenting on power conversion and on BIPV are relative strengths.

Finally, Figure 14 considers the PV materials categories. The strong growth in patents on organics (including perovskites) and on DSSC materials is striking. In the 2013 breakdown, these two categories account for over 50 % of patent families in all regions except the USA. For crystalline silicon (mono- and poly-), the USA, EU and RoW remain leaders, in that order.

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[32] There is a time lag of 4 years to obtain complete data for a given year.
[33] CPC Y02E 10/549 includes perovskites, although these are hybrid organic/inorganic materials.
[34] Patent documents are grouped in families, with the assumption that one family equals one invention.

Figure 10 Global trend in patent filings under PV related families per year.

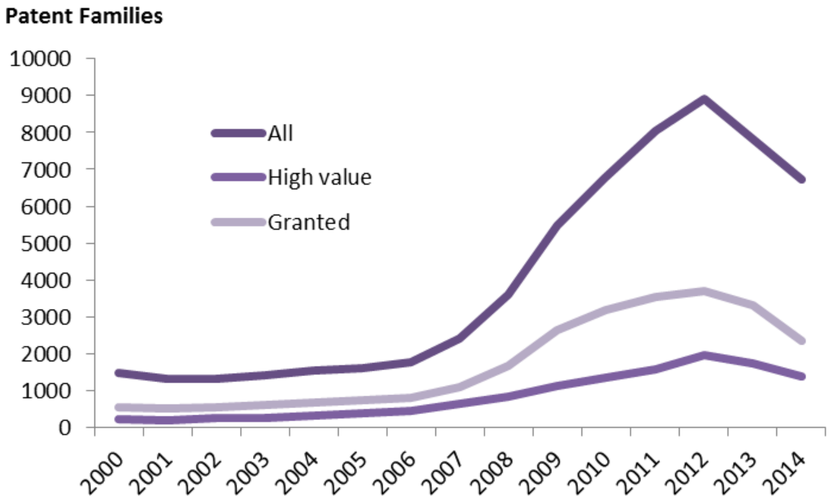


Figure 11 Regional breakdown of patent families (high value indicates applications in two or more patent offices)

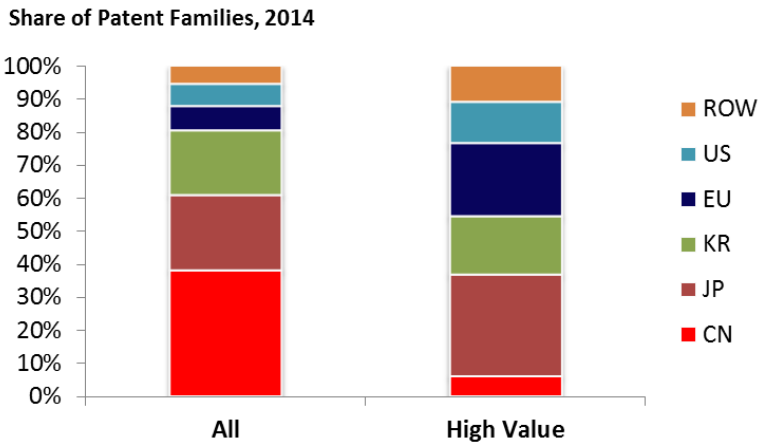


Figure 12 Trends in patenting under the main application groups for 200-2013

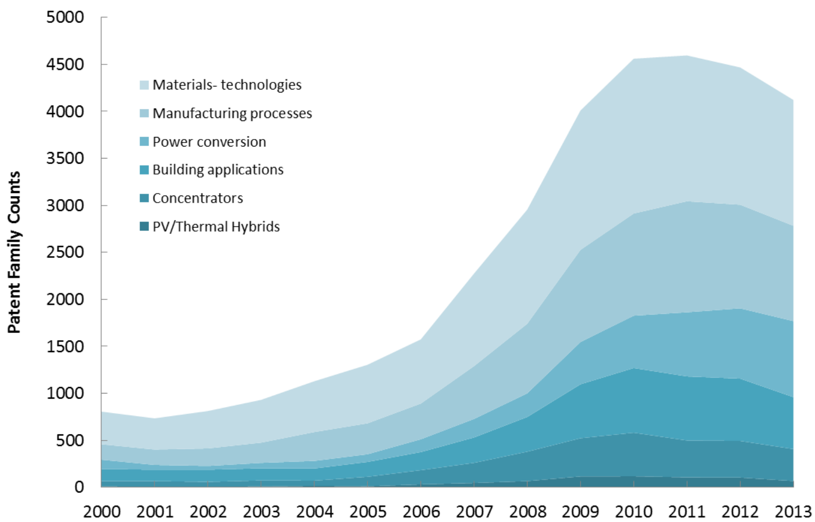


Figure 13 Regional breakdown for 2013 for patents under the main application groups.

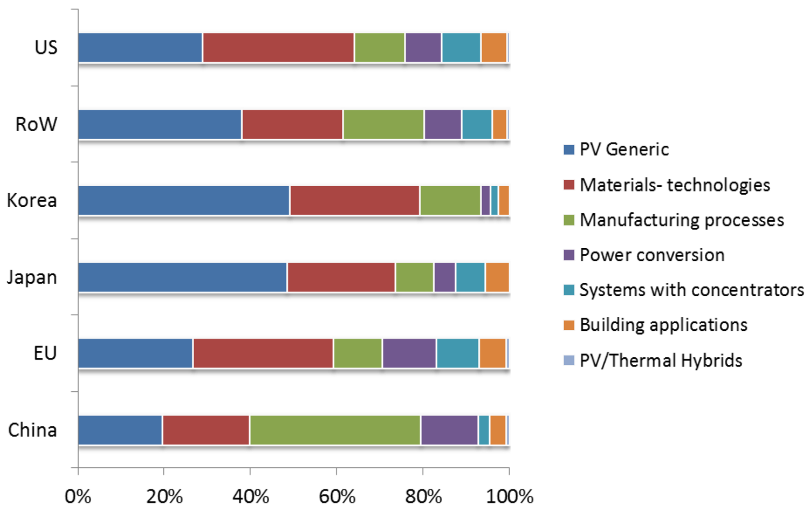


Figure 14 Trends and breakdown of patents in terms of PV materials groupings.

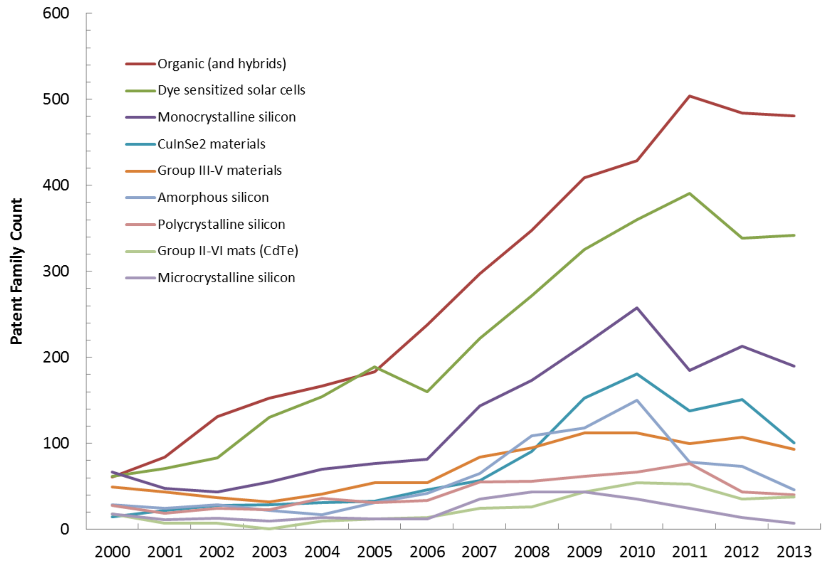
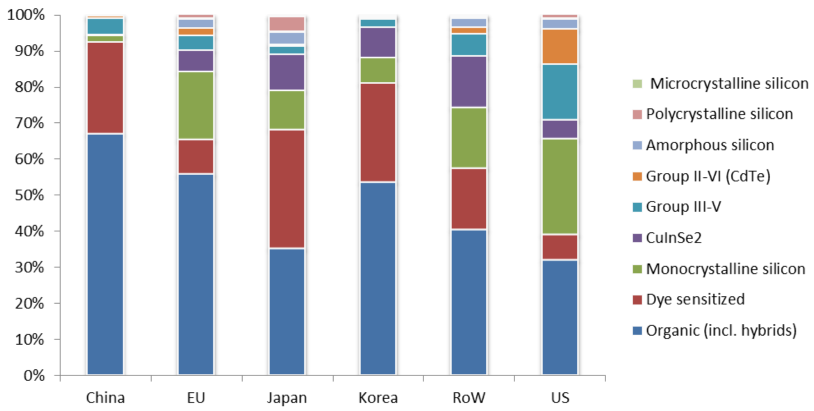


Figure 15 Regional breakdown of patents in terms of PV materials groupings for 2013.



3.2 EU Policy and Programmes

3.2.1 Energy Union and the SET-Plan

The Energy Union sets out a strategic vision for the transition to a low-carbon, secure and competitive economy in the European Union. It consists of five dimensions: security of energy supply; internal energy markets; energy efficiency; decarbonisation of the energy mix; and research and innovation [24]. The Strategic Energy Technology Plan (SET-Plan) is an integral part of this framework and aims to accelerate the development and deployment of low-carbon technologies. The working group on photovoltaics involves representatives of Member States, other stakeholders and the European Commission, and in 2015 it released the "Declaration of Intent on Strategic Targets in the context of an Initiative for Global Leadership in Photovoltaics" [9].This was followed in 2017 by a detailed implementation plan [25].

The European Technology and Innovation Platforms (ETIPs) were created to support the implementation of the SET-Plan by bringing together EU countries, industry, and researchers in key areas. The photovoltaics platform, ETIP-PV[35] provides consensus-based strategic advice in the areas of research and innovation, market development, including competitiveness, education and Industrial policy.

Also under the SET-Plan governance, the European Energy Research Alliance (EERA) aims to accelerate technology development by cooperation amongst non-profit research institutes and universities on pan-European programmes. The EERA PV joint programme[36] focuses primarily on cost reduction of PV systems, through enhancement of performance, development of low-cost, high-throughput manufacturing processes, and improvement of lifetime and reliability of PV systems and components.

3.2.2 Horizon 2020

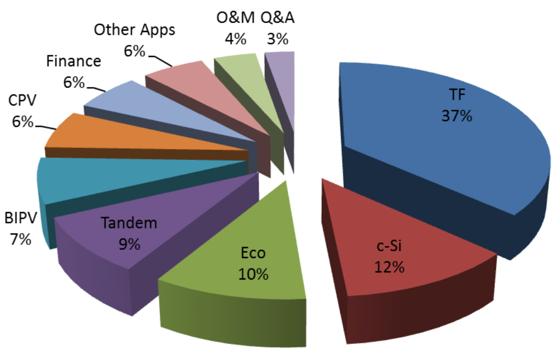
Horizon 2020 is the EU's financial instrument implementing the Innovation Union, a Europe 2020 flagship initiative aimed at securing Europe's global competitiveness. In the period 2014-2017, 100 PV-related projects and actions have been funded. Table 8 gives the breakdown of the different programmes in terms of the EC financial contribution. Figure 16a shows the breakdown in terms of applications, with the area "flat plate modules" is split into c-Si, thin-film and tandem technologies. Overall this category accounts for the bulk of funding (58 %). The significant part dedicated to tandem cell and module concepts shows the interest in this area. Furthermore of the 8 "tandem" PV projects, 6 use silicon wafers for the bottom cell, with 5 working on III-V materials for the top cell and 1 on perovskites. Figure 16b shows the breakdown in terms of materials technology (here tandem concepts are counted 50 % for the top cell and 50 % for the bottom cell material). About a quarter of project EC funding is accounted for by crystalline silicon, and both III-V and CIGS thin-film materials also have significant shares. The "other FET" category reflects ERC funding of basic science projects. The groupings "OPV/DSSC" and "perovskites" are at the same level.

Table 8 Breakdown of programmes and EC funding for PV-related projects, H2020, 2014-2017.

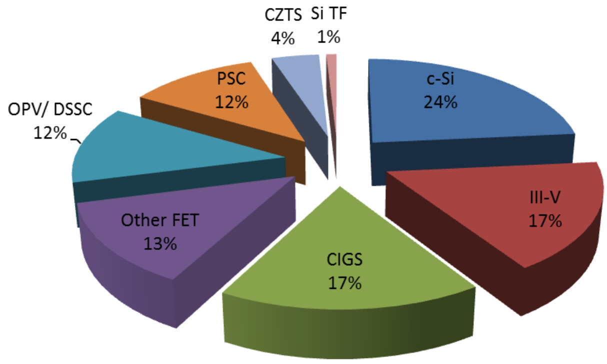
Programme	EC contribution	%	No. Projects	Average per project
Research and Innovation Actions	50 009 287	36	13	3 846 868
European Research Council	28 817 654	21	18	1 600 981
Integrated Action	24 862 365	18	7	3 551 766
Marie Skłodowska-Curie Actions	13 000 351	9	28	464 298
Small Medium Enterprise	11 379 829	8	28	406 422
Cost Shared Action	9 086 988	7	5	1 817 398
EURAMET	2 000 000	1	1	2 000 000
Total	139 156 473			

[35] http://www.etip-pv.eu/homepage.html
[36] https://www.eera-set.eu/eera-joint-programmes-jps/photovoltaic-solar-energy/

Figure 16 Technology and application breakdown by EC funding for PV-related projects, H2020, 2014-2017



a) Application areas (flat plate is sub-divided into c-Si, thin-film and tandem)



b) PV materials breakdown

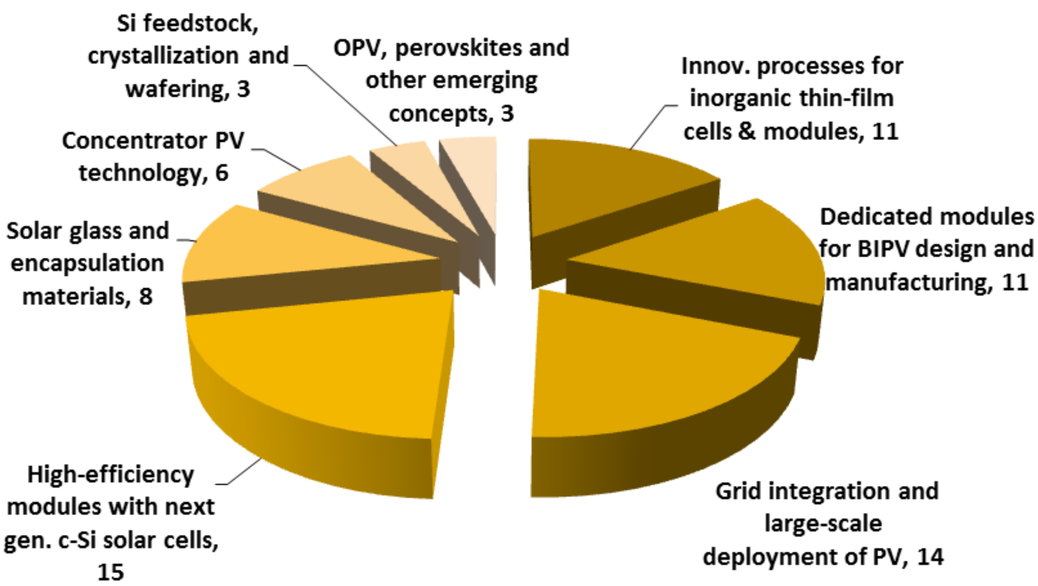
3.2.3 SOLAR- ERA.NET

SOLAR-ERA.NET is a network of more than 20 European RTD and innovation programmes in the field of solar electricity technologies [26] and itself receives funding from the EU framework programmes for coordination. It contributed to implementing the SET-Plan and aims to:

- initiate / support innovative, industry-led projects;
- improve cooperation between national RDI programmes;
- strengthen Europe‘s position in the solar sector.

Under the FP7 SOLAR-ERA.NET funded a total of 39 PV projects were funded. They represent a project volume of MEUR 50 of which over half comes from public funding. Figure 17 shows the breakdown of the thematic areas addressed. Compared to the directly-funded EU programmes, there is more emphasis on applied research and demonstration, and less on low TRL research. The consortium has produced a useful collation of the project description and budgets, but as yet no systematic information on the results and impact.

Figure 17 Distribution of projects funded by SOLAR-ERANER under the first call [26].



3.2.4 European Cooperation in Science and Technology (COST)

COST Actions are bottom-up science and technology networks with duration of four years. There is no funding for research itself. Four current projects involve PV technology or are relevant to PV applications:

- CA16235 | Performance and Reliability of Photovoltaic Systems: Evaluations of Large-Scale Monitoring Data (PEARLPV) 05 October 2017 - 04 October 2021
- MP1406 | Multiscale in modelling and validation for solar photovoltaics (MultiscaleSolar) | 07 May 2015 - 06 May 2019
- TU1401 | Renewable energy and landscape quality (RELY) | 16 October 2014 - 15 October 2018
- MP1402 | Hooking together European research in atomic layer deposition (HERALD) | 04 December 2014 - 04 December 2018

3.2.5 EIT Innoenergy

InnoEnergy was established in 2010 and is supported by the European Institute of Innovation and Technology (EIT) as one of a series Knowledge and Innovation Communities (KICs). The InnoEnergy network includes 24 shareholders, as well as more than 360+ associate and project partners. It invests in businesses and helps develop innovative products, services, and solutions. According to the information on its web site, it has invested in at least 6 PV-related projects (see Appendix 1), although little information is provided on the project results. The most recent notable investment was EUR 2 million in 2017 in Nexwafe (a Fraunhofer ISE spin-off), for its kerfless wafer technology.

3.2.6 InnovFin

The European Investment Bank set up the InnovFin (EU Finance for innovators) financing tools to cover a wide range of loans, guarantees and equity-type funding, which can be tailored to innovators' needs. Two specific investments in PV technology have been identified:

- In 2016 the European Investment Bank provided EUR 20 million of quasi-equity under the InnovFin Mid Cap Growth Finance program to Heliatek (based in Germany) to help boost production capacity of its HeliaFilm product. HeliaFilm is an organic photovoltaic solar film for integration into building facades
- In 2017 the (EIB) awarded EUR 15 million to Oxford PV Germany GmbH under the InnovFin Energy Demonstration Projects scheme to support the transfer of its disruptive perovskite on silicon tandem solar cell technology from lab scale to commercialisation.

3.2.7 NER-300

NER 300 is a demonstration programme for CCS and RES projects involving all Member States. The programme aimed to support a wide range of CCS technologies and RES technologies (bioenergy, concentrated solar power, photovoltaics, geothermal, wind, ocean, hydropower, and smart grids). For the period 2021-2030 the Commission has proposed a new programme called the ETS Innovation Fund.

The only PV project selected so far is the Santa Luzia Solar Farm, located near Lagos, Portugal. The nominal capacity is 20 MWe and the technology is concentrator photovoltaics with Magsun TRK-60 modules (23 % nominal efficiency at 800 suns). Maximum NER 300 funding is EUR 8 million. The final investment decision is estimated for June 2018 with entry into operation in July 2019.

3.3 Other R&D Programmes

3.3.1 EU Member States

The 2017 SET-Plan PV Implementation Plan outlines the main member state activities in each of the priority areas [25].

3.3.2 IEA Photovoltaic Power Systems Programme

The IEA Photovoltaic Power Systems Programme (PVPS) involves Australia, Austria, Belgium, Canada, China, Denmark, European Union, Finland, France, Germany, International Copper Association, Israel, Italy, Japan, Korea, Malaysia, Mexico, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Thailand, Turkey and the United States. Its mission is "*To enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems*". The PVPS tasks don't involve research *per se*, but focus on bringing together and analysing information from the participants. There are 8 ongoing tasks:
Task 1: Strategic PV Analysis & Outreach;
Task 9: Deploying PV Services in emerging and developing countries;
Task 12: PV Sustainability;
Task 13: Performance and Reliability of Photovoltaic Systems;
Task 14: High Penetration of PV Systems in Electricity Grids;
Task 15: Enabling Framework for the Development of BIPV;
Task 16: Solar Resource;
Task 17: PV for Transport.

3.3.3 USA

Sunshot is an initiative run by the US Department of Energy Solar Energy Technologies Office (SETO) with the overall goal of making solar energy (PV and solar thermal) affordable for all Americans. The 2020 cost targets for utility scale PV (USD 0.06/kWh) have already been achieved and focus has shifted to the 2030 goal of USD 0.03/kWh, as well as USD 0.04/kWh and 0.05/kWh for commercial and residential systems respectively. These targets can be met with different mixes of technology, cost and performance.

The solar subprograms include:

- Photovoltaics;
- Concentrating Solar Power;
- Systems Integration;
- Soft Costs;
- Technology to Market;
- National Laboratory Research.

Table 9 shows the scope of the current photovoltaics sub-programmes, which include substantial investment in research at the national laboratories and the National Center for Photovoltaics at the National Renewable Energy Laboratory.

Table 9 US Department of Energy research programmes for PV

Programme	Year Announced	Amount Awarded USD million	Objective
Photovoltaic Research and Development 2: Modules and Systems (PVRD2)	2017	20	•Small exploratory projects •Significant improvements in the performance, energy yield, manufacturability, and reliability of completed PV modules as well as the development of advanced methods for module characterization and analysis •Hardware and software solutions to facilitate the rapid, safe, and cost-effective deployment and commissioning of PV systems
Photovoltaic Research and Development (PVRD)	2016	17	Improvements to nearly every aspect of cell design from grain boundary recombination and module design from layout geometry to choice of encapsulant can help to lower the cost of solar energy.
Photovoltaic Research and Development: Small Innovative Projects in Solar (PVRD-SIPS)	2016	2	Understanding of the optical, thermal, and electrical concerns associated with the performance of completed modules
Physics of Reliability: Evaluating Design Insights for Component Technologies in Solar 2 (PREDICTS 2)	2015	7	provide access to improved predictive models, accelerated testing techniques, and more reliable products that will ultimately lead to reduced risk in long-term PV performance
SunShot National Laboratory Multiyear Partnership (SuNLaMP)	2015	110	advance PV cell and module technology as well as prediction of PV module and system performance.
Next Generation Photovoltaics 3	2014	14	10 projects, funding of the order EUR 1 million each: 5 on perovskites, 3 on III-V materials, 1 on OPV and 1 on DSSC

3.3.4 China

3.3.4.1 Top Runner Programme[37]

China's National Energy Administration (NEA) launched the "Technology Top Runner Program" in 2015 to prompt using high-efficiency PV products and to accelerate PV industry transformation. Initially Top Runner projects were required to use mono-si PV modules with efficiency higher than 17 % or multi-si modules with efficiency higher than 16.5 %. The overall scale of support is for installations amounting to several GW annually.

Figure 18 shows a breakdown of technologies of winner bids in the 2017 phase. Notable points include: over 50 % bifacial products; over 80 % PERC /PERT; 19% n-Si. The latest phase is for 1.5 GW of solar capacity to be grid connected by June 2019 and is reserved next-generation technology that has yet to enter mass production.

[37] Based on EnergyTrend (Taiwan) press releases

Figure 18 Breakdown of technologies of winner bids in the Chinese 2017 Top Runner Programme (in total 5 GW). Source: EnergyTrend, Taiwan.

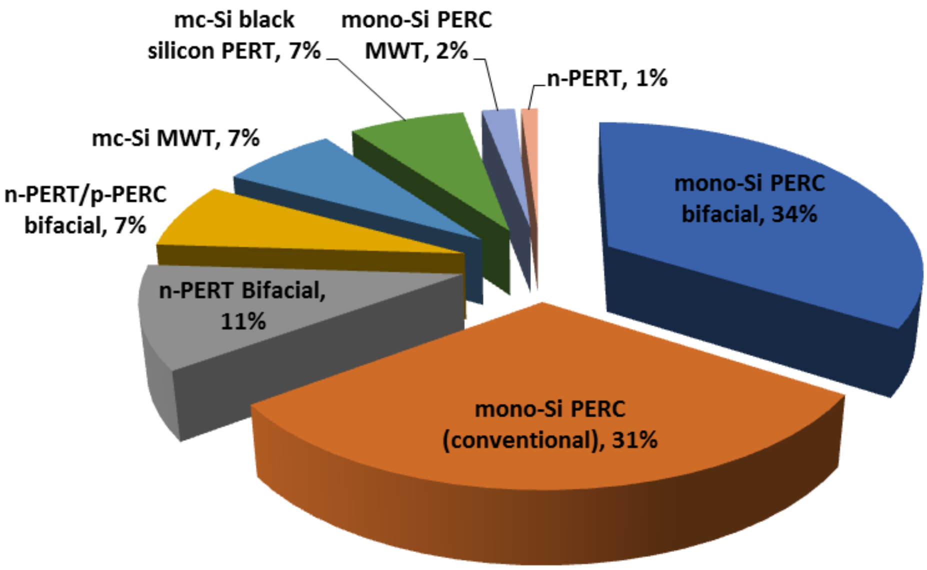


Table 10: Chinese results for maximum efficiency (%) of thin-film solar cells and modules 2012-2016.

Year	Si-based		CIGS		CdTe		GaAs	
	Cell	Module	Cell	Module	Cell	Module	Cell	Module
2012	12.06					8.94		
2013	15.06	9.59						31
2014	16.07							
2015			20		16.28	13.1	34.5	
2016			20.33	12.6	17.33			32

3.3.4.2 PV Technology R&D[38]

- Crystalline silicon cell efficiency

China’s research level for crystalline silicon solar cell can be described as "leading" and "catching up" at the same time. Top class is the lab research for polycrystalline solar cells. Trina Solar's PV Science and Technology State Key Laboratory realised a world record of 21.25 % efficiency polycrystalline solar cell, while Jinko Solar Co., Ltd announced 21.63 % efficiency for the same product. For monocrystalline solar cells, Trina joined efforts with the Australia State University to develop a small size (2 cm^2) IBC cell with lab efficiency of 24.4 %. The efficiency of large size 156 mm x 156 mm monocrystalline solar cell independently developed by Trina Solar reached 23.5 %, the highest efficiency for large size IBC cells. In addition, the Shanghai Institute of Microsystem and Information Technology under Chinese Academy of Sciences achieved their highest efficiency of large size HJT cell (156 mm x 156 mm) with 23.3 %.

- Thin-film research: Since 2011, efficiency of various types of thin-film solar cell has improved steadily (Table 10).

- New type and concentrator cell efficiency: Solar cell efficiency for perovskites is over 22 %. The highest efficiency for dye-sensitized solar cells certified by a third party is 11.9 %, with 14 % reported in a paper. Polymer solar cell efficiencies remains at a lower level, and improvement on efficiency and stability is the problem to be solved in the future.

[38] Based on and adapted from IEA PVPS National Progress Report 2017

3.3.5 Japan PV Technology R&D

R&D activities are divided between the New Energy and Industrial Technology Development Organization (NEDO), which promotes technology development towards commercialization, funded by METI, and the Japan Science and Technology Agency (JST), which promotes fundamental R&D, funded by the Ministry of Education, Culture, Sports, Science and Technology (MEXT).

NEDO has been promoting PV technology development consistently over the last 35 years. It manages a large portfolio of R&D projects. Its PV Development Strategy (NEDO PV Challenges) was announced in September 2014 with a headline cost target of JPY 7/kWh (approximately EUR 0.06/kWh). It identified measures to achieve target power generation costs as well as the development of recycling technologies. This cost target has now become part of the "Energy/Environment Innovation Strategy" launched by Japan's Cabinet Office in March 2016.

The National Institute of Advanced Industrial Science and Technology (AIST), one of the largest public research organizations in Japan, includes substantial activities on photovoltaics [27]:

AIST Renewable Energy Research Center (Fukushima)

- Crystalline Si, energy rating;
- Energy network.

AIST Research Center for Photovoltaics (Tsukuba and Kyushu)

- Improvement in cell and module performance: CIGS, CZTS, thin-film Si, organic TFs, DSSC, perovskites.
- Innovative solar cells: multijunction, quantum-dot, plasmonics, etc.,
- Module reliability and robust modules
- Calibration, measurement, PV system safety, maintenance, and diagnosis

NEDO manages two demonstrative research projects and three technology development projects based on the NEDO PV Challenges, a guidance for technology development in which a target to realize the power generation cost of JPY 14/kWh by 2020 and JPY 7/kWh by 2030 is set. Three technology development projects are currently running:

- Development of Solar Power Recycling Technology (FY 2014 to FY 2018)
- Technological development for improvement of system performance and operation and maintenance (O&M) (FY 2014 to FY 2018) and
- Development of high performance and reliable PV modules to reduce levelised cost of energy (FY 2015 to FY 2019). This budget line includes 19 projects under four main headings:
    i. "Development of crystal silicon PV modules using advanced multiple technologies and high performance CIS modules",
    ii. "Research and development of innovative new structure solar cells",
    iii. "Development of common components for solar cells and modules" and
    iv. "Development of Common Fundamental Technologies". Under the technology development, development of high efficiency solar cell technology and development of fundamental technologies for commercialization using pilot mass production line are carried out on various types of solar cells such as crystalline silicon solar cells, II-VI compound solar cells and organic solar cells.

In addition a "R&D project for international joint development of innovative technologies" is jointly conducted with G7 countries since 2015 and research themes on new structure solar cells were adopted in 2016.

R&D activities administered by MEXT by the Japan Science and Technology Agency (JST):

- Photoenergy Conversion Systems and Materials for the Next Generation Solar Cells and
- Creative Research for Clean Energy Generation using Solar Energy

Under the project of "Technological development for improvement of system performance and operation and maintenance (O&M) (FY 2014 to FY 2018)", development and demonstration are conducted on technologies to increase power generation amount by improving functions of BOS, technologies to reduce BOS cost including installation cost. In 2016, under this project, NEDO started demonstrations on structure of PV systems and ensuring electrical safety. In order to ensure safety against disaster risks, development of design method and technology, demonstration test and research of facilities are conducted. Based on the knowledge acquired through demonstration test, NEDO aimed to formulate a guideline for designing safer and more economical ground-mounted PV systems by February 2019.

4 ASSESSMETN OF R&D PROJECTS WITH EU CO-FUNDING

Table 11 gives an overview of major[39] EU-supported projects in Horizon 2020 oriented to PV technology development. It includes a summary for the main technology goals stated in the description of work, together with a note on main achievements based in the project available at the time of writing (end 2018). An estimate of initial and final (or target) TRL is given as one measure of the impact of the work.

a) Wafer-based crystalline silicon

Three major projects are being supported:

- NextBase: Next-generation interdigitated back-contacted silicon heterojunction solar cells and modules by design and process innovations
- DISC: Double side contacted cells with innovative carrier-selective contacts
- AMPERE: Automated photovoltaic cell and Module industrial Production to regain and secure European Renewable Energy market

Both NextBase and DISC address TRL levels 3/4/5, aiming to developed innovative very high efficiency cells but also with manufacturing processes with potential to be commercially exploited. Ampere has larger ambitions, namely to bring to production the heterojunction technology developed over the last ten years in EU labs. The EU supported this process in FP7, in particular with the HETSI, 20Plus and Hercules projects.

STILORMADE is a running SME project addressing commercialisation of an existing quarter-wafer cell concept called iCell.

b) Thin-films

CIGS is being addressed in the Sharc25 project (super high efficiency CU(In, Ge)Se2 thin-film solar cells approaching 25 % efficiency). ARCGIS-M addresses high efficiency CIGS with high manufacturability and runs to November 2019.

The SWInG project targets kesterites. The information available suggests that the chosen technology route (Ge-based kesterite) has not up to now brought a breakthrough in terms of efficiency (target is 15 %). Another EU-supported project (also with international partners) called Starcell started in 2017 with an 18 % target by 2019.

In the area of perovskites CHEOPS looks at single junction devices and tandems with silicon wafers. The ESPResSo project has specific durability objectives for the cell and modules devices being developed.

Tandem Concepts

For silicon with III-V material top cells, two projects are running, both targeting a TRL level of 4: Nanotandem on cells with GaS nanowires and SiTaSol looking at two different deposition/fabrication processes. The SME project NanoSol addresses commercialisation of an existing prototype called SolFilm using Aerotaxy Naowires on silicon.

The CHEOPS project is also addressing perovskite on silicon tandems. The partners include Europe's foremost groups working in this area (Oxford PV, EPFL, CHOSE etc.).

d) BIPV

This area is being supported through several projects with a range of techno-economic objectives. PV-SITES encompasses a number of facilitation activities (design tools, energy forecasting tools) as well as development and demonstration of products at several sites. Two SME projects target specific products. In Advanced- BIPV the company Onyx successfully developed two building façade products (Onyx is also a partner in PV-SITES). SoTile is a 2nd phase project to develop a moulded tile and validate it on 18 roofs.

[39] Here the term "major" refers to projects with over EUR 500 000 EU contribution.

e) CPV

Despite the difficulties in achieving competitive cost levels for concentrating PV technology, several projects are active. The largest, CPVMatch, set ambitious goals (world record efficiency and a scalable fabrication process). There are also several SME projects working on combined CPV – heating/cooling concepts. CogemCPVT aims to take prototype concept closer to production. SOcool also takes an existing prototype (SunOyster) for development in three niche product packages (electricity generation and thermal chillers). REPHLECT targets an HCPV concept with a pilot line in Spain and a clone on Morocco.

f) Recycling

The CABRIS project aimed to improve high value material retrieval rates and re-manufacturing from recycled materials. ELSi is working on the realisation of a pilot plant (TRL 8/9).

It is noted that these projects are relevant to the on-going CEN mandate M/543: standardisation request to the European standardisation organisations as regards Ecodesign requirements on material efficiency aspects for energy-related products. Both can provide relevant to the needed PV product specific standards, for instance durability, disassembly and remanufacturing of PV systems.

Table 11 Major EU-funded projects under Horizon 2020 (status in December 2018)

Acronym	Title	Start/ End Date	Main Technology & Cost Objectives in DoW	TRL start	TRL (*target)*	EC funding €
SWInG	Development of thin-film solar cells based on wide band gap kesterite absorbers	01/06/2015 31/05/2018	- Wide band gap thin-films solar cells with 15 % efficiency on a laboratory scale and 12 % for a mini-module prototype. - Specifications for the synthesis of high quality Cu_2ZnXY_4 absorber as well as suitable back/front contacts .	3	3	3 254 755
CPVMatch	Concentrating photovoltaic modules using advanced technologies and cells for highest efficiencies	01/05/2015 23/10/2018	CPV solar cells and modules working at a concentration ≥ x800 and with efficiency of 48 % and 40 %, respectively (current 4-J cell record is 46 % @ 508 suns)	3-4	4?	4 949 596
Sharc25	Super high efficiency Cu(In,Ga)Se2 thin-film solar cells approaching 25 %	01/05/2015 31/10/2018	Objective: conversion efficiency CIGS towards 25 %, create a small area CIGS solar cell with an efficiency > 24 % and a monolithically interconnected sub-module with an efficiency > 20 %.	3-4	*3-4*	4 563 123
Nano-Tandem	Nanowire based Tandem Solar Cells	01/05/2015 30/04/2019	- Demonstrate a tandem solar cell composed of a top pn-junction formed in III-V nanowires and series connected to a bottom pn-junction in silicon, with > 25 % efficiency - Scale-up: develop technologies for arrays > 10 cm²	3	*4?*	3 561 842
CHEOPS	Production technology to achieve low Cost and Highly Efficient phOtovoltaic Perovskite Solar cells	01/02/2016 31/01/2019	- Scale up to single junction modules manufactured in a pre-production environment while maintaining >14 % stable efficiency, area >15x15 cm². - Demonstrate low cost potential (<0.3€/Wp) - Develop PK-HJS tandems cells (>29 % efficiency on 2x2 cm², at low cost (target <0.4€/Wp)	PK cell: 4 Tandem: 3	5 4	3 299 095
ADVANCED-BIPV	New generation of BIPV-glass with advanced integration properties	01/04/2015 31/03/2017	- Develop a new family of products (Novel XL-BIPV glazing units, with high-mechanical resistance and high performing vision glazing, based on PV thin-film transparent panes (transparency over 50 %). - estimated selling price of175-200€/m²	7	8	1 887 121
Cogem CPVTM	COGEM CPV - An innovative Ceramic Heat Spreader within HCPV	01/06/2015 28/02/2019 (extended)	Develop the original HS prototype with new materials including in order to reduce energy production costs of about 25 %, and an improvement on the performance at least of 3 %. - >40 year lifetime	5?	*(7)*	2 098 456

Acronym	Title	Start/ End Date	Main Technology & Cost Objectives in DoW	TRL start	TRL (*target)*	EC funding €
PVSITES	Building-integrated photovoltaic technologies and systems for large-scale market deployment	01/06/2016 30/06/2019	- Drive BIPV technology to a large market deployment by demonstrating an ambitious portfolio of building-integrated solar technologies and systems - High impact demonstration and dissemination actions will be accomplished in terms of cost-effective renewable generation, reduction of energy demands and smart energy management.	5	*(6/7)*	5 467 612
SolTile	A roof integrated solar tile system to develop cost-effective distributed solar power generation (Phase 2 project)	01/10/2016 30/09/2018	- In Phase 1 Soltiles developed a moulded tile (patented) that can incorporate c-Si and TF technologies - Phase 2 aim is to re-engineer the tiles for increased efficiency; optimise the manufacturing processes; establish compliance with regulations; install and test 18 roofs for system validation.	6	*(9)*	1 542 733
SiTaSol	Application relevant validation of c-Si based tandem solar cell processes with 30 % efficiency target	01/05/2017 31/10/2020	- Increase efficiencies of c-Si solar cells to 30 % by combining it with III-V top absorbers. - Prototype module with efficiency > 24 %. - Additional costs for the 2-5 µm Ga(In)AsP epitaxy and processing below 1 €/wafer (for module costs <0.5 €/Wp). - Demonstrate devices in a industrial relevant environment.	3	4	4 298 201
NextBase	Next-generation interdigitated back-contacted silicon heterojunction solar cells and modules by design and process innovations	01/10/2016 30/09/2019	- IBC-SHJ cells with efficiency above 26.0 % and corresponding solar modules with efficiency above 22.0 %. - Development of a new industrial manufacturing tool and low-cost processes for a competitive IBC-SHJ solar module cost of < 0.35 €/Wp.	3/4	4/5	3 800 421
DISC	Double side contacted cells with innovative carrier-selective contacts	01/10/2016 30/09/2019	- Target efficiencies >25.5 % on large area cell and >22 % at module level - Demonstrating pilot manufacturing readiness at competitive costs. - Reduce non-abundant material consumption (Ag, In), with an enhancement of the energy yield, with modern module design ensuring outstanding durability	3/4	to 5/6	4 743 519
AMPERE	Automated photovoltaic cell and Module industrial Production to regain and secure European Renewable Energy market	01/05/2017 30/04/2020	Setting-up of a 100 MW full-scale automated pilot line in production environment at the 3Sun fab (Catania) based on silicon heterojunction technology (HJT) developed within preceding European projects (CEA-INES & MBS platforms) .	5-6	7-8	14 952 065

Acronym	Title	Start/ End Date	Main Technology & Cost Objectives in DoW	TRL start	TRL (*target)*	EC funding €
iDistributedPV	Solar PV on the Distribution Grid: Smart Integrated Solutions of Distributed Generation based on Solar PV, Energy Storage Devices and Active Demand Management	01/09/2017 28/02/2020	- Develop affordable integrated solutions to enhance the penetration of distributed solar PV (buildings) based on the effective integration of solar PV equipment, energy storage, monitoring and controlling strategies and procedures, active demand management, smart technologies and the integration of procedures in the power distribution system according to market criteria. - 5 demo sites (ES, DE, PL, LI, EE)			2 706 940
EU HEROES	EU routes for High pEnentration of solaR PV into lOcal nEtworkS	01/09/2017 30/08/2020	- To identify at least 7 existing community energy projects that illustrate current theory and best practice on grid connection of solar PV in the context of social enterprise business models - To support and analyse the implementation of at least 7 pilot projects informed by the business models developed for the project and working in partnership with electricity network operators.	N/A	N/A	1 230 558
SOcool	SunOyster cooling (SOcool)	01/09/2017 31/08/2019	- Develop three product packages (SOcool) consisting of the SunOyster and selected thermal chillers to create standardized packages for the supply of electricity, cold and heat for commercial and residential buildings - Build up a pilot productionn and start commercializing	7	(8)	1 398 478
CABRIS	Implementation of a CirculAr economy Based on Recycled, reused and recovered Indium, Silicon and Silver materials for photovoltaic and other application	01/06/2015 30/05/2018	- Retrieving up to 90 % of the high value raw materials: silicon, indium and silver. · Manufacturing of PV from the recycled materials achieving lower cost (25 % less) and at least the same cells efficiency as conventional processes.		*(≥6)*	7,844,565
STARCELL	Advanced strategies for substitution of critical raw materials in photovoltaics	01-01-2017 31-12-2019	- device efficiency up to 18 % at cell level and targeting 16 % efficiency at mini-module level, - demonstrate CRM free thin-film PV devices with manufacturing costs ≤ 0.30 €/Wp	3?	*(5)*	4,832,189
Eco-Solar	Eco-Solar Factory - 40 % plus eco-efficiency gains in the photovoltaic value chain with minimised resource and energy consumption by closed loop systems	01-10-2015 31-09-2018	PV modules with optimised recovery, reuse and resource efficient production methods. Demonstrator modules specs: • industrial size (60cells) • less than 2 % degradation in IEC 61215 • 260 Wp for mc-Sis and 285 Wp for sc-Si • monitoring system for identifying faulty panels and repairing/replacing • cost-competitive aiming for 5-8 ct/kWh	4	*(5/6)*	5,642,708

Acronym	Title	Start/ End Date	Main Technology & Cost Objectives in DoW	TRL start	TRL (*target*)	EC funding €
REPHLECT	Recovering Europe´s PHotovoltaics LEadership through high Concentration Technology	01/08/2015 30-04-2018	- Develop new "near –market" manufacturing lines for HCPV receivers and an assembly line for HCPV modules - Demonstrate migration of manufacturing line to a pilot satellite production centre - Product quality certification N.B. Basis is BSQ' 820X HCPV technology and the new generation 1000X prototype	6	*(8)*	1,633,601
NanoSol	Accelerating Commercialization of Nanowire Solar Cell Technologies	01-02-2016 31-07-2018	- integrate nanowire III-V films with Si devices - increase efficiency from 16 % to 27 % on tandems - prepare for large-scale industrialization N.B. Basis is Sol Voltaics (SE) SolFilm product to transfer and correctly orient GaAS nanowires	6	*(8)*	1,740,375
ELSi	Industrial scale recovery and reuse of all materials from end of life silicon-based photovoltaic modules	01-05-2016 30-04-2018	To recover >95 % of end of life silicon-based PV modules; materials recovered to be of value and ready for reuse. - Recover materials from 100 metric tonnes of PV-waste - validate the ELSi process economic viability with a representative full scale unit having an annual throughput of 968 metric tonnes of disused PV modules, equivalent to 44,000 modules per year.	6/7	*(8/9)*	2 529 607
ARCIGS-M	Advanced aRchitectures for ultra-thin high-efficiency CIGS solar cells with high Manufacturability	01-12-2016 30-11-2019	Develop the CIGS technology towards higher efficiency (up to 23 % for solar cells and up to 18 % for solar cell modules), by using novel approaches in passivation, patterning and optical design	4	*(6)*	4 498 700
STILORMADE	Highly efficient non-standard solar modules manufactured through an automated, reconfigurable mass production processes delivering 30 % reduction in costs	01-01-2017 31-12-2018	- Module eff. >19.5 % (>21.5 % for PERC) - pilot production line of 15MW (for BIPV and solar street lighting markets), then scale up to 60MW, and then 200MW - BIPV: >18 % efficiency, tailored design, cost <€4/W (prod. & instal.), lifetime >25 years - Street Lights: >18 % efficiency, cost <€2000 / light unit, >12-hour operation at average light intensity of 100W, lifetime of >25 years	6/7	*(9)*	2 940 596
SUNINBOX	Portable SolUtioN for dIstributed geNeration in a BOX (Phase 2 project)	01-02-2017 31-01-2019	- market readiness of product ("plug & play" 12 kW system solar with a tracker), transported and stored in a standard container) - objective price of 4.25 €/W for a 12kW system, for electricity <0.35 €/kWh)	6	(9)	1 407 542
SOLARSHARC *(originally EVERCLEAN but changed for copyright*	SOLARSHARC - a durable self-clean coating for solar panels to improve PV energy generation efficiency	01-05-2017 30-04-2019	Product is a patented coating technology that uses silica nano-particles bonded in a polymer matrix to give a robust self-cleaning coating:	6	*(9)*	2 267 636

Acronym	**Title**	**Start/ End Date**	**Main Technology & Cost Objectives in DoW**	**TRL start**	**TRL (*target)***	**EC funding €**
reasons)			- 25 year lifetime without recoating - repellent to water, dust, and bio-fouling - Cost <€10 per m2 - High transparency and anti-reflective properties			
ESPResSo	Efficient Structures and Processes for Reliable Perovskite Solar Modules	01-05-2018 30-04-2020	- cell efficiency > 24 % (on $1 cm^2$) and < 10 % degradation following IEC thermal stress cycle - modules ($35 \times 35 cm^2$) with > 17 % efficiency and long-term (>20 years) reliable performance - façade elements demonstrating a LCoE of ≤ 0.05€/kWh in southern Europe.		*(5)*	5 412 657

5 TECHNOLOGY DEVELOPMENT OUTLOOK

5.1 Cost Trends

The cost of PV electricity from a system depends on several elements (as for instance in levelised cost of electricity calculations), but here the focus is on the investment needed for a PV system (Figure 19) and for the module, as the main energy conversion component. Indeed this is also the most significant component, accounting for up to half the total capital investment needed for utility scale systems (although less for residential systems where economies of scale for installation are less and soft costs are higher).

a) Modules

Module costs have decreased dramatically over the last 20 years, with a learning rate of 24 % (the decrease in price for every doubling of total installed capacity). Table 12 shows the June 2016 wholesale spot prices for several technologies. These confirm a sharp decrease in prices over the period 2016-2017 (Figure 20). According to ITRPV analysis, this is driven largely by increased manufacturing efficiency, with improvement in energy conversion efficiency playing a lesser role. It should also be noted that many commercial products are priced higher than these spot levels on a €/watt peak basis, but are competitive by offering features such as higher efficiency (therefore less area and lower balance of system costs), bifaciality (potential for higher overall power output depending on the reflected light at the rear side of the module), better actual energy yield for the conditions at a specific location, improved reliability and degradation resistance, lower CO_2 footprint etc..

Table 12 Wholesale spot prices for PV modules, without taxes

Technology	Average €	High €	Low €
Poly Silicon Solar Module	**0.25**	0.36	0.23
Poly High Eff / PERC Module	**0.29**	0.39	0.26
Mono High Eff / PERC Module	**0.32**	0.48	0.28
Thin-film Solar Module	**0.27**	0.37	0.24

(source: PVInsights web site 6/6/2018, exchange rate $/€ = 1.15)

Figure 19 PV system cost breakdown for a utility-scale system (source: JRC elaboration of ITRPV 2017 data)

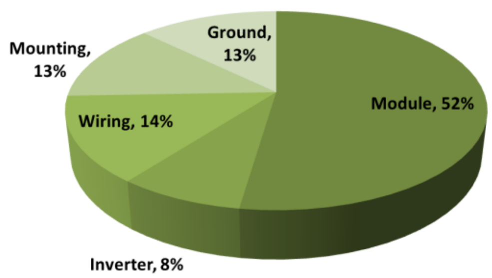
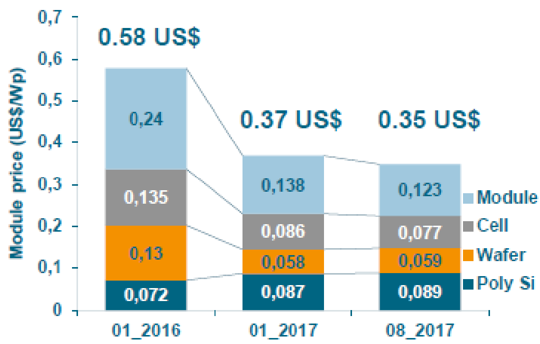


Figure 20 Trends in PV module spot prices for 2016/2017, also showing the component breakdown (source ITRPV 2017).



Concerning future module price trends, Figure 21 shows the historical data up to 2017 as a function of global cumulative installed capacity[40]. The decrease rate (learning curve) over the previous ten years has been steeper than the historical rate, adding further uncertainty to future projections. Nonetheless, based on the capacity estimates from the IEA 2017 sustainable development scenario, the price range for 2030 would be 0.19 to 0.24 EUR/W and by 2040 would have fallen further to 0.09 to 0.19 EUR/W (corresponding to cumulative installed capacities of 1 846 GW and 3 246 GW respectively). Whether the technology is still crystalline silicon or thin-film or a combination of both is another matter.

b) BIPV

Cost information on building integrated PV products is less commonly reported. SUPSI perform an annual survey in Europe [28] and Figure 22 shows the range of prices obtained (100 to 400 EUR/m^2) for various applications.

Figure 21 PV module cost reduction trends curve based on data for commercially available modules of all technologies (source: JRC analysis of data from Fraunhofer PV Report and own sources)

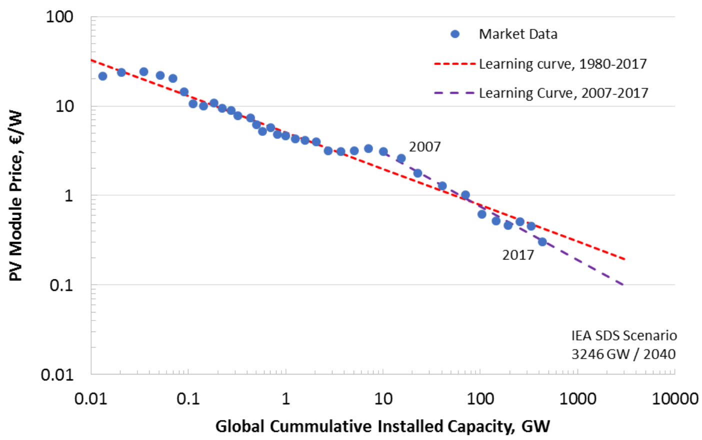
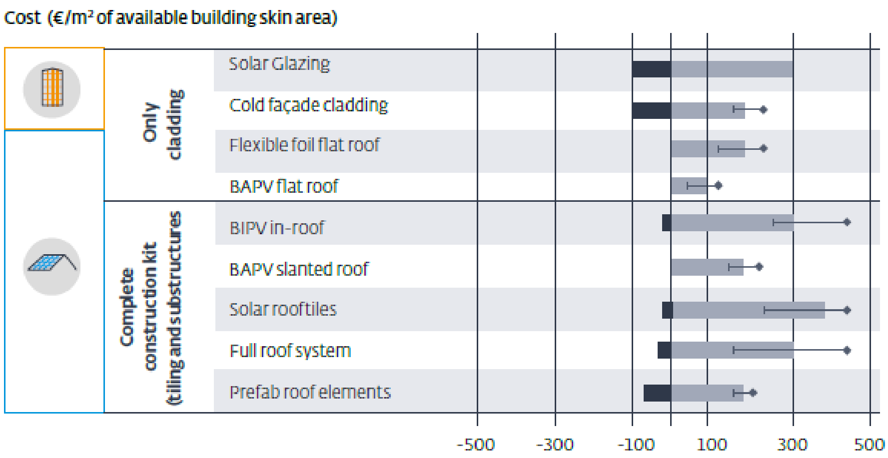


Figure 22 BIPV costs according to the 2017 SUPSI survey: *"The black bars represent the share of the costs that is avoided because no conventional building material has to be used. The grey bars represent the true additional costs that contractors need to spend in order to apply a PV functionality in their building skin. The total cost results from the sum of both. The error bars show the full range (min-max) of all the different quotes we received"*



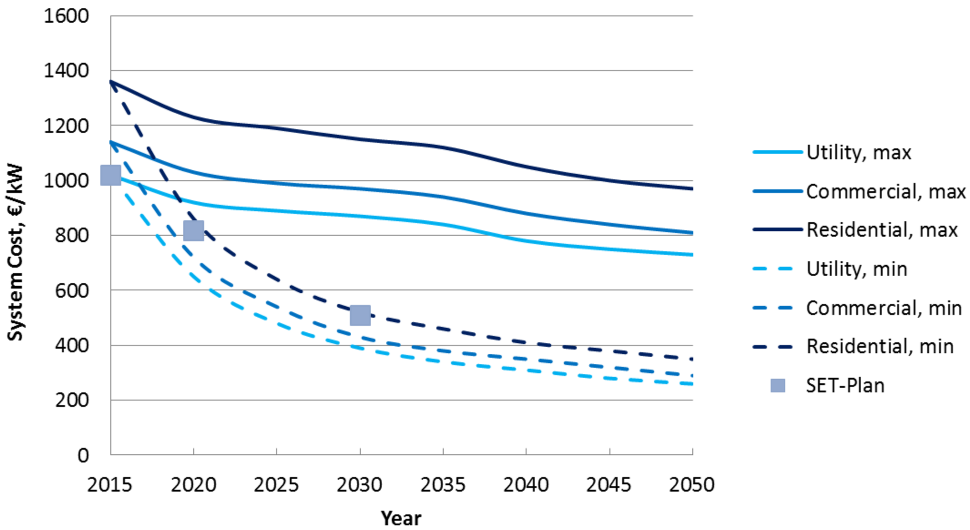
[40] This combines data for all commercially available modules, the recent spot price levels are set by crystalline silicon products, and effectively these values set the benchmark for the market, independent of whether the technology is wafer-based, thin-film or concentrating. Learning curve analysis for just thin-film products show a comparable reduction rate and price levels, an achievement since the production volumes are more than an order of magnitude lower.

c) PV Systems

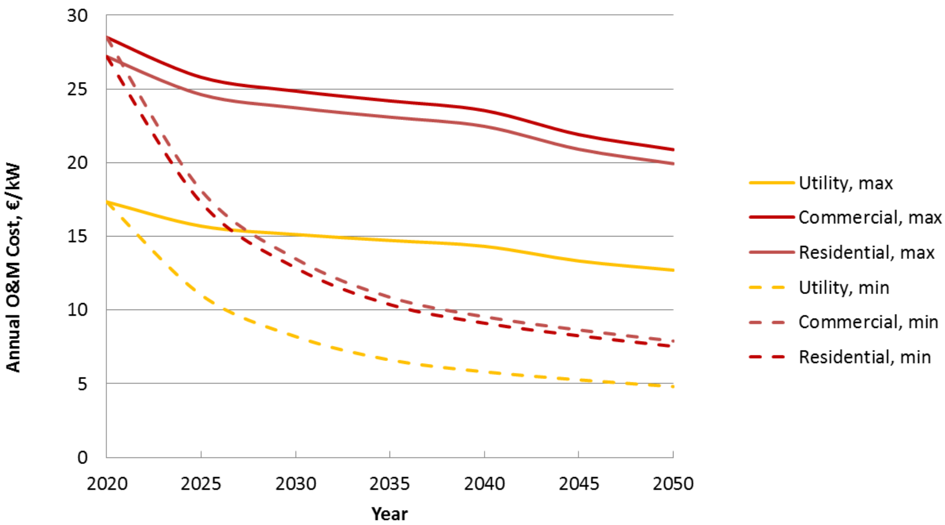
In January 2018 the price range for commercial systems was 0.61 to 1.26 EUR/Wp [3]. The world-wide average system price for residential systems with installation, but without permitting or connection costs, was reported as EUR 1.22/Wp, ranging from EUR 1.05/Wp in Europe up to EUR 1.38/Wp in the US.

In the framework of the JRC-EU-TIMES modelling work, long-term trends for the costs of utility-scale, commercial and residential rooftop systems prices have been examined. Figure 23 shows projections of CAPEX and OPEX for three deployment categories: utility, commercial and residential[41]. In this analysis a learning curve approach was used, whereby the variation in costs is linked to the extent of deployment observed. This has been done for several scenarios and the results are shown as maximum and minimum values that evolved in the course of the simulations. Also included is the trend in system cost reduction foreseen in the SET-Plan targets, which broadly corresponds to the highest learning rate (lowest cost trend) emerging form the model scenarios.

Figure 23 Range of PV system and operating costs in the JRC-EU-TIMES models a) CAPEX and b) OPEX



(a)



(b)

[41] For OPEX costs, the initial 2020 residential value is slightly below that for a commercial system. This may reflect that the latter category spend less on programmed O&M.

5.2 Future Deployment Scenarios

The JRC-EU-TIMES model [29] offers a tool for assessing the possible impact of technology and cost developments. It represents the energy system of the EU28 plus Switzerland, Iceland and Norway, with each country constituting one region of the model. It simulates a series of 9 consecutive time periods from 2005 to 2060, with results reported for 2020, 2030, 2040 and 2050. The model was run with three baseline scenarios:

Baseline: Continuation of current trends; no ambitious carbon policy outside of Europe; only 48 % CO_2 reduction by 2050

Diversified: Usage of all known supply, efficiency and mitigation options (including CCS and new nuclear plants); 2050 CO_2 reduction target is achieved

ProRES: 80 % CO_2 reduction by 2050; no new nuclear; no CCS

In addition, a further 13 sensitivity scenarios were run. LCEO deliverable report D4.7 [30] presents the scenarios and the overall results. This technology development report focusses on the 3 baseline scenarios and the associated sensitivity runs for the high and low learning rates, considering the EU as a whole. Further analysis including country breakdowns will be included in the technology market report.

For PV the specific inputs include: a) CAPEX and fixed operating and maintenance (FOM) cost trends, together with learning rate values for three PV deployment options: utility scale, commercial (rooftop) scale and residential scale (see section 5.1 above); b) Load factor: country-specific values are included for the solar resource in terms of full load hours per year, as well as an upper bound on installed capacity.

Figure 24 gives an overview of the results for the three main scenarios. A notable feature is the large increased in electricity production in the Pro-RES scenario (Res1), reflecting a deep electrification of transport and the use of electricity to produce hydrogen, synfuels and other previously petrochemical-based products. Solar (essentially PV) plays a significant role in all scenarios, and particularly in ProRes.

Figure 25 shows this in more detail by extracting the installed capacity values for PV and plotting these as a function of time period. The installed capacity by 2050 in ProRes is almost 2 TW, and a factor of more than 4 above that in the diversified scenario. In terms of the type of PV deployment, Figure 26 shows a breakdown for the diversified and pro-res scenarios. This follows the costs: the cheapest form (utility scale PV) dominates, with a smaller role for commercial scale installations. In the current model configuration the more expensive residential scale PV is not used. In this respect, it would be useful if the model could include a means of accounting for the prosumer investment perspective, where the energy produced can be sold or used directly, thus avoiding the costs of buying it.

In relation to the sensitivity to the assumed learning rate for cost decrease, Figure 26 shows the impact of the high and low learning rate values on the level of PV deployment for the 2050 time period. It should be noted that for these sensitivity cases the model applies the modified learning rates across all technologies, not just for PV. For the diversified scenario, the high learning rate case produces a modest 8 % increase in PV capacity for 2050 and the low value a 33 % decrease. The situation for Pro-Res scenario is more complex: counter-intuitively, the high learning rate results in 33 % decrease in PV capacity in 2050 compared to the main scenario. This occurs because other technologies (in particular wind) become even more competitive with the high learning and take a larger share of overall production.

Figure 24 JRC-EU-TIMES model: distribution of power generation (TWh) by technology for the baseline, diversified (Div1) and pro-renewables (Res1) scenarios. Solar is represented by the yellow segments; PV accounts for the vast majority of this and CSP for the remainder.

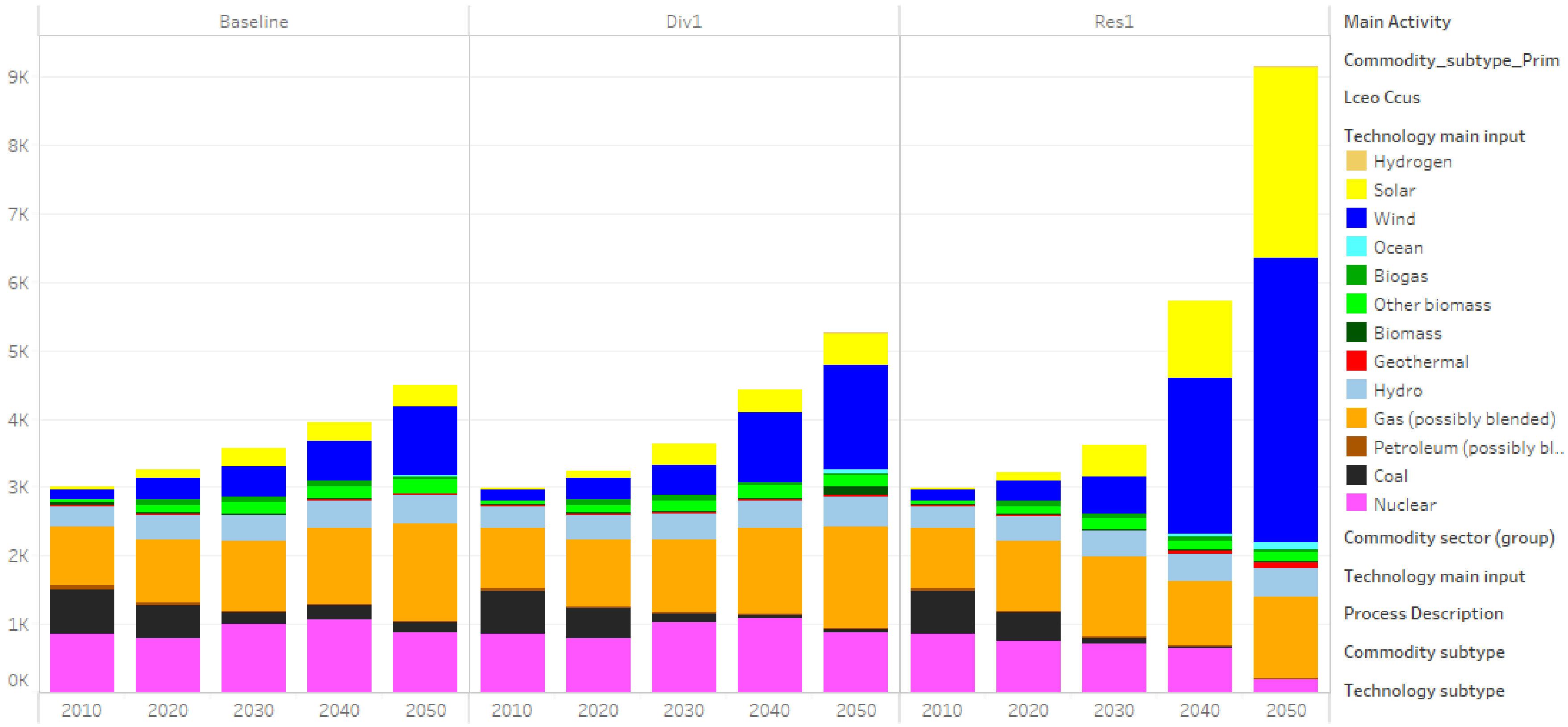


Figure 25 Growth of PV capacity over time in the baseline, diversified and Pro-Res scenarios.

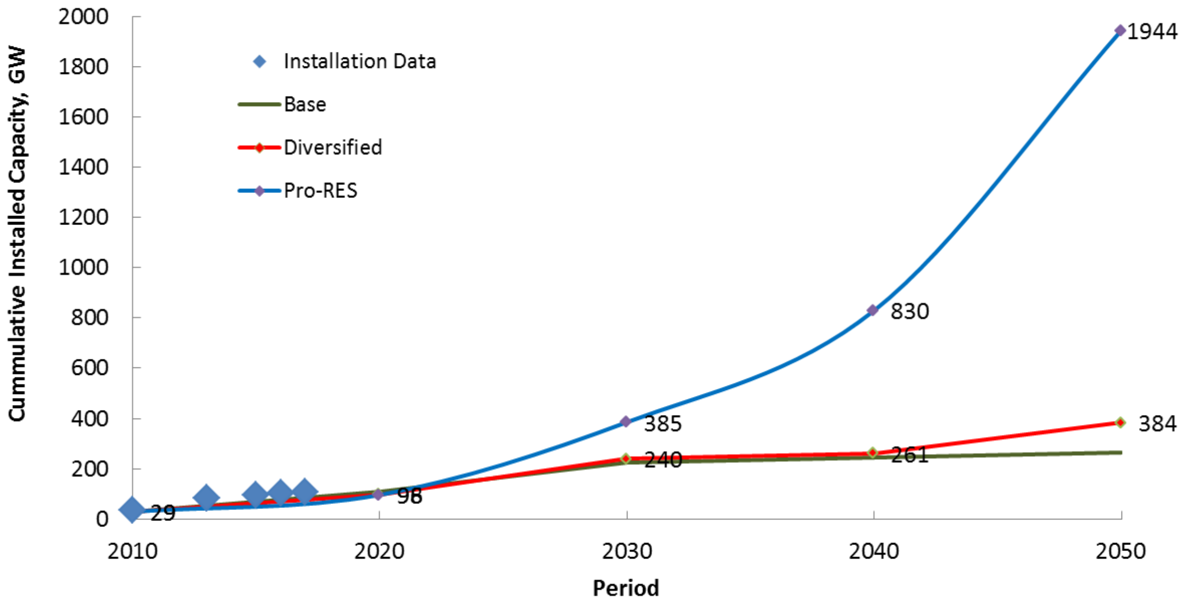
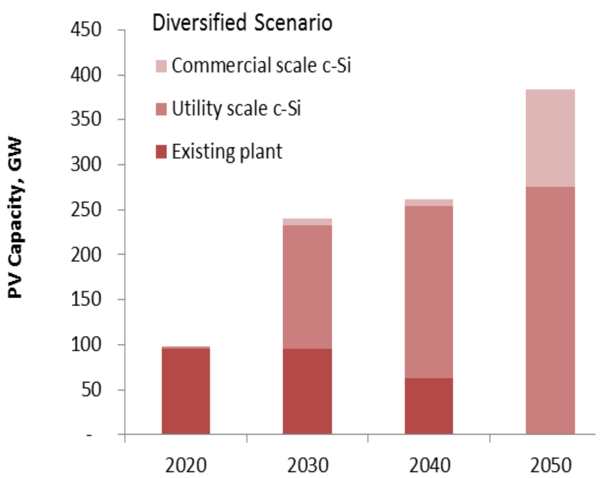
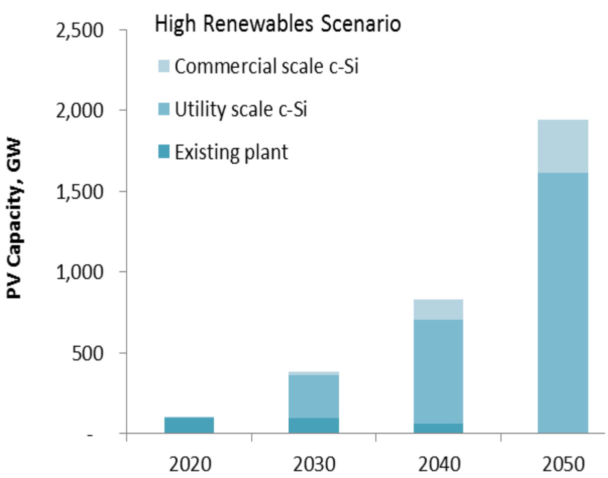


Figure 26 Breakdown of the PV deployment categories for the a) diversified and b) pro-renewables scenarios.

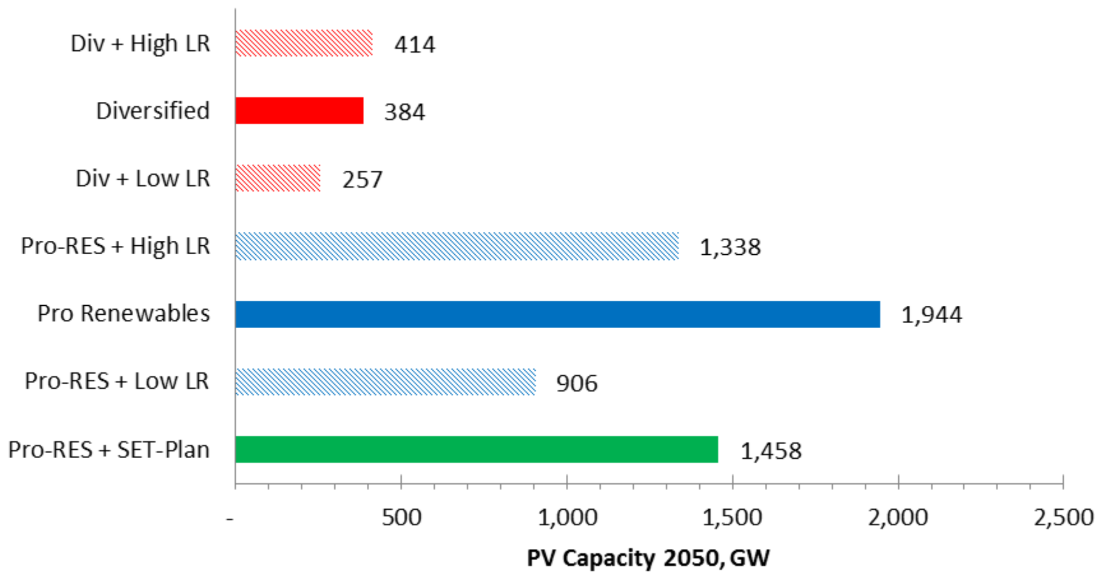


a)



b)

Figure 27 Effect of varying the PV system cost learning rate on PV capacity for 2050



5.3 Challenges

The 2017 SET-Plan Implementation Plan for PV gives a comprehensive picture of the technical challenges for PV technology development (see Text Box 1). The following points are intended as supplementary to these.

a) For the mass- production market, price per W of cells and modules appears set to decrease strongly; indeed the sector needs this to be truly competitive in the electricity market. This trend will further reinforce the fact that "size matters" in manufacturing. Indeed PV modules are seen as amenable to mass production, given the relatively low number of components and no moving parts. Also increasing levels of automation may help to minimise the role of labour costs in production.

b) EU industrial policy: the recent call[42] by German institutes and industry for a more proactive industrial strategy on PV manufacturing is the latest in series of such initiatives. The 2017 RTD study report "Assessment of Photovoltaics (PV)" 2016/17, identifies three pillars that can form a basis for such a strategy to rebuild the EU's PV manufacturing sector, as shown in Figure 28. This distinguishes a mass market and a tailored market. For equipment manufacturing and for inverters, the focus is on nurturing remaining strengths for the mass market, while also aiming to lead in tailored products. For PV products themselves, for the mass market the focus is on next generation technology, while also aiming to lead on tailored products.

c) Manufacturers are increasingly using long-term degradation rates as a marketing tool, and R&D roadmaps target module "lifetime" values of 30 years and more. However as yet there are no standard tests to substantiate such claims in reliable and transparent way. This is an issue of key importance to investors, as it impacts directly on the expected financial returns. Efforts at EU level and in international cooperative efforts such as PV-QAT should be reinforced to find robust and transparent procedures for addressing this issue, as well as for rapidly resolving unforeseen degradation issues that may arise in danced technologies (as has been done recently for PID and LeTiD phenomena).

d) The scale-factor can be also important for demonstrating advanced technologies and establishing market credibility. The contrast is stark between the Chinese Top Runner Programme that encompasses several GW of installations and programmes in EU and the USA at multi-MW level.

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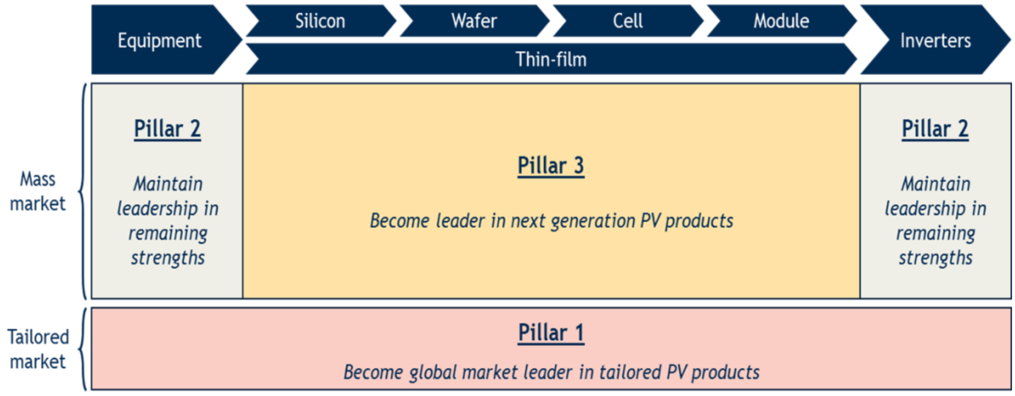
[42] Fraunhofer ISE Presseinformation #14 Solarindustrie will deutschen Neustart – Nachhaltigkeitskriterien für PV-Ausschreibungen gefordert, 25.5.2018

e) Standards: the on-going Ecodesign preparatory study has identified several topics that lack European or international standards:

- Ex-ante calculation of energy yield of PV systems;
- Durability of modules;
- Durability of PV inverters;
- Dismantlability[43] of PV modules;
- Disassemblability[44] of PV systems;
- Remanufacturing[45] of PV systems.

The PV community will need to find appropriate solutions to these in a relatively short-time frame.

Figure 28 Basis for a strategy to rebuild the EU's PV manufacturing sector (source: Study Report "Assessment of Photovoltaics", Contract PP-02161-2014)



[43] Dismantle: process whereby parts and/or materials are separated by mechanical, chemical, metallurgical or thermal means, inter alia such that the item cannot subsequently be reassembled to make it operational.
[44] Disassemble: non-destructive taking apart of an assembled product into constituent components, which can be re-assembled
[45] Re-manufacture: production process that creates products using parts taken from previously used products.

Text Box 1: SET-Plan PV Implementation Plan Priorities 2017

1. PV for BIPV and similar applications

The R&I activity on BIPV aims at developing a market pull approach for innovative and integrated PV solutions that will allow a faster market uptake of new PV technologies and a more intensive and multi-functional use of the available surface area in Europe, including quality and reliability. This requires a multidisciplinary approach and close collaboration between the PV/BIPV and building sectors.

On the one hand, for BIPV it seems likely that thin-film technologies (especially CIGS) are well suited. Therefore, a combined development of thin-film PV and BIPV is suggested. On the other hand, BIPV solutions based on other PV technologies can also offer attractive solutions. Sub-activities cover bifacial applications and PV installations on roads & waterways.

2. Technologies for silicon solar cells and modules with higher quality

Wafer-based silicon (c-Si) technologies have the largest market share (>90 %) in the worldwide solar PV sector. The main objective of this Activity is to develop and implement advanced c-Si PV technologies for high-quality, high-performance cells (≥24 %) and modules in high-throughput industrial manufacturing processes, including (for the PV sector) new materials and production equipment. These products will serve as differentiator for the European PV industry by means of significant efficiency benefits and better performance related to sustainability aspects and recyclability of modules (PV Ecolabel, Ecodesign and Energy labels). Through this, the European PV industry will be able to strengthen its global position.

3. New technologies & materials

Crystalline silicon based solar cells as well as some thin-film technologies are gradually reaching their theoretical efficiency limit. The most promising approach (at least on the short and medium term) to go beyond this limit are tandem technologies. Concrete options are III/V-semiconductor or perovskite top cells on silicon bottom cells. Another option is a stack of two thin-film cells. A third route is the development of cost-effective concentrating PV (CPV).

The aim of this activity is to bring these technologies to an economically feasible level. …

…… Therefore the cell processing needs to be scaled-up on an industrial level and the cost needs to be reduced. New materials and the combination of two cell technologies need new interlayer development. Also the stability needs to be enhanced (or maintained if already sufficient). In the end the environmental impact of these new materials needs to be evaluated including quality and reliability.

4. Development of PV power plants and diagnostics

The aim of this activity is to develop and demonstrate business models and streamline the processes for effective operation and maintenance of residential and small commercial plants in order to keep the plant performance and availability high over the expected lifetime. Especially advanced monitoring is essential. Due to incompatibility and the accompanying extra costs this is often not done according to good industry practices.

Aspects of energy system integration are included, but as an integral part of the PV system.

5. Manufacturing technologies (for c-Si and thin-film)

Further reduction of system and generation costs (LCoE) for silicon wafer based PV and thin-film technologies is strongly supported by the implementation of high-throughput, high yield industrial manufacturing technology. This includes production equipment (Capital Expenditure; CAPEX) and material (Bill of Materials; BOM) costs as well as product quality (efficiency and performance). Advances in this field will strengthen the European manufacturing industry. The introduction of new materials and cell/module designs enforces advances in the field of manufacturing technologies, including the introduction of Industry4.0 ("smart factory") in PV, and will also strengthen the European manufacturing equipment industry.

6. Cross-sectoral research at lower TRL

With respect to high level R&D, European research labs are still the leading institutions worldwide. A closer cooperation of these labs could help maintaining this position in order to support European industry with cutting edge research results.

On a topical level this activity covers all the other activities described above, with a focus on the low TRL-parts of the total R&I programs

6 CONCLUSIONS

R&D Resources and Programmes

Europe retains a strong basis in research and innovation on PV technologies, but also faces strong and increasing competition at global level. EU authors are involved in approximately 25 % of the annual output of scientific articles. However while EU scientific output almost doubled from 2010 to 2014, it plateaued in the period 2015-2016. In terms of patents, in 2014 the EU accounted for 22% of so-called "high-value" patent family applications, although in terms of absolute numbers Asian countries (specifically China, Japan and Korea) lead the way. For the EU, areas of relative strength include patenting on power conversion and BIPV.

With photovoltaics now recognised as becoming a major energy source by mid-century, Europe can continue to develop and exploit these research resources and remain a global leader (but not the only one) in the field. Indeed the SET-Plan PV implementation plan offers a coordinated approach, which could be further expanded to embrace storage, digitalisation and market aspects.

The EU is currently supporting a broad range of projects relating to PV under H2020. Many of these projects are running or have only recently finished, so insufficient information is available at this point to assess the overall impact in terms of technology readiness level. However the following general observations are made:

- There appears to be scope for improved communication and coordination between the research and innovation actions and the programmes for SMEs. Examples noted here include the work on concentrating PV and on tandem concepts.
- In striving for higher TRLs, the issue of scale becomes a critical factor to achieving cost competiveness. This applies not just to the bulk market for free-standing or roof-applied systems, but also to building integrated products. It is not clear if some of the EU-supported projects targeting high TRLs have sufficient resources to address this, particularly those requiring further technical development as well as pilot manufacturing. Development of GW-scale demonstration programmes could be beneficial in adding market-pull stimulus for advanced concepts.
- PV, like all renewables, inherently supports EU policy for long-term decarbonisation. However more focus could be given to specific aspects such as circular economy aspects and socio-economic effects. In this respect, more awareness of the "policy readiness level" of results could be useful. Pre-normative work on standards needs to arrive at codes and procedures, in addition to providing supporting evidence. Socio-economic studies relating to cost-effectiveness can best target the issues likely to be addressed in policy impact assessments, for instance regarding the cost-benefit of different routes for large-scale PV integration at utility scale and on the distribution network.

Technology Outlook

Wafer-based silicon technology is set to remain the predominant PV technology in the least in the medium term. Chinese manufacturers already have module production costs as low as EUR 0.30/W (and current wholesale spot prices even lower). This is accompanied by a major shift in production to PERC and bifacial PERC cell architectures, bringing efficiency gains with relatively low cost changes to the production process. Further cost savings should come from cheaper polysilicon via fluidised bed processes and smaller kerf losses. Reduction of wafer thickness to save material costs is also an option, but thicknesses of below 80 µm (compared to the current industry standard of 180 µm) pose challenges for automated handling in production. Some additional cost reduction potential is envisaged for the non-silicon cost components. Intensive R&D is in progress in Asia, Europe and the US, targeting not just efficiency and cost reduction but also improving sustainability aspects such as energy pay-back time. While p-type cells continue to be optimised, in the mid-term (2025+) analysts predict that n-type cells will become dominant. Already commercial available technology options include PERT architectures, passivated contacts, heterojunctions and interdigitated back-contact cells.

Looking further ahead, three basic options are available (and may also be combined):

- tandem devices to create a broader absorption window; here current research focus is on silicon + perovskite and silicon + III-V materials, but the TRL level is still modest (about 4 to 5);
- improved contacting, minimising reflection and improving light trapping;
- spectrum adjustment.

For thin-films, both copper indium gallium diselenide disulphide (CIGS) and cadmium telluride technologies have recently established cell efficiency records of 22 % or more. There is therefore an immediate technology challenge to transfer these gains to modules at competitive cost levels. On the other hand silicon-based thin-film technologies and kesterite face major challenges to increase efficiencies above 12 % and the market outlook is not encouraging. CPV technology continues to progress but faces a major challenge to become cost-competitive with other PV technologies quickly enough in order to reach substantial production volumes and the associated economies of scale.

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APPENDIX 1 – LISTING OF EU-SUPPORTED R&D PROJECTS RELATING TO PV

Table: H2020 PV Projects receiving EU funding (status end 2017)

Project Number	Project Acronym	Project Title	Call year	Free Keywords	Weighted EU contribution	Project Topic Code
637367	HyMoCo	Hybrid Node Modes for Highly Efficient Light Concentrators	2014	solar concentrators, waveguides, nanotransfer printing, silver island films, coalescence control, surface plasmon polaritons, hybrid modes	1 485 000	ERC-StG-2014
638133	ThforPV	New Thermodynamic for Frequency Conversion and Photovoltaics	2014	Optical frequency-conversion, Photovoltaics, thermodynamic of radiation	1 500 000	ERC-StG-2014
638857	CHROMTISOL	Towards New Generation of Solid-State Photovoltaic Cell: Harvesting Nanotubular Titania and Hybrid Chromophores	2014	nanotubes, solar cells, charge-carrier separation.	1 644 380	ERC-StG-2014
639760	PEDAL	Plasmonic Enhancement and Directionality of Emission for Advanced Luminescent Solar Devices	2014	Solar Energy Systems	1 447 410	ERC-StG-2014
640868	SWInG	Development of thin-film Solar cells based on WIde band Gap kesterite absorbers	2014	thin-film, photovoltaic, semiconductor, kesterite, CZTSSe, wide band gap, high efficiency, tandem	3 254 755	LCE-01-2014
640873	CPVMatch	Concentrating Photovoltaic modules using advanced technologies and cells for highest efficiencies	2014	Photovoltaics, high efficiency, III-V multi-junction solar cells, Concentrating Photovoltaics (CPV), CPV modules, spectrum matching, advanced materials, SiGeSn, wafer-bonding, light management	4 949 596	LCE-02-2014
641004	Sharc25	Super high efficiency Cu(In,Ga)Se2 thin-film solar cells approaching 25 %	2014	Cu(In,Ga)Se2, highly efficient, novel PV concepts, towards theoretical limits, thin-film solar cell	4 563 123	LCE-02-2014
641023	Nano-Tandem	Nanowire based Tandem Solar Cells	2014	photovoltaic, multi-junction solar cells, nano wires, nano technology, III-V-compounds	3 561 842	LCE-01-2014
641972	CABRISS	Implementation of a CircularAr economy Based on Recycled, reused and recovered Indium, Silicon and Silver materials for photovoltaic and other applications	2014	Photovoltaics, recycling, critical materials, silicon , silver, indium, feed-stock	7 844 565	WASTE-1-2014
646554	PV FINANCING	PV FINANCING	2014	Photovoltaic, PV, financing schemes, business models for PV	2 050 939	LCE-04-2014

Project Number	Project Acronym	Project Title	Call year	Free Keywords	Weighted EU contribution	Project Topic Code
647311	Sol-Pro	Solution Processed Next Generation Photovoltaics	2014	Printed Electronics, Flexible Photovoltaics, Solution Processed Opto-Electronic Materials, Research and Product Development, Organic Solar Cells, Electrodes, Processing, Devices	1 840 940	ERC-CoG-2014
651970	POLYSOLAR	A light weight, recyclable, tracking support system, for solar photovoltaic modules based on inflatable polymer membranes	2014	Solar, photovoltaic, PV, support system, polymer membrane, tracking, renewable energy, rooftop, building integrated	50 000	SIE-01-2014-1
652490	FLOTA	Floating Offshore Photovoltaic systems	2014	floating PV systems for marine aquaculture	50 000	BG-12-2014-1
653184	MPerS	Sustainable Mixed-ion Layered Perovskite Solar Cells	2014	Perovskite, Sustainble lowcost Solar cell,	195 455	MSCA-IF-2014-EF
653296	CHEOPS	Production technology to achieve low Cost and Highly Efficient phOtovoltaic Perovskite Solar cells	2015	Perovskite, thin-film, module, large area, high efficiency tandem solar cell	3 299 095	LCE-02-2015
655039	NANOSOLAR	HYBRID QUANTUM-DOT/TWO-DIMENSIONAL MATERIALS PHOTOVOLTAIC CELLS	2014	Photovoltaics, Solar Cells, Quantum Dots, Two-Dimensional materials, Graphene	158 122	MSCA-IF-2014-EF
655272	HISTORIC	High efficiency GaInP/GaAs Tandem wafer bonded solar cell on silicon	2014	Multijunction solar cells, III-V/Silicon, Wafer bonding	159 461	MSCA-IF-2014-EF
655852	Quokka Maturation	A mature Quokka for everyone – advancing the capabilities and accessibility of numerical solar cell simulations	2014		171 461	MSCA-IF-2014-EF
656658	NanoCuI	Nano-Copper Iodide: A New Material for High Performance P-Type Dye-Sensitized Solar Cells	2014	copper iodide, p-type dye sensitized solar cells, sensitizer dyes, electrochemistry	195 455	MSCA-IF-2014-EF
657115	c-SiOnGlass	Development of high-quality crystalline silicon layers on glass	2014	Solar cells, liquid-phase crystallization, silicon thin-film, photoluminescence, spectral response	171 461	MSCA-IF-2014-EF
659225	Crystal Solar	Organic-Inorganic perovskite and organic semiconductor films with improved crystal properties via reel-to-reel solution coating; application to photovoltaics and field effect transistors	2014	Photovoltaics, solution processed semiconductors, Organic-inorganic perovskites, crystal formation	251 858	MSCA-IF-2014-GF
659747	HCAPT	High Current All Printed Transistors	2014	printed electronics roll-to-roll transistors organics oxides metal-organics standalone devices optics nanostructures energy power heat current crystallinity sustainability morphology flexo electricity	84 878	MSCA-IF-2014-EF

Project Number	Project Acronym	Project Title	Call year	Free Keywords	Weighted EU contribution	Project Topic Code
661480	PlasmaPerovSol	A full plasma and vacuum integrated process for the synthesis of high efficiency planar and 1D conformal perovskite solar cells	2014	Perovskite, solar cell, photovoltaic, plasma, vacuum, nanomaterials, Carbon Nanotubes, Graphene	158 122	MSCA-IF-2014-EF
662792	Suninbox	Portable SolUtioN for dIstributed geNeration in a BOX	2014	Distributed generation, off-grid energy, solar tracking, photovoltaics	50 000	SIE-01-2014-1
666507	ADVANCED-BIPV	NEW GENERATION OF BIPV-GLASS WITH ADVANCED INTEGRATION PROPERTIES	2014	BIPV, Sustainable, See-thru, Resistance, Dimensions, Sizes	1 887 121	SIE-01-2014
673874	SBskin	SBskin. Smart Building skin	2014	BIPV, Glassblock, Smart Building Envelope, Energy Efficiency, Photovoltaics, Innovative Products	50 000	SIE-01-2014-1
673917	MLSYSTEM	MLSYSTEM - heatable, integrated photovoltaics with insulated glass units	2014	photovoltaics, carbon dioxide emission, energy efficiency, BIPV	50 000	SIE-01-2014-1
674102	SOLARGE45	Towards a SOLAR enerGy Efficiency of 45 %	2014	solar energy high concentration photovoltaics efficiency module CPV system advanced optics manufacturing costs low carbon clean electricity industrialisation pilot plant utility	50 000	SIE-01-2014-1
674311	Cogem CPVTM	COGEM CPV - An innovative Ceramic Heatsprider within HCPV (High Concentration Photovoltaic) Technology	2014	HCPV, Concentration Photovoltaic, Ceramics, Energy, Heatsprider, Convex-Lens, Glass, Solar Technology	2 098 456	SIE-01-2014
674628	RAYGEN	A unique innovative utility scale solar energy technology that utilises a field of low cost heliostat collectors to concentrate sunlight onto an ultra-efficient multi-junction photovoltaic cell array	2014	Solar Energy, Concentrated Photovoltaics, Utility scale solar energy, Renewables, World record pv performance, capital expenditure, multi-junction solar, CPV.	50 000	SIE-01-2014-1
679692	Eco-Solar	Eco-Solar Factory - 40 %plus eco-efficiency gains in the photovoltaic value chain with minimised resource and energy consumption by closed loop systems	2015	PV, crystalline silicon technology, solar cells, repair, reuse, recycling, remanufacturing, module, disassembly, resource efficiency, aluminum, silver, silicon, LCA, LCC	5 642 708	FoF-13-2015
679789	CONTREX	Controlling Triplet Excitons in Organic Semiconductors	2015	Conjugated Polymers, Organic Solar Cells	1 499 223	ERC-StG-2015
681881	SEEWHI	Solar Energy Enabled for the World by High-resolution Imaging	2015	Solution-cast solar cells, ultrahigh resolution imaging, ultrafast imaging of charge currents, modelling of charge generation and transport	2 000 000	ERC-CoG-2015
683876	SoHo3X	Introducing a novel concept of solar photovoltaic module in the market	2015	hologram, CPV, TIR	50 000	SIE-01-2015-1

Project Number	Project Acronym	Project Title	Call year	Free Keywords	Weighted EU contribution	Project Topic Code
683928	REPHLECT	Recovering Europe´s PHotovoltaics LEadership through high Concentration Technology	2015	Photovoltaics, HCPV,	1 633 601	SIE-01-2015
684019	Soltile	A roof integrated solar tile system to develop cost-effective distributed solar power generation.	2015	Solar energy, distributed-power, photovoltaics, roof-integrated, renewables, cost-saving, zero-energy building	50 000	SIE-01-2015-1
684347	SUN4GREEN	MAXIMISING SUNLIGHT RESOURCES FOR COST, ENERGY AND YIELD EFFICIENT GREENHOUSES	2015	GREENHOUSE, PHOTOVOLTAIC, CROP YIELDS, DUAL HARVESTING	50 000	SIE-01-2015-1
684528	PVFINAL	Photo Voltaic Fully Integrated and Automated Line	2015	Solar energy, photo voltaic, renewable energy	50 000	SIE-01-2015-1
687008	GOTSolar	New technological advances for the third generation of Solar cells	2015	Solar cells, efficiency, stability.	2 993 404	FETOPEN-RIA-2014-2015
687336	SiLaSpaCe	Si based Layer Stacks for Rear-Side Passivation and Enhanced Reflection of GaInP/GaInAs/Ge Triple-Junction Space Solar Cells	2015	Additive Layer Manufacturing Techniques	997 466	COMPET-03-2015
687409	EASY Pv	EGNSS high Accuracy SYstem improving PhotoVoltaic plants maintenance	2015	Photovoltaic maintenance, RPAS, EGNSS high accuracy, RTK, EDAS, computer vision	935 973	GALILEO-2-2015
691768	PVSITES	Building-integrated photovoltaic technologies and systems for large-scale market deployment	2015	Market, deployment, BIPV, system, demonstration.	5 467 612	LCE-03-2015
695116	AMETIST	Advanced III-V Materials and Processes Enabling Ultrahigh-efficiency (50 %) Photovoltaics	2015	Photovoltaics, High efficiency solar cells, III-V solar cells, dilute-nitride solar cells, multi-junction solar cells, Molecular Beam Epitaxy, CPV, satellite solar cells	2 492 719	ERC-ADG-2015
696519	NanoSol	Accelerating Commercialization of Nanowire Solar Cell Technologies	2015	nanowire, photovoltaic	1 740 375	SIE-01-2015
699935	Crystal Tandem Solar	Single-Crystal Perovskite Tandem Solar Cells For High Efficiency and Low Cost	2015	Solar Cells, Photovoltaics, Perovskites, Crystal Growth, Single Crystals, Shape Control, Epitaxial Growth, Tandem Solar Cells, Ultrafast Spectroscopy, Advanced Characterisation, Device Physics	269 858	MSCA-IF-2015-GF
701104	ELSi	Industrial scale recovery and reuse of all materials from end of life silicon-based photovoltaic modules	2015	Photovoltaic modules, recycling, end of life, separation, electrically driven processes, silicon, valuable metals, raw material recovery, aluminum, silver, gold, copper, waste	1 011 843	FTIPilot-1-2015

Project Number	Project Acronym	Project Title	Call year	Free Keywords	Weighted EU contribution	Project Topic Code
				management, logistics		
702629	R2R-3G	Towards Roll-to-Roll Production of Third Generation Solar Cells	2015	R2R, 3G, Solar cells, TCO, DMD, NWSC, GaAs, InP, light trapping, Monte Carlo, solar cells	187 420	MSCA-IF-2015-EF
705113	2for1-SingletFission	2 for 1: Quantum Dynamics of Singlet Fission	2015	singlet fission, ultrafast spectroscopy, photovoltaic solar cells	78 182	MSCA-IF-2015-EF
706094	TONSOPS	Titanium Oxide Nanocomposites for Scalable Optimized Perovskite Solar cells	2015	Solar cells, Perovskites, Nanocomposites, TiO_2 nanotubes, Thermoplastics	170 122	MSCA-IF-2015-EF
706552	APPEL	Approaching efficiency limits of perovskite solar cells by overcoming non-radiative recombination losses	2015	Photovoltaics, light-emitting diodes, electroluminescence	195 455	MSCA-IF-2015-EF
706744	COLIBRI	Carrier-selective contacts for silicon photovoltaics based on broadband-transparent oxides	2015	high efficiency photovoltaics, c-Si solar cells, carrier-selective contacts, tandem solar cells	175 420	MSCA-IF-2015-EF
707168	MatchForSola r	Mechanochemical Approach to Inorganic-Organic Hybrid Materials for Perovskite Solar Cells	2015	photovoltaic, mechanochemistry,	131 565	MSCA-IF-2015-EF
715027	Uniting PV	Applying silicon solar cell technology to revolutionize the design of thin-film solar cells and enhance their efficiency, cost and stability	2016	Photovoltaics, PV, Solar cells, Thin-film, $Cu(In,Ga)Se_2$, CIGSSe, CIGSe, CIGS, Silicon, Si, PERC	1 986 125	ERC-2016-STG
715354	p-TYPE	Transparent p-type semiconductors for efficient solar energy capture, conversion and storage.	2016	Dye-sensitized solar cells, renewable energy, artificial photosynthesis, solar fuel, electrochemistry	1 499 840	ERC-2016-STG
716792	SOFT-PHOTOCONVE RSION	Solar Energy Conversion without Solid State Architectures: Pushing the Boundaries of Photoconversion Efficiencies at Self-healing Photosensitiser Functionalised Soft Interfaces	2016	Soft interfaces	1 499 044	ERC-2016-STG
717956	HyTile	Sensitive integrated Solar Hybrid Roofing for historical buildings.	2015	photovoltaic, solar thermal, building integrated, energy production, solar power, hybrid, roof coverage, solar roof	50 000	SIE-01-2015-1
720887	ARCIGS-M	Advanced aRchitectures for ultra-thin high-efficiency CIGS solar cells with high Manufacturability	2016	CIGS, thin-film solar cell, ultra-thin, passivation,	4 498 701	NMBP-17-2016
720907	STARCELL	Advanced strategies for substitution of critical raw materials in photovoltaics	2016	kesterite, CZTS, solar cells, In, Ga, sustainable, thin-film PV	4 832 185	NMBP-03-2016

Project Number	Project Acronym	Project Title	Call year	Free Keywords	Weighted EU contribution	Project Topic Code
721452	SOLAR-TRAIN	Photovoltaic module life time forecast and evaluation	2016	Renewable energy, PV modules, PV systems, reliability, service life prediction, accelerated testing, yield prediction	3 576 248	MSCA-ITN-2016
722651	SEPOMO	Spins for Efficient Photovoltaic Devices based on Organic Molecules	2016	Organic electronics, organic solar cells, organic semiconductors, spin processes, charge transfer states, upconversion, donor-acceptor materials, photon harvesting, triplet-triplet annihiliation	3 826 024	MSCA-ITN-2016
724424	No-LIMIT	Boosting Photovoltaic Performance by the Synergistic Interaction of Halide Perovskites and Semiconductor Quantum Dots	2016	Photovoltaics	1 999 072	ERC-2016-COG
725165	HEINSOL	Hierarchically Engineered Inorganic Nanomaterials from the atomic to supra-nanocrystalline level as a novel platform for SOLution Processed SOLar cells	2016	Solar cells, colloidal nanocrystal, heterojunctions, physics of solar cells, solution-processed thin-films	2 486 865	ERC-2016-COG
726360	MOLEMAT	Molecularly Engineered Materials and process for Perovskite solar cell technology	2016	Photovoltaics, Perovskites, Electro-optical properties,	1 878 085	ERC-2016-COG
726703	SolTile	A roof integrated solar tile system to develop cost-effective distributed solar power generation	2016	Solar energy, distributed-power, photovoltaics, roof-integrated, renewables, cost-saving, zero-energy building	1 542 733	SMEInst-09-2016-2017
727272	ETIP PV - SEC	Support to all stakeholders from the Photovoltaic sector and related sectors to contribute to the SET-Plan	2016	Photovoltaics, SET-Plan, ETIP, Innovation	596 813	LCE-36-2016-2017
727497	SiTaSol	Application relevant validation of c-Si based tandem solar cell processes with 30 % efficiency target	2016	Photovoltaics, Si Tandem Solar Cells, HVPE, Semiconductor bonding, Next-generation Si cells	4 298 201	LCE-07-2016-2017
727523	NextBase	Next-generation interdigitated back-contacted silicon heterojunction solar cells and modules by design and process innovations	2016	c-Si photovoltaics	3 800 421	LCE-07-2016-2017
727529	DISC	Double side contacted cells with innovative carrier-selective contacts	2016	high efficient photovoltaic cells, carrier selective junctions, rooftop instalations, non-abundant material consumption, renewable energy production process	4 743 519	LCE-07-2016-2017
727722	PRINTSolar	Printable Perovskite Solar Cells with High Efficiency and Stable Performance	2016	Metal halide Perovskite Solar Cells, High Efficiency modules, Scaleup printable modules	150 000	ERC-PoC-2016

Project Number	Project Acronym	Project Title	Call year	Free Keywords	Weighted EU contribution	Project Topic Code
728378	RollArray	A disruptive mobile photovoltaic array that can pack up to 20kWp of generating power into a domestic trailer and 100kWp of generating power into an ISO 20-foot shipping container.	2016	Solar Power; Mobile Solar Power; PV; Photovoltaic; Emission Reduction; Renewable Energy; Green Energy; Efficiency; Remote Generation; Remote Power Supply; Off Grid Energy; Disaster Response;	50 000	SMEInst-09-2016-2017
728894	CDRONE	Towards un-subsidised solar power – Cleandrone, the inspection and cleaning solution	2016	UAV Drone solar cleaning automatic unmanned aerial vehicle	50 000	SMEInst-09-2016-2017
734948	e-SPACE monitoring	e-Solar Performance Analysis and data Collection for Energy Monitoring: an innovative solution based on measures correlation between an autonomous ground-based solar sensor and Earth observation data	2017	Solar power, PV, PV monitoring, geostationary satellites, Sentinel satellites, Copernicus programme, Service, Software as a Service, Cloud, energy grid, Operations & Maintenance, Earth Observation	50 000	SMEInst-04-2016-2017
736314	EBFZ	Float zone silicon from electron beam grown rods	2017	advanced technology, silicon, power microelectronics, photovoltaic, electron beam, float zone	20 000	SMEInst-01-2016-2017
736795	PAWAME	CONDUCTING A FEASIBILITY STUDY ON THE VIABILITY OF AN INNOVATIVE BUSINESS MODEL FOR BRINGING SOLAR ENERGY TO REMOTE COMMUNITIES AND DEVELOPING COUNTRIES	2017	Energy-as-a-Service, off-grid communities, renewable energy, solar energy, developing world, energy poverty	50 000	SMEInst-12-2016-2017
737447	PHYSIC	Photovoltaic with superior crack resistance	2016	Photovoltaics, cracks, durability, optimized residual stresses, innovative pre-stressing technique, increase lifetime and energy production	149 500	ERC-PoC-2016
737884	STILORMADE	Highly efficient non-standard solar modules manufactured through an automated, reconfigurable mass production processes delivering 30 % reduction in costs	2016	customised solar modules, solar street lighting, building integrated photovoltaics, market replication	2 836 035	FTIPilot-01-2016
738842	SUNINBOX	Portable SolUtioN for dIstributed geNeration in a BOX	2016	Distributed generation, Photovoltaic energy, portable solar solution, solar irrigation, plug and play system, lower cost of energy, off grid solution	1 407 543	SMEInst-09-2016-2017
743667	STORM	SMART PLANT MANAGER FOR UTILITY SCALE PHOTOVOLTAIC PLANTS WITH STORAGE SYSTEMS	2016	Solar PV, Storage, Grid Support, Grid Ancillary Services, Predictability, Interoperability, Clustering, Low carbon energy, Security of supply, Internet of electricity	50 000	SMEInst-09-2016-2017

Project Number	Project Acronym	Project Title	Call year	Free Keywords	Weighted EU contribution	Project Topic Code
746516	RECHARGE	Photon-recycling for high-efficiency energy harvesting in GaAs photovoltaic devices on silicon	2016	energy harvesting, wireless sensor, photovoltaics, GaAs, silicon	248 063	MSCA-IF-2016
746964	FERROVOLT	For a better understanding and design of ferroelectric photovoltaics: First-principles study of optical absorption and charge-carrier transport at ferroelectric domain walls in BiFeO3	2016	ferroelectrics, domain walls, perovskites, photovoltaics, electronic transport, first principles, density-functional theory, many-body perturbation theory	175 866	MSCA-IF-2016
747221	POSITS	High Performance Wide Bandgap and Stable Perovskite-on-Silicon Tandem Solar Cells	2016	solar cells, photovoltaics, perovskites, silicon, tandem, stability	175 420	MSCA-IF-2016
747422	FibrillarMICROSTRUCT	Controllable Growth and Charge Carrier Transport of Fibrillar Microstructure of Semiconducting Polymers in Field-Effect Transistors and Photovoltaics	2016	Polymer solar cell, polymer transistor, polymer fibril, charge transport	66 240	MSCA-IF-2016
747599	PerovSAMs	Molecular glues for perovskite materials	2016	perovskites, self-assembled monolayers, interfaces, optoelectronics, nanocrystals	170 122	MSCA-IF-2016
750600	NAROBAND	Environmental friendly narrow band-gap colloidal nanocrystals for optoelectronic devices	2016	colloidal quantum dots, solar cells, solution processed opto-electronics, thin-films	158 122	MSCA-IF-2016
751159	SRec BIPV	Smart Reconfigurable photovoltaic modules for Building Integrated PhotoVoltaic applications	2016	Photovoltaic energy, Power converters, Reconfigurable architectures, Maximum Power Point Tracking	172 800	MSCA-IF-2016
751375	TinPSC	Towards Stable and Highly Efficient Tin-based Perovskite Solar Cells	2016	Sn-based perovskites, Solar cells, Stable, High power conversion efficiency	185 857	MSCA-IF-2016
752117	PVMINDS	Bottom-up PV module energy yield and integrated reliability model for site-specific design optimization	2016	Photovoltaic Modules; Reliability Model; Failure Analysis; Energy Yield Simulation; Design-for-Reliability	172 800	MSCA-IF-2016
756962	HYPERION	HYbrid PERovskites for Next GeneratION Solar Cells and Lighting	2017	Photovoltaics, light-emitting diodes, metal halide perovskites	1 759 733	ERC-2017-STG
758885	4SUNS	4-Colours/2-Junctions of III-V semiconductors on Si to use in electronics devices and solar cells	2017	Highly mismatched alloy materials, diluted nitrogen, multiband solar cells, multijunction solar cells, silicon technology, solar energy	1 499 719	ERC-2017-STG
760311	EverClean	EVERCLEAN - A DURABLE SELF-CLEAN COATING FOR SOLAR PANELS TO IMPROVE PV ENERGY GENERATION EFFICIENCY	2016	Photovoltaic, buildings, solar energy, repellent coatings, self-cleaning, energy saving, PV, BIPV	2 267 636	FTIPilot-01-2016
764452	iDistributedPV	Solar PV on the Distribution Grid: Smart Integrated Solutions of Distributed Generation based on Solar	2017	Prosumers, distributed solar PV, energy storage devices, effective integration with the power	2 706 940	LCE-21-2017

Project Number	Project Acronym	Project Title	Call year	Free Keywords	Weighted EU contribution	Project Topic Code
		PV, Energy Storage Devices and Active Demand Management		system, development of effective solutions, active demand management, business and management models		
764786	PV-Prosumers4Grid	Development of innovative self-consumption and aggregation concepts for PV Prosumers to improve grid load and increase market value of PV	2017	Self-consumption, grid, regulation, support scheme, photovoltaic, solar	2 501 739	LCE-21-2017
764805	EU HEROES	EU routes for High pEnentration of solaR PV into lOcal nEtworkS	2017	Community solar, high penetration PV, grid integration, sustainable business models beyond net metering, new solar market segments	1 230 558	LCE-21-2017
773639	INNO PV-SWITCH	Innovative Fireman's Switch for Photovoltaic Systems: towards large-scale production	2017	photovoltaic systems, DC switching device, photovoltaic installations	50 000	SMEInst-02-2016-2017
774686	AlbaSolar	Developing perovskite-based solar panels	2016	Perovskite based composite, solar panels, photovoltaic	50 000	SMEInst-09-2016-2017
774717	PanePowerSW	Transparent Solar Panel Technology for Energy Autonomous Greenhouses and Glass Buildings	2016	PV panel glass, transparency; DSSC technology; Reliability; energy savings; renewable energy; low manufacturing cost; energy efficiency	50 000	SMEInst-09-2016-2017
774973	SENSEE	Replicating the SUN through affordable, efficient and accurate LEDs	2016	Solar simulation, LEDs, solar spectrum, solar testing	50 000	SMEInst-09-2016-2017
776362	RadHard	Ultra High Efficiency Radiation Hard Space Solar Cells on Large Area Substrates	2017	high efficiency radiation hard four junction solar cells, semiconductor bonding technology, BOL efficiency above 35 %, EOL efficiency above 31 %, ultra large (200 mm) Ge wafers	3 072 973	COMPET-1-2017
777968	INFINITE-CELL	International cooperation for the development of cost-efficient kesterite/c-Si thin-film next generation tandem solar cells	2017	kesterite; c-Si thin-film; tandem devices; cost-efficient solar cells	1 318 500	MSCA-RISE-2017
16ENG02	ENERATE	Advanced PV energy rating	2017		2 000 000	

Table: SOLAR-ERA.NET Projects, status March 2018

No	Acronym	Title	Topic	End	Budget
1	SLAGSTOCK	Low-Cost Sustainable Thermal Energy Storage Systems Made of Recycled Steel Industry Waste	CSP	30/04/2018	1 273 286
5	LIMES	Light Innovative Materials for Enhanced Solar Efficiency	Glass	31/03/2017	1 931 696
9	BLACK	Black Silicon and Defect Engineering for Highly Efficient Solar Cells and Modules	Si	30/09/2017	1 244 391
12	INTESEM	Intelligent Solar Energy Management Pipeline from Cell to Grid	System	31.12.2016	1 358 900
13	NOVACOST	Non Vacuum Based Strategies for Cost Efficient Low Weight Chalcogenide Photovoltaics	TF	30/09/2017	1 121 134
36	NovaZOlar	All-non-Vacuum Processed ZnO-based Buffer and Window Layers for CIGS Solar Cell Technology	TF	31/08/2016	1 589 688
37	HyLighT	Design, Development and Application of a Technologically Advanced System of Natural Daylight and Artificial PV Lighting - Hybrid Light Tube	BIPV	31/08/2016	239 149
39	InnoModu:	Leadfree Modules with Low Silver Content and Innovative Busless Cell Grid	Si	31/03/2016	809 345
47	AER II	Industrialization and System Integration of the Aesthetic Energy Roof Concept	BIPV	30/04/2016	587 241
49	SNOOPI	Smart Network Control with Coordinated PV Infeed	System	30/09/2018	1 029 883
71	PV4FACADES	Photovoltaics for High-Performance Building-Integrated Electricity Production Using High-Efficiency Back-Contact Silicon Modules	BIPV	31/08/2016	2 607 307
77	ACCESS-CIGS	Atmospheric Cost Competitive Elemental Sulpho-Selenisation for CIGS	TF	28/02/2018	1 946 839
78	PV me	Organic PhotoVoltaic Systems Integrated in Manufactured Building Elements	BIPV	30/06/2018	2 480 390
82	PV2GRID	A Next Generation Grid Side Converter with Advanced Control and Power Quality Capabilities	System	31/03/2018	199 056
84	THESEUS	Tandem High Efficiency Solar Cells Utilizing III-V Semiconductors on Silicon	Tandem	30/11/2017	672 000
90	U-light	Ultra Lightweight PV Modules and their Applications in Innovative PV Systems Achieving Lowest Levelized Cost of Electricity	BIPV		
92	HESiTSC	High efficiency silicon based tandem solar cell PV module	Tandem		
93	InGrid	High efficiency PV modules based on back-contact cells and novel interconnecting grid	Si		
95	Monoscribe	Roll-to-Roll Monolithic Interconnection of Customizable Thin-film Solar Modules	TF		
102	HighCast	High Performance Silicon Casting and Wafering	Si		
108	EDITOR	Evaluation of the Dispatchability of a Parabolic Trough Collector System with Concrete Storage	CSP		
112	APPI	Atmospheric Pressure Processing for Industrial Solar Cells	TF		

120	FunGlass	FunGlass – Multi-Functional Glass for PV Application	BIPV
123	SITEF	Silicon Fluid Test Facility	Si
128	PROOF	Competitive Industrialized Photovoltaic Roofing	BIPV
138	SolFieOpt	Optimal Heliostat Fields for Solar Tower Power Plants	CSP
142	SPRINTCELL	Sulfide-based Ink for Printable Earth-Abundant Solar Cell	TF
143	DINAMIC	Dilute Nitride Based Concentrator Multijunction Solar Cells, with Efficiencies Over 47 %	CPV
147	IPERMON	Innovative Performance Monitoring System for Improved Reliability and Optimized Levelized Cost of Electricity	System
150	HVolt-PV	High Voltage IBC Photovoltaic i-Cells and Modules	Si
152	Bifalo	Bifacial PV modules for lowest levelized cost of energy	Si
155	CNT-PV	Carbon nanotube hole-transporting and collecting layers for semi-transparent, flexible and low-cost solid-state photovoltaic cells	?
160	HIPPO	High-efficiency poly-Si passivated contact solar cells and modules	Si
419	Liquid Si 20	Liquid phase deposition of Functional Silicon Layers for Cost-Effective High Efficiency Solar Cells	Si
428	FrontCIGS	Re-designing front window in flexible CIGS modules for cost-effective moisture protection	TF
431	SIMON	Silicone Fluid Maintenance and Operation	?
436	DURACIS	Advanced global encapsulation solutions for long-term stability in industrial flexible Cu(In,Ga)Se2 photovoltaic technology	TF
438	Refined PV	Reduction of Losses by Ultra Fine Metallization and Interconnection of Photovoltaic Solar Cells	Si
441	ENHANCE	Enhanced rooftop PV integration through kinetic storage and wide area monitoring	BIPV
450	PEARL TF-PV	Performance and Electroluminescence Analysis on Reliability and Lifetime of Thin-Film Photovoltaics	TF

Table: PV-related project supported by KIC-Innoenergy (source: data from KIC-Innoenergy web site, April 2018)

Project	Scope	Consortium	Status
BIPV-Insight	integrated software tool for performance prediction of BIPV and BAPV products.	Tecnalia, Enerbim, TFM Energía Solar Fotovoltaica, Bear Holding, BV, Université Bordeaux 1, Comsa Corporación	Available as a product BIM-Solar from Enerbim (2016)
EFFIC	A back-end interconnection system for thin-films CIGS	Meyer Burger, Centre for Concept in Mechatronics (CCM), TNO, ECN, Avancis	No public info found
EnThiPV	Product that measures the permeability of high and ultra high barrier materials used for thin-film PV	CEA, Amcor, Disatech, Vinci Technologies, ESADE, IREC, UPC, Tecnalia, KIT	- Patent request - Commercial helium permeameter in 2013?
Epicomm	NEXWAFE's kerfless wafer technology aims for a drop-in replacement for Cz silicon wafers	NexWafe, Fraunhofer ISE, ISC Konstanz, Ecosolifer	January 2017: InnoEnergy invests €2 m in NexWafe
FASCOM	Advanced concept of solar streetlight.	SIARQ, Sunplugged, Tecnalia, SECE	- Prototype made - No public info available
POWCELL	Powder substrate based photovoltaic cell for thin-film crystalline silicon & 15 MW pilot line	S'tile, CEA, Karlsruher Institut für Technologie, INSA Lyon, SiLiMixt, Tesconsol	Project complete No public info available

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