European Commission

LOW CARBON ENERGY OBSERVATORY

PHOTOVOLTAICS
Technology development report

Joint Research Centre

EUR 30504 EN

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

EU Science Hub
https://ec.europa.eu/jrc

JRC123157

EUR 30504 EN

PDF	ISBN 978-92-76-27274-8	ISSN 2600-0466 ISSN 1831-9424 (online collection)	doi:10.2760/827685
Print	ISBN 978-92-76-27275-5	ISSN 2600-0458 ISSN 1018-5593 (print collection)	doi:10.2760/215293

Luxembourg: Publications Office of the European Union, 2020

How to cite this report: Taylor, N., Jäger-Waldau, A., *Photovoltaics Technology Development Report 2020,* EUR 30504 EN, Publications Office of the European Union, Luxembourg 2020, ISBN 978-92-76-27274-8, doi:10.2760/827685, JRC123157.

Contents

Foreword

The Low Carbon Energy Observatory (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.

Acknowledgements

The authors thank Maria Getsiou for her review and valuable comments.

We would also like to thank

- JRC.C.2 colleagues Harald Muellejans, Robert, Kenny, Tony Sample and Ewan Dunlop for their critical but constructive reviews and comments and to Ruben Urraca and Ana Gracia Amillo for input on solar resource.
- The JRC.C.7 JRC-EU-TIMES team for energy modelling: Wouter Nijs, Pablo Ruiz Castello, Ioannis Tsiropoulos, Dalius Tarvydas
- Data on patent statistics and R&I investments at EU, national and corporate level have been provided by the JRC.C.7 SETIS R&I team: Francesco Pasimeni and Aliki Georgakaki.

Authors
Nigel Taylor
Arnulf Jäger Waldau

1 Introduction

Over the past decade, solar photovoltaic (PV) electricity has grown rapidly to 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] and climate change objectives [2, 3] as well as to support EU jobs and economic growth in the context of the Green Deal [4].

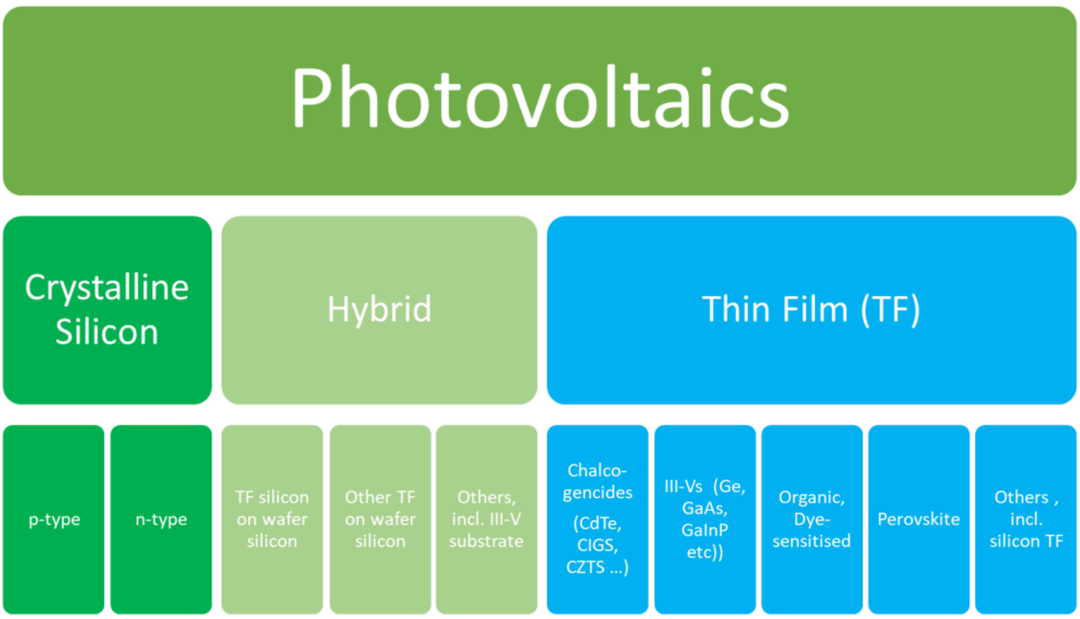
This LCEO Technology Development Report aims to provide an unbiased assessment of the state of the art, development trends, targets and needs, technological barriers, as well as techno-economic projections until 2050. In this third edition (previous technology development reports were released in 2016 [5] and 2018 [6] and a PV technology market report in 2019 [7]) particular attention is given to how projects funded under Horizon 2020 are contributing to technology advancements in this field and to the related SET plan objectives [8].

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’. These are then combined with suitable power electronics in a PV power system. The electricity power output ranges from a few watts in portable consumer products to multi-megawatt power stations.

Figure 1 shows a schematic of the main PV technologies. These 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 (cSi) PV, as well as the thin-film technologies of copper indium/gallium disulfide/diselenide (CIGS) and cadmium telluride (CdTe). There is also growing interest for hybrid “thin-film on wafer[1] concepts.

Figure 1 Overview of photovoltaic technologies



(source: adapted by JRC from a schematic at: **http://pvthin.org/**).

Thin-film silicon PV (amorphous and microcrystalline silicon) and concentrating photovoltaics (multijunction technology using III-V semiconductors, e.g., GaAs and InGaP) have lost market shares due to their lack of

(1) Silicon wafers are typically 180 microns thick, while thin-films are a few microns

efficiency improvements or problems with overall system cost reductions respectively. Some organic and dye-sensitized solar PV devices have been commercialised, but for the most part this technology remains in the novel and emerging categories. Hybrid organic-inorganic perovskite materials have emerged in the last five as promising option, in particular combined with wafer-based silicon to offer high efficiency and attractive manufacturing costs. A recent technology roadmap by international authors gives more detail on potential improvement pathways, also considering economic factors [9].

In terms of current market share, silicon wafer based photovoltaics are by far the dominant technology on the global market, with a 2019 share of over 95%. This report focuses on the commercial and emerging technologies, while the LCEO future and emerging technologies reports address novel approaches (technology readiness level less than 4). The SET plan Implementation Plan for PV gives a comprehensive picture of the technical challenges for PV technology development (see Text Box 1). The SET plan 2019 report [10] includes an assessment of progress on PV technology.

Text Box 1: SET plan PV Implementation Plan Priorities 2017 [8]

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 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

1.2 Current Market Status

At the end of 2019 global installed PV capacity reached over 630 GW[2], following annual growth of 120 GW in 2019 [11]. PV provided a 2.1% of total electricity generation, still a modest share but its importance for our future energy mix is now acknowledged.

An annual market at the 100+ GW level makes reaching the IEA's [12] 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 IRENA roadmap for 2050 [13] 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, to production processes and to operation, as well as integration and sustainability.

The EU reached a cumulative capacity of about 134 GW at the end of 2019. New installations amounted to 16.5 GW, continuing the market rebound after slipping below 6 GW in 2017 [14]. Indeed to reach the EU's 2030 target of 32% renewables and -45% greenhouse gas (GHG) emissions, installed PV should reach approximately 300 GW [14]. The new European Commission's European Green Deal foresees a deeper cut towards a 55% reduction in GHG emissions by 2030 and a climate neutral Europe by 2050. To achieve this PV capacity would need to reach 455 to 605 GW, depending on the strategic policy scenario [15].

There are two main PV market segments:

a) Ground-mounted PV power plants (utility-scale or industrial) that feed their entire electricity generation into the grid, typically owned or contracted by a utility company or large consumer. The electricity price is determined either by direct power purchase agreements (PPAs) between the owner and the electricity off-taker, or by public auctions or tenders. Floating PV and PV on infrastructure are growing niches in this segment.

b) PV systems on buildings (commercial or residential), in which part or all of the electricity produced is used directly on site, and part is feed into the grid. Building integrated PV is a sub-segment.

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. 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 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.

Every effort has been made to use recent data, at least up to the end of 2019. That said, PV is a fast moving field, and some very recent developments (e.g. performance records, new project data) may not be included here. It is noted that the term "EU" may refer to the EU28 for data for the period up to 31/1/2020 when the UK was a member of the EU.

The main data sources considered are as follows:

i) R&D projects:

  - EU-funded projects in H2020;
  - SOLAR-ERA-NET projects;
  - EIT InnoEnergy projects;
  - COST programme;
  - NER-300;
  - InnovFin Energy Demo Projects;

[2] PV power capacity here is W_{DC}, i.e the DC output of the PV modules. This value is most relevant to describe a technology's capability and the market size for cells and modules. The W_{AC} output i.e. the maximum power of the DC to AC inverter, is more important for grid operation or for other uses of the power output. In this report, the power capacity is DC unless otherwise specified.

- Member States' activities reported to the SET plan Temporary Working Group;
- major international projects, e.g. IEA Technical Cooperation Programme PVPS;
- 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, including the proceedings of the annual European Photovoltaic Solar Energy Conference (EUPVSEC); publications of the European Technology and Innovation Platform for Photovoltaics (ETIP-PV), the Fraunhofer ISE Photovoltaics Reports 2019 [16] and the 2020 International Technology Roadmap for Photovoltaics [17].

Concerning technology performance and cost targets, the 2017 SET plan Implementation Plan for Photovoltaics [8] provides the main benchmark. Table 1 below summarises the relevant key performance indicators. Table 2 shows indicative absolute values of the module efficiency targets, many of which have already been reached.

For assessment of impact, focus is on the technology readiness level (TRL) parameter, using the technology-specific guidance developed in the 2017 [18] as shown in Annex 1.

Table 1: Technical goals in the 2017 SET plan PV Implementation Plan [8]. N.B. The PV Temporary Working Group has earmarked the highlighted items for update in 2020.

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[3]***
	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[4]
	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 (approx. 2 GW annual)
	Concepts for highly automated installation

Table 2 Module efficiency values calculated from the percentage increases stated in the 2017 SET plan PV Implementation Plan [8].

PV TECHNOLOGY		2015[5]	2020	2030	*COMMERCIAL MODULES, END 2019*
SET plan target increase		-	+20%	+35%	
Wafer-silicon	mc-Si	16.2	19.4	21.9	19.9%
	mono-Si	17.0	20.4	23.0	20.4% *(Hanwha Q-Cells, DS cast-mono PERC)*
	HJT	19.0	22.8	25.7	21.7% (REC, HJT + SWCT)[6]
Thin-film	CI(G)S	13.8	16.6	18.6	*18.6% (Miasole)*
	CdTe	14.6	17.5	19.7	*19.0% (First Solar)*

[3] In February 2016 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.

[4] 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).

[5] 2015 reference data for commercial modules as reported in the Fraunhofer ISE Photovoltaics Report, November 2015.

[6] ENEL Green Power report 22.4% for production modules from the 3SUN plant, EUPVSEC September 2020.

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 smelting of silica (SiO_2) to produce metallurgical silicon. This is then refined and either cast as polycrystalline or monocrystalline ingots (directional solidification) or drawn in the form of large single crystal ingots (Czochralski process). The ingots are sliced into wafers, which are processed into solar cells (adding passivation layers, antireflective layers and electrical contacts). The final step is the module assembly, in which 60 or 72 cells are usually laid up, interconnected and sealed as weatherproof packages, designed to last for at least 25 years.

Silicon PV is a complex field, encompassing a broad range of technology variants (**Figure 2**). These are distinguished by doping (p- or n-type), by whether cast in multicrystalline or quasi–mono form or drawn as a monocrystalline ingot or by the type of contacting used to extract current. **Figure 3** provides schematic details of the main cell architectures.

Figure 2 Schematic of the silicon wafer sub-technologies, with examples of recent cell efficiency records.

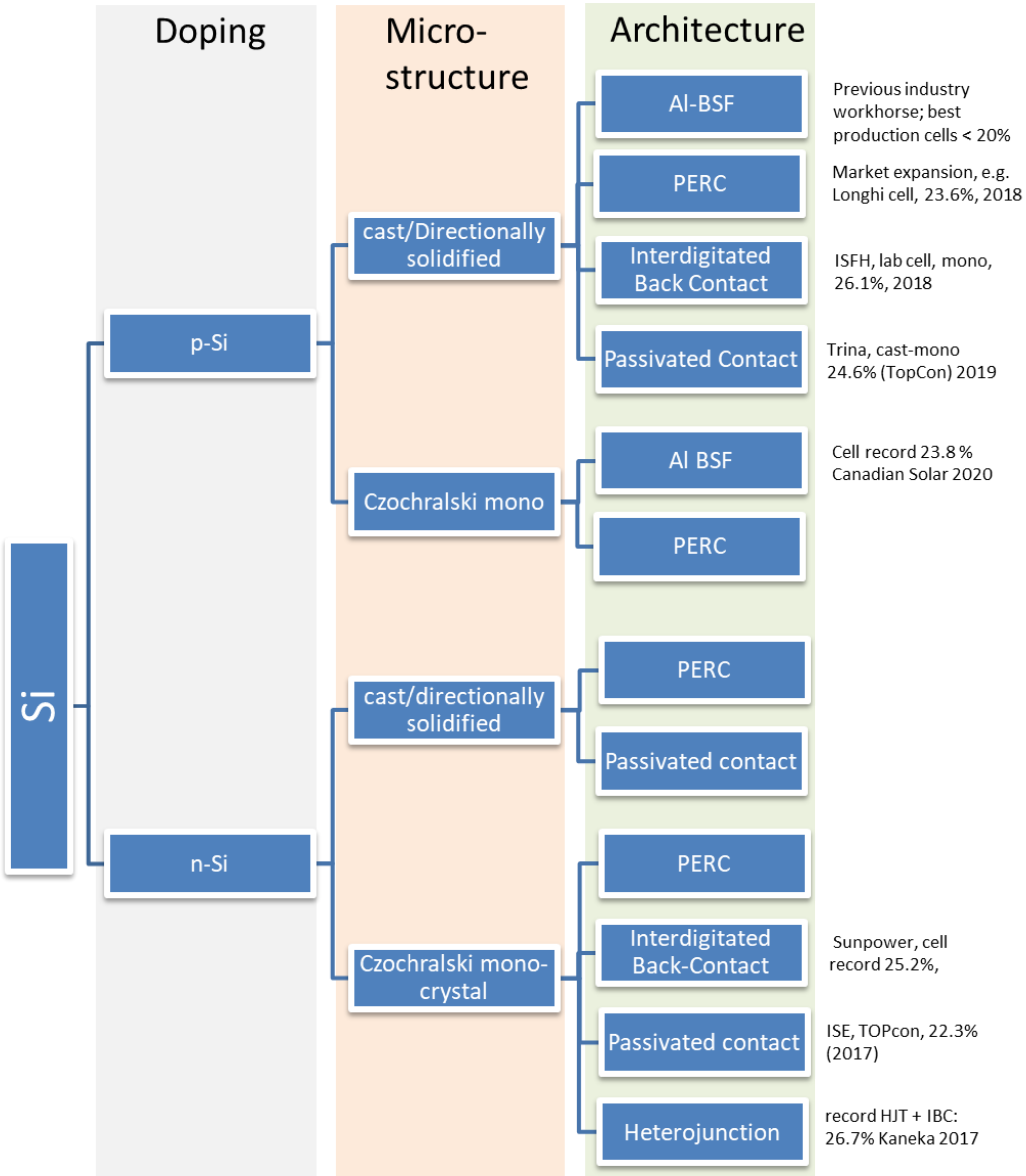
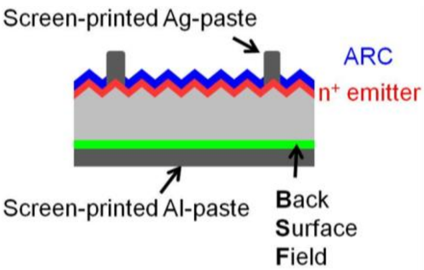
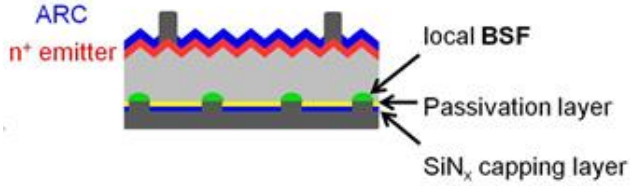
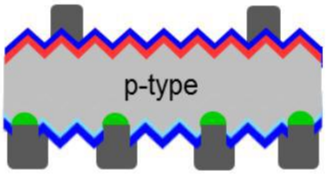
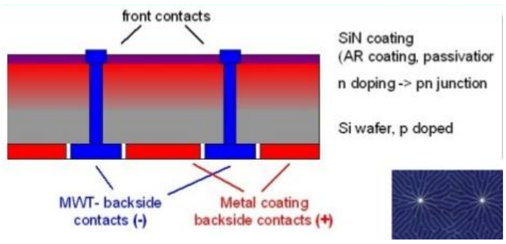


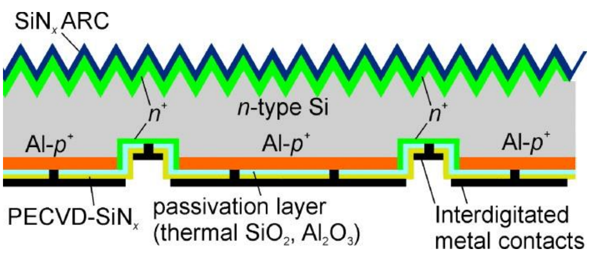
Figure 3 Major PV cell architectures

<table>
<tr><th>Cell cross-section/schematic (not to scale)</th><th>Description and market status</th></tr>
<tr><td>
</td><td>Aluminium Diffused Back Surface Field Cell (AL-BSF)

This technology is used on p- or n-type, multi- or mono-crystalline wafers and still represents an industry standard, even if its market share halved in 2019, compared to the over 85% in 2015.</td></tr>
<tr><td>
</td><td>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.

PERC/PERT/PERL solar cells started to emerge in production from 2012 onward and have increased their market share from less than 10% to about 50% between 2015 and 2019.</td></tr>
<tr><td>
</td><td>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.
The market share of the various bifacial technologies in 2019 was about 12%.</td></tr>
<tr><td>
</td><td>Metal Wrap Through (MWT)

Back contact option with lower silver paste consumption as the architecture leads to smaller shaded front area</td></tr>
<tr><td>
</td><td>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.

Market shares for MWT and IBC together increased only slightly between 2015 and 2019 from below 4% to about 5%.</td></tr>
</table>

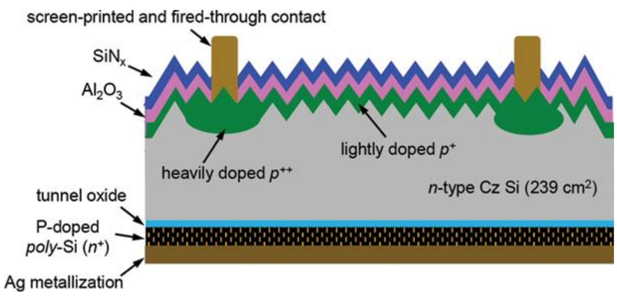
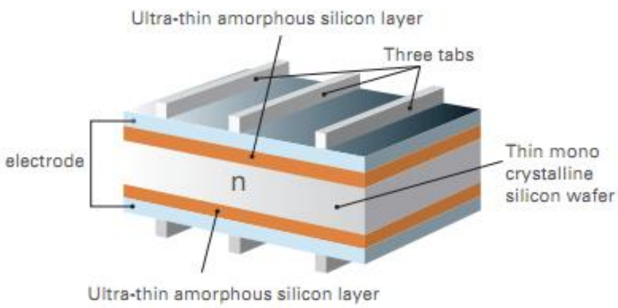
Cell cross-section/schematic (not to scale)	Description and market status
	**Full Area Passivated Cell:** the bottom of the wafer is given a thin-film structure that passivates and serves as a conductive contact to the cell. This eliminates (i) the need for diffusion or implantation doping of the wafer and (ii) complicated patterning of selective emitter/BSF. This technology is just emerging in large-scale production
	**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. Previously a niche product, but now being developed for large scale production by several manufacturers

Figure 4 shows the current and projected market shares of the main commercial technologies from the annual ITRPV report [17]. Up to 2018 p-type multicrystalline cells with aluminium diffused back-surface field (Al-BSF) architecture, dominated the market. There has since been a massive shift to PERC (passivated rear emitter and rear cell[7]) architectures, which in 2019 became the predominant silicon wafer technology with multi-GW factories. Cell efficiencies in industrial production are at 22% and better [19]. A further important driver is that the PERC production process can be adapted to make bi-facial cells i.e. they can use light falling on the rear surface as well as the front. In this way a relatively small and 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 may claim much higher values).

These developments have not been without some problems. In particular, the industry has had to develop ways to cope with degradation processes such as:

a) light induced degradation (LID) can cause modules to lose a percentage of power after first exposure to light;

b) potential induced degradation (PID) can lead to significant power losses in longer-term operation, depending on the system configuration, and

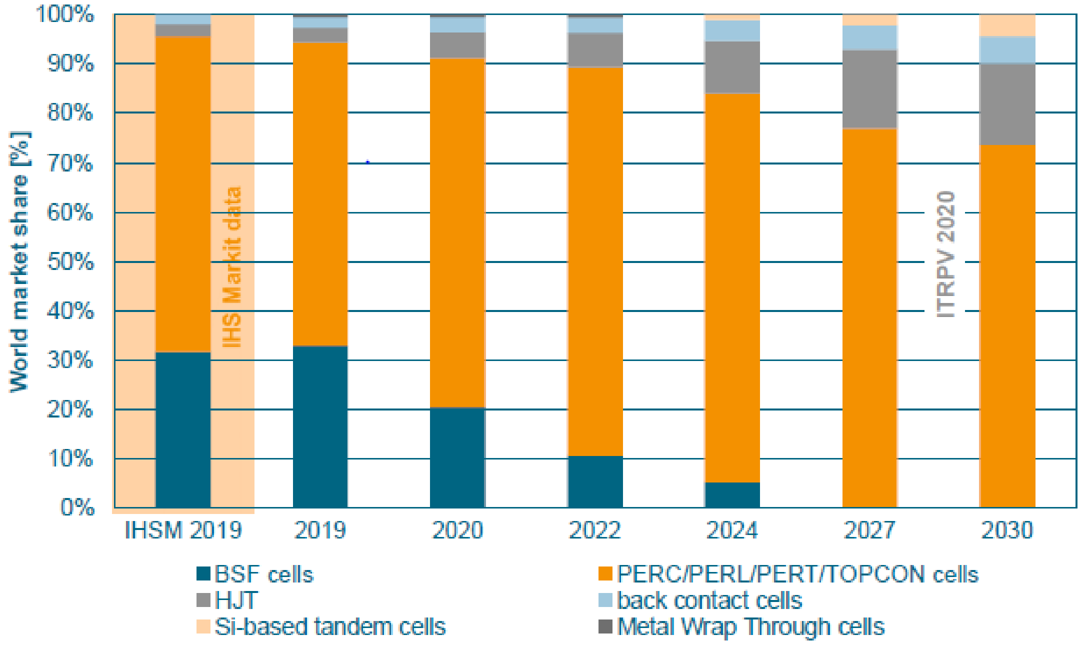
c) LeTID (Light and elevated Temperature Induced Degradation) causes a progressive loss of performance and is more likely to occur at high operating temperatures.

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 10% [17]. Sunpower 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 [20]. Other technology options include passivated contacts, in the PERC architecture, in full-area passivated designs (such as TopCon) and also in heterojunction (HJT) cells that include

[7] 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.

thin layers of amorphous silicon deposited on the n-type monocrystalline silicon wafer substrate. Although the market share for HJT modules is still relatively small (only a few percent in 2019), the ITRPV report forecasts it to reach 15% by the end of decade. 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 the specific production process is not commercially viable. Current industrial HJT manufacturing processes produce modules with 21.5 to 22.5% efficiency.

Figure 4 Current and projected global market shares of c-Si cell concepts**.**



(Source: ITRPV Roadmap [**17**])

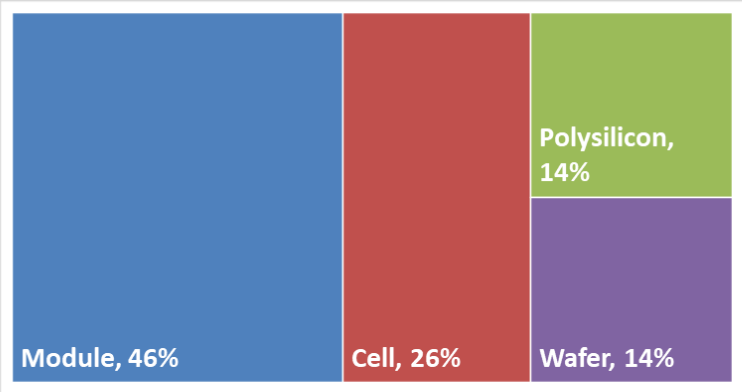
It's worth noting that value chain for c-Si modules consists in several stages, all of which need to be addressed by R&D in order to reduce costs (**Figure 5**). Issues include:

- 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 project 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.
- Kerfless wafer technologies are being developed that eliminate the sawing process. So-called epitaxial wafers/foils are fabricated by chemical vapour deposition of Si layers in the thickness range between 40 and 150 µm on re-usable seed substrates. The ITRPV roadmap [17] 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.
- Contacting: the use of passivated contacts (deposited as a thin-film layer) offers a step to higher efficiency by either enhancing the contacts in PERC-type cell or to go beyond PERC entirely, as in the full-area passivated contact designs such as TopCon.
- 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[8]), France (CEA-INES) and Switzerland (EPFL). Institutes in many other countries also contribute significantly. These activities are mainly funded by national programmes and by industry collaborations (now often with Asian companies).

Figure 5 Proportional costs of the main elements in in c-Si PV module production.



(Source: ITRPV Roadmap [17]).

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. Thin-film PV emerged some decades ago exploiting advances in deposition methods. 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. Overall the market share has been decreasing in recent years, on account of the booming silicon wafer market and in 2019 was less than 5% of total annual PV module production, so in the order of 6 GW production.

Commercially, First Solar, USA, is a multi-GW scale producer with its established CdTe module technology. Although CIGS offers comparable or even higher efficiency, production is fragmented over a range of companies in Europe, US, Japan and China, with several contending manufacturing processes. The Japanese company Solar Frontier has now reached 1 GW capacity for its cadmium-free product. The 2019 CIGS White Paper by an industry/research consortium [21] claims that the technology can be competitive in many applications, including as building integrated products. ZSW, Germany, is Europe's leading lab for CIGS. It has boosted the efficiency of its solar cells to 23.5%, and estimate that values could reach 25%.

Over the last five years, a new class of hybrid organic-inorganics lead halides compounds, known as perovskites, have emerged as an important thin-film technology, not least for the high efficiencies achieved in labs (the cell record is 22.1%). The European Perovskite Initiative [22] brings together 73 entities to exploit European research in this area, in particular to work on the challenges of overall efficiency and stability, as well as further understanding of the eco-sustainability and environmental impacts in industrial scenarios. An important application of perovskites is for tandem devices, as discussed in section 2.4 below.

[8] Now includes the former ECN activities

Table 3 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).

Table 3 Characteristics of the principal thin-film photovoltaic technologies (based on the scheme presented in [23]).

TECHNOLOGY	RECORD EFFICIEN.		MAIN FEATURES	CHALLENGES
	Cell	Module		
Cadmium Telluride	21.0%	19.0%	- Competes with c-Si for utility scale projects - Potential for efficiency to reach 25% for cells and over 21% for modules - Lowest EPBT (0.6 years) - Cadmium toxicity: not technically an issue for CdTe as a compound and in the quantities used in PV products	- Tellurium scarcity is a potential limitation to very large scale deployment - Production dominated by a single company (First Solar USA) - Extend module lifetime
Copper Indium (Gallium) Diselenide CI(G)S	23.35%	19.2%	- 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); important for commercial rooftop installations	- C 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 ^{o}C) - Hybrid modularisation schemes including metal grids in combination with scribing processes for definition of individual cells
Perovskites (hybrid organic-inorganic lead or tin halide-based material)	22.25%	16.1%	- high efficiency - uses abundant elements - Low temperature solution-based production processes, suitable for tandem applications on silicon wafers - Tuneable band gap - good for flexible, light weight and semi-transparent applications	- Toxicity, although claimed that Pb-content meets RoSH criteria, more info needed on wash-out risk - Stability, new cost efficient encapsulation materials and processes - Industrial scalability - Identification of suitable buffer layers for optimal buffer/absorber front interface
Amorphous silicon and a-Si/micro a-si tandems	11.9% (a-Si cell)	12.3% (tandem module)	- 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	13.45%	8.7%	- Active material in form of small carbon-based molecules, dendrimers and polymers - Low-cost production[9], 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%

[9] 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 EFFICIEN.		MAIN FEATURES	CHALLENGES
	Cell	Module		
Dye sensitised solar cells (DSSCs)	12.2%	8.8%	- 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
Kesterites CZTS	12.7%[10]		- free of critical raw materials - high stability - 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

2.1.1 Tandem PV

A major theme in PV research is how to raise the energy conversion efficiency above the Shockley-Queisser limit of 29% for single junction silicon cells[11]. 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 value above 30%[12]. Further challenges include the development of solutions for contacting the layers and for production processes 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 4 shows recent record results for several tandem concepts, both with silicon + thin-film and thin-film + thin-film. The efficiency record for such multijunctions is for a silicon cell with a monolithically added III-V material layer, with the cell record value now at 35.9%. However, the costs of large-scale production of such cells and the availability of the III-V materials used restricts the commercialisation potential of such devices.

The combination attracting most interest is the perovskite on silicon tandem. The UK-German firm Oxford PV stands out as currently the most advanced: it has secured over EUR 100 million in funding (including a EUR 15 million grant in 2017 from the European Investment Bank) and is installing a 200 MW cell production line in Brandenburg an der Havel, Germany.

Concerning thin-film on thin-film concepts, CIGS – perovskite devices are leaders in terms of efficiency [24]. Previous efforts to realise higher efficiencies for all-silicon thin-film devices looked at tandem devices with a high band gap amorphous silicon top cell and lower band gap microcrystalline silicon cells [25]. However, the stabilized efficiencies stalled at the 13% level. Many of the highest efficiency OPV devices are tandems, but up to now the efficiency/lifetime combination is not able to compete with mass production silicon wafer technology.

[10] IBM device, result certified; reported (but uncertified) efficiency value of 13.9% from DGIST, Korea
[11] Concepts with optical concentration of sunlight are discussed in section 2.1.4 below
[12] PV-Magazine interview with Martin Green, 19/05/2018

Table 4 Reported energy conversion efficiencies of tandem PV cells (active areas of the order of 1 cm^2) , as of March 2020.

BOTTOM CELL	TOP CELL	EFFICIENCY	INTEGRATION	YEAR/MONTH	ORGANISATION
Silicon	III-V	35.9%	Stacked	2016	NREL/EPFL/CSEM
Silicon	III-V	34.1%	Wafer-bonded	2019	Fraunhofer ISE
Silicon	Perovskite	29.15%	Monolithic	2020/01	HZB
Silicon	Perovskite	28.0%	Monolithic	2018/12	Oxford PV
CIGS	Perovskite	24.6%	Stacked	2019/09	IMEC/ZSW (0.5 cm^2)
CIGS	Perovskite	23.3%	Monolithic	2019/06	HZB

2.1.2 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 the CPV sector there is a differentiation according to concentration factor: low concentration refers to values less than 10, whereas high concentration implies a factor of several hundred (intermediate concentration levels are not generally used). The latter require the use of tracking devices. Despite its technical promise, up to now CPV has failed to make an impact in the market, struggling in particular with the intense cost competition from standard silicon wafer products.

For HCPV systems, the most commonly used cell is a multijunction device based on III-V material combinations such as GaInP/GaAs/Ge, with a record efficiency of 47.0% [20] at 143x concentrated light for a 6-junction device. With appropriate optics, module efficiencies now reach over 35%. It is however noted that HCPV systems require a high fraction of direct (vs diffuse) irradiation, and is thus only suited for very sunny regions with the optical systems currently available. Approximately 340 MW of HCPV systems are operating worldwide.

An alternative approach uses micro-lenses to concentrate light individually on a large array of small PV cells. The resulting product resembles a conventional flat-plate PV module, but with potential for higher efficiency. For example, the Swiss start-up Insolight SA[13] has developed a prototype using self-tracking micro-lenses together with an array of high efficiency space-grade III-V space cells. Insolight is developing this further in the H2020 HIPERION project.

.

2.2 Power conversion equipment

The key interface/integration element for PV systems is the DC-AC inverter (including maximum power point tracking). Its cost makes up approximately 8% of system CAPEX. A recent review of the technology and market situation for the PV Ecodesign Preparatory Study [27] identified 3 main inverter categories.

- Central inverters are mainly used in utility-scale power plants. The individual PV module strings are parallel-connected in DC combiner boxes and then to the inverter. The main advantages are simplicity in design and connection, and low O&M costs. Disadvantages include an increase of mismatch losses under non-uniform operating conditions, higher installation costs and larger land use footprint.
- String inverters can be used for a wide range of plant sizes from a few kWs to large multi-MW installations. For utility-scale systems they offer the possibility to reduce mismatch, provide more detailed operational diagnostics and straightforward replace/repair maintenance. The drawback has been a higher cost, but this may be now changing with mass-production.
- The third category is module level power electronics[14], which up to now focussed largely on power optimizers (DC-DC converters) and micro-inverters (DC-AC). The ITRPV roadmap [17] foresees a 20% market share for so-called smart junction boxes by 2026, 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.

[13] https://insolight.ch/technology/

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

In terms of power conversion efficiency, central and string inverter products from leading manufacturers typically have a "Euro-efficiency"[15] value of 98% and above [7], with module level devices somewhat lower (95%).

Inverter development trends [27] include digitalisation, repowering, new features for grid stabilization and optimization of self-consumption; storage, as well as use of innovative semiconductors. In particular, the introduction of new wide bandgap semiconductors, such as silicon carbide and gallium nitride used in MOSFETs can bring improvements to efficiency, higher voltages, better reliability and designs that are more compact. Lifetime is a critical parameter. A 10–year design warranty is common, but inverters can be sensitive to thermal loads on the main electronic components under location-specific mounting and operational conditions.

Lastly, the sizing of inverters maximum power to the PV field nominal DC power is changing. The average DC to AC ratio for large plants in Europe is 1.22 according to the WikiSolar database. However, there is a trend to higher ratios for utility-scale projects in order to maximise the period systems operate at their rated AC power even if more modules are installed. Factors between 1.3 and 1.5 may become common in the future [28].

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 130 documents, which have laid the foundations for today's global 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 status of IEC and CENELEC activities [29] with regard to PV. A comprehensive review of standards for PV devices and systems was also prepared for the Ecodesign preparatory study [30].

PV modules on the EU market must comply with the requirements of the Low Voltage Directive and specifically the PV module safety standard series EN IEC 61730. Although not legally required, all module designs 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 aims to ensure low initial failure rates in the PV products entering service. Extended testing protocols are being developed to give increased confidence for operational reliability and include:

- Extreme environments (high temperature applications): IEC TS 63216
- Testing of polymeric components: IEC 62788 series
- Extended stress testing IEC TS 63209 (draft)
- Sequential testing is necessary for some failure modes: IEC TR 63279 (draft)

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 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. Under the scheme conformity assessment certificates can be issued

[15] an averaged operating efficiency over a yearly power distribution corresponding to middle-Europe climate.

for individual PV power plants at various stages of design and implementation. It aims to give confidence that the plant will perform to specifications and reduce costs with a standard methodology. The certificate categories 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, CEN-CLC Joint Technical Committee 10 on Energy-related products - Material Efficiency Aspects for Ecodesign has published the following eight standards over the course of 2019 and 2020:

- EN 45552:2020 'General method for the assessment of the durability of energy-related products';
- EN 45553:2020 'General method for the assessment of the ability to remanufacture energy-related products';
- EN 45554:2020 'General methods for the assessment of the ability to repair, reuse and upgrade energy-related products';
- EN 45555:2019 'General methods for assessing the recyclability and recoverability of energy-related products';
- EN 45556:2019 'General method for assessing the proportion of reused components in energy-related products';
- EN 45557:2020 'General method for assessing the proportion of recycled material content in energy-related products';
- EN 45558:2019 'General method to declare the use of critical raw materials in energy-related products';
- EN 45559:2019 'Methods for providing information relating to material efficiency aspects of energy-related products'.

Product-specific standards for PV modules and inverters can now be developed in this framework.

2.3.2 Building and Other Integrated Applications

A unique feature of photovoltaic technology is its potential for integration. Examples include:

- Use of PV in buildings is a well-established concept and BIPV technologies have achieved impressive cost reductions and a high level of technical maturity. Nonetheless the market for multifunctional building-integrated products has taken longer to develop than many had predicted. With the right support in place and especially in the context industrial deployment and innovative manufacturing processes, BIPV could become a mainstream construction material in Europe [31]. Renewed efforts to decarbonise the building sector as part of the European Green Deal can boost the sector.
- Floating PV is already well developed, with several GW installed worldwide and a pipeline of new projects. These are generally on inland water bodies or sheltered coastal sites, but researchers are also looking at open sea units.
- Agri-PV allows dual use of productive land or of greenhouse structures [32]. The sector is receiving increasing attention, with total installations at already at the GW level.
- Vehicle-integrated PV has potential to contribute to decarbonising transport and become a standard part of electric cars. A dedicated IEA PVPS task group has been set up to exchange research results internationally
- Infrastructure integrated PV covers a range of applications, from lighting of urban areas to roadside structures.

All integrated applications present a research and engineering challenge to achieve a functional product at reasonable cost. In addition, dedicated standards may be needed to meet performance, environmental and safety requirements.

2.3.3 Sustainability and the Circular Economy

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

- energy used over the entire life cycle of 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 of main materials, in particular the smelting of polysilicon for silicon wafer PV devices;
- 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 (PV modules are in the scope of the WEEE Directive since 2012, and a pan-European producer scheme called PV CYCLE offers WEEE compliance and waste management services for solar energy system products).

Carbon footprint and energy payback time (EPBT) have received particular attention. The world average carbon footprint of PV electricity generation is estimated at 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 gCO_2-eq/kWh for Iceland, which has a low irradiation[16] [33]. Regarding technologies, thin-film modules have the lowest emissions, followed by poly-crystalline silicon and then mono-crystalline silicon. There is considerable scope to reduce these values, and projections for 2050 indicate that life cycle emissions for PV can drop to 10 gCO2-eq/kWh and below [34].

At international level the IEA PVPS Task 12 group issued methodology guidelines on PV-specific parameters used as inputs in LCA [35].

EU Raw Materials Initiative aims to help ensure their secure, sustainable and affordable supply. Of relevance to PV, the 2020 critical materials list [36] includes gallium, indium and silicon metal. However, indium and gallium are only used in CIGS, and therefore not in the 95% of the PV produced today). Silicon metal is included due to the current import dependence on Chinese PV products; however silicon oxide feedstock is abundant. Usage of silver for connections is sometimes cited as a cause for concern, but the industry is working to decrease its use for cost reasons alone. R&D efforts concentrate on minimising silver use or on substitute materials like copper. Assessing future issues associated with large scale PV deployment is complicated by the associated assumptions of technology paths [38]. However the fact that PV offers a very broad range of options for materials and their sources can mitigate concerns that may arise from projections based on current device technologies.

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) [39]. Photovoltaic electricity generation was assessed as a pilot product, and the resulting Product Environmental Footprint Category Rules [17] provide a methodology for assessing the environmental impacts of PV technologies based on life cycle assessment.

[16] 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.
[17] Available online at https://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm

In regard to Ecodesign, the Commission recently performed a preparatory study on solar panels, inverters and systems. It considered the mandatory Ecodesign and Energy Labelling tools as well as the voluntary Ecolabel and Green Public Procurement tools. The resulting policy recommendations were published in December 2019[18].

2.3.4 Performance, operation, reliability and lifetime

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

The rated peak power value at standard test conditions (1000 W/m^2, 25 °C module temperature, AM1.5 solar spectrum) remains the key parameter for commerce in photovoltaic products, as well as for regulatory purposes (e.g. in trade cases) and for determining energy conversion efficiency.

However, to provide a measure of likely energy produced in operation conditions, an energy yield rating for PV modules is now available under the IEC 61853 series. This allows calculation of annual energy produced 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 expected operational performance, and can support product performance differentiation. The PV-ENERATE project[19] supported under the EU EURAMET programme is looking at further development of the energy rating approach, both in terms of methodology and in technical scope, for instance to cover also bifacial PV modules.

b) Reliability and Operational Lifetime

Today's market requires performance warranties[20] that are decades long. Producers typically guarantee that modules will retain at last 80% of the label (initial) peak power after 25 years, and increasingly 30 years. The ITRPV report [17] notes a trend to stipulate an initial power loss in the first year of operation e.g. 2% and thereafter an average annual degradation rate e.g. 0.5%.

However, the subject of degradation of PV modules is still under 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 new technologies and packaging are explored. The IEC 61215 series standard for design certification is valuable for rapidly revealing well-known failure mechanisms; however, it is insufficient for assessing long-term risk, for evaluating newer or less common materials and designs or establishing field performance degradation.

Field data can be used to give estimates for degradation rates. A comprehensive 2016 review [40] found a median degradation rate[21] for c-Si technologies of (0.5-0.6)%/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 30 000 modules down to small roof systems of a few kW. Issues include:

- early detection of performance anomalies;

- optimisation operation and f 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. Spectroradiometers are used for measuring spectral content. Within these categories are instruments in various price and performance classes.

[18] Available online at https://susproc.jrc.ec.europa.eu/solar_photovoltaics/documents.html

[19] a EURAMET project under the European Metrology Programme for Innovation and Research (EMPIR) programme, co-financed by the Participating States and by H2020

[20] Modules also typically have a product warranty of 10 to 12 years

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

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 via online tools. The JRC's PVGIS[22] provides free and open access to PV potential for different technologies and configurations of grid connected and standalone systems and full time series of hourly values of both solar radiation and PV performance at any geographical location.

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 PV 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 many areas long-term time series of data are available, e.g. for Europe, North America, Africa and most of Asia.

For planning of utility scale projects, developers favour so-called site-adaptation techniques [41]. Initially satellite-based data are used to select a promising location and then a pyranometer is installed to record ground data. This data (typically one year) is then used to correct the bias of the satellite-based estimations in order to reduce the uncertainty of the long-term PV yield estimations, and thus, reduce the financial risk of the project.

Power forecasting is 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 [42] and since 2016 the dedicated Task 16 is working to "lower barriers and costs of grid integration of PV and lowering planning and investment costs for PV by enhancing the quality of the forecasts and the resources assessments".

For solar/power forecasting, recent reviews [43, 44] classify models in terms of:

(i) Output: electric power or solar irradiance? If solar irradiance is forecast, which is the usual case, a model of the actual plant is needed to calculate the power output.
(ii) Forecast horizon: intra-hour, intra-day, and day-ahead forecasts.
(iii) Modelling approach: data-driven models (statistical models, machine-learning), physics-based models (NWP, remote sensing, shadow imagery) and hybrid models.

The uncertainty of the estimations (RMSE) changes with the (i) forecast horizon, (ii) temporal resolution of the data, and (iii) climatic zone. The 2014 SET plan Integrated Roadmap originally specified an RMSE of <8% of installed power by 2020 for an intra-day single-site power forecast in NW-Europe. Recent work [45] recommends use of an RMSE skill score based on combination of climatology and persistence methods to allow reliable comparison of forecasts.

[22] https://ec.europa.eu/jrc/en/pvgis

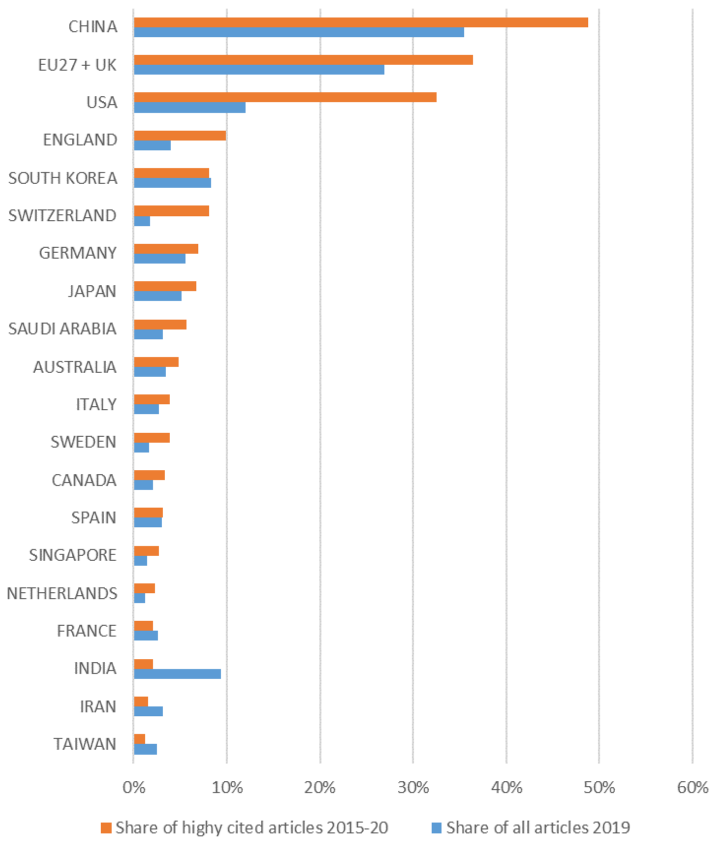
3 R&D Overview

3.1 Global and European Research and Innovation Landscape

3.1.1 Scientific Publications

In 2019 the scientific output on photovoltaics continued its steady growth, reaching just over 14,000 peer-reviewed articles according to data from Clarivate Analytics. **Figure 6** shows countries with the highest share number of author affiliations[23]. China is clear leader, followed by the USA and then England. Europe is well represented in the top-20 by Germany, UK, France, Italy and Switzerland. The EU as whole is second only to China, underlining the high-level scientific excellence in photovoltaics in Europe. Compared to a decade ago, Asian countries account for a very significant fraction of scientific output. Clarivate Analytics also provides the category of highly cited articles[24] that can be used a measure of quality. **Figure 6** includes data on each countries' share of such articles for the period 2015-2019. The overall ranking is relatively unchanged, although the leading countries or regions tend to have a larger share of the highly cited articles than of the total output. A number of countries, in particular USA, UK and Switzerland, appear to influence research much more than the simple volume of articles would suggest, whereas India had considerable output but with proportionally less impact up to now.

Figure 6 Top countries/regions for author affiliations in journal articles



(source: JRC analysis, Clarivate data)

[23] Search string used: TI=(photovoltaic* OR "solar cell*") OR AK= (photovoltaic* OR "solar cell*") OR KP= (photovoltaic* OR "solar cell*") AND PY=2019; Refined by: DOCUMENT TYPES: (ARTICLE);

[24] a "highly cited paper" receives enough citations to place it in the top 1% of its academic field of based on a threshold for the field and publication year.

In terms of content, **Table 5** shows the most cited key words (edited for relevance) in 2019. The focus on perovskites is striking, and on thin-films in general. The huge current interest in perovskites is confirmed by their prevalence in the listings of most- cited articles. The key word statistics also indicate strong research interest on PV systems and performance.

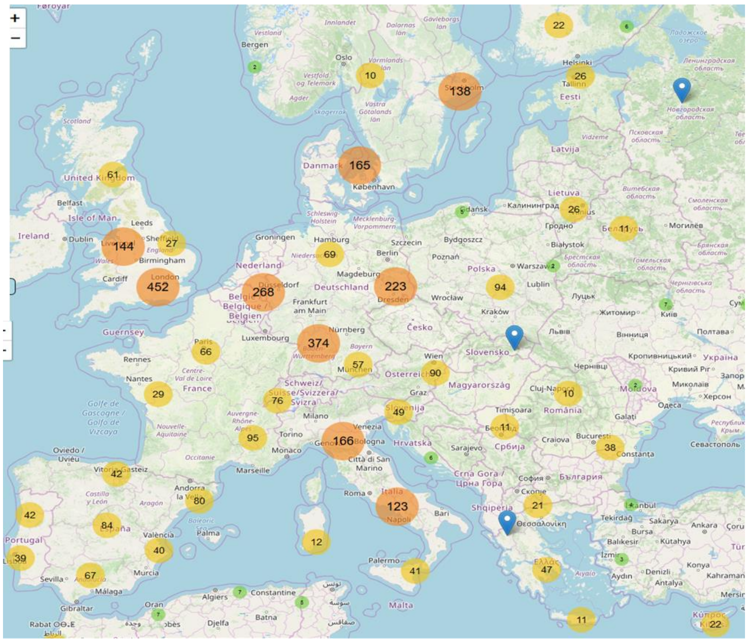
For Europe, **Figure 7** shows the geographic distribution of organisations publishing on PV and highlights the well-known centres of excellence in PV research in Western Europe. The ranking of organisations with the largest number of highly cited articles also reflects this (**Table 6**) , NB This analysis is complicated since authors sometimes use different names for the same organisation, as well as the occurrence of umbrella organisation names (e.g. Chines Academy of Sciences, US Department of Energy, Helmholtz Association etc.) as well as specific universities and research institutes.

Lastly, Clarivate also identifies funding organisations where authors specific these. **Figure 8** shows top 25 funding organisations in terms of number of articles in the highly cited articles for 2015 to the present. Chinese and US institutions lead, but it is encouraging that the European Commission and the European Research Council are both included in 9^{th} and 12^{th} positions respectively.

Table 5 Statistics on most used keywords in 2019 journal articles on PV (source Scopus)

KEYWORD	OCCURRENCES
Perovskite	2784
Photovoltaic Cells	2732
Solar Power Generation	2539
Efficiency	2243
Photovoltaic System	1453
Thin Films	1226
Open Circuit Voltage	1213
Energy Gap	1197
Dye-sensitized Solar Cells	1065
Lead Compounds	1062
Titanium Dioxide	941
Heterojunctions	936
Organic Solar Cells	891
II-VI Semiconductors	853
Photovoltaic Performance	808
Silicon Solar Cells	705
Energy Efficiency	685
Polymer Solar Cells	602
Charge Transfer	582
Light Absorption	572
Layered Semiconductors	563
Morphology	550
Performance Assessment	547
Electron Transport Properties	519
Nanocrystals	515
Optical Properties	509
Copper Compounds	508

Figure 7 Geographical distribution of European organisations involved in articles on PV



(source JRC TIM technology)

Table 6 Top 20 European organisations for highly cited scientific articles on PV in 2019-2020

ORGANISATION	HIGHLY CITED ARTICLES
ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE	96
UNIVERSITY OF OXFORD	62
UNIVERSITY OF CAMBRIDGE	42
IMPERIAL COLLEGE LONDON	29
LINKOPING UNIVERSITY	29
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	26
ISTITUTO ITALIANO DI TECNOLOGIA IIT	26
HELMHOLTZ ASSOCIATION	25
CONSIGLIO NAZIONALE DELLE RICERCHE CNR	23
UNIVERSITY OF ERLANGEN NUREMBERG	22
UNIVERSITY OF BATH	18
FRAUNHOFER GESELLSCHAFT	17
HELMHOLTZ ZENTRUM FUER MATERIALIEN UND ENERGIE GMBH HZB	15
ISTITUTO DI SCIENZE E TECNOLOGIE MOLECOLARI ISTM CNR	15
UNIVERSITAT JAUME I	14
SWISS FEDERAL LABORATORIES FOR MATERIALS SCIENCE TECHNOLOGY EMPA	13
EUROPEAN COMMISSION JOINT RESEARCH CENTRE	11
POLYTECHNIC UNIVERSITY OF MILAN	11
RESEARCH CENTER JULICH	9
ROYAL INSTITUTE OF TECHNOLOGY	9

(source: extraction from Clarivate data)

Figure 8 Top funding organisations of highly-cited articles on PV in the period 2015 to 2020.

(source: Clarivate)

3.1.2 Patents

Patent statistics can also provide an insight into the development of new technology. The analysis below uses the PATSTAT database 2019 autumn version (JRC update: December 2019). The methodology behind the indicators is provided in [46, 47, 48] for the period to 2016[25]. Although the overall volume of patents (>85 000) precludes a detailed analysis of content, the CPC classification codes (see Appendix 1) allow a degree of technology–related information to be extracted.

Figure 9 shows the overall trend in counts of patent families[26] per year for three categories: all patent families, the so-called "high-value" patent families i.e. application made to two or more patent offices and lastly granted patent families. Overall filings grew strongly from 2000 up to 2012. They decreased in 2013 and 2014, but rose again in 2016, due a new surge in Chinese patents (**Figure 10**). EU patenting peaked in 2012 and has since decreased by half. Overall, the data suggest a link between patenting and industrial manufacturing activity.

In terms of global regional breakdown for 2016, China took the largest share of all patent family applications, followed by Japan and Korea (**Figure 11**). However, there is a significant difference between a US, Japanese or Chinese patent, where an idea can be patented, compared to Europe where proof of concept is required. Nonetheless if just the "high-value" patent families are considered a different picture emerges, with Japan as leader, South Korea second and the EU in third positon.

Regarding the content of the patents, **Figure 12** shows the time trend for the three major categories: “integration of renewable energy sources in buildings”, “energy generation through renewable energy sources” and “climate change mitigation technologies” in the production process for final industrial or consumer products. The “energy generation category” is clearly the largest, accounting for 69% of patents in 2016, followed by production technologies on 22% and building applications on 9%. In terms of PV material technologies, **Figure 13** shows that patenting activity is strongest on organics (including perovskites) and on DSSC materials. In the 2016 breakdown, these two categories account for over 80% of patent families, a trend also noted in the European Patent Office’s analysis in 2019 [49]. Lastly, **Figure 14** shows the technology breakdown for European patents applications in 2016. The “energy generation” category is predominant, but there were also significant levels of activity for power conversion technologies, for PV with concentrators and PV in building. Encouragingly, the manufacturing category also maintained a 10% share, perhaps reflecting the continued market strength of the European PV manufacturing equipment sector.

[25] There is a time lag of 3 years to obtain complete data for a given year.
[26] Patent documents are grouped in families, with the assumption that one family equals one invention.

Figure 9 Global trend in patent filings under PV related families per year.

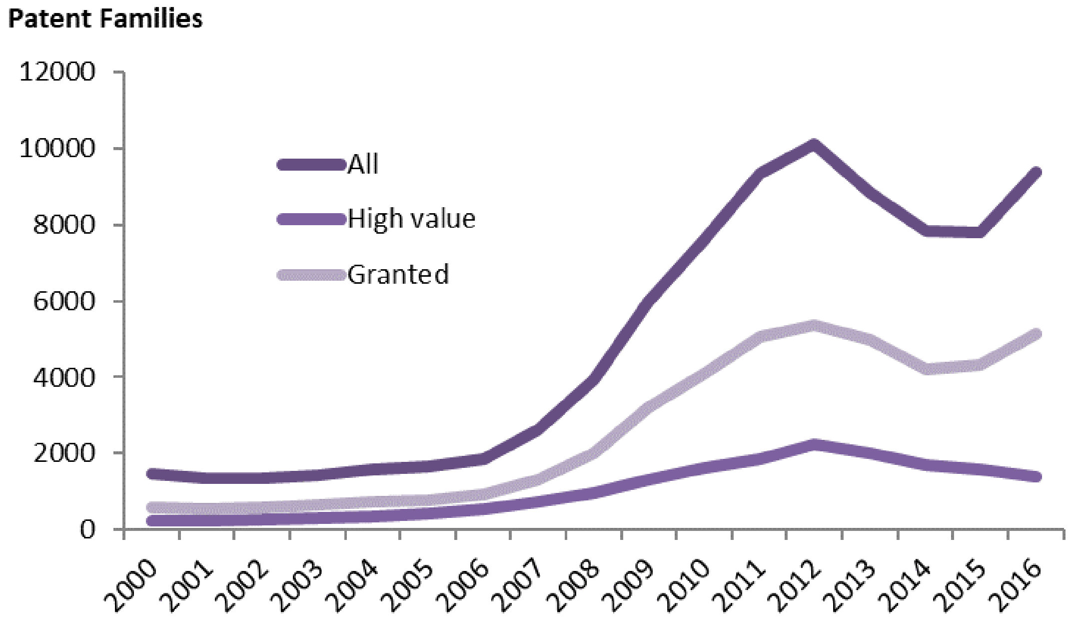


Figure 10 Trend in patent filings by major global players for 2000-2016.

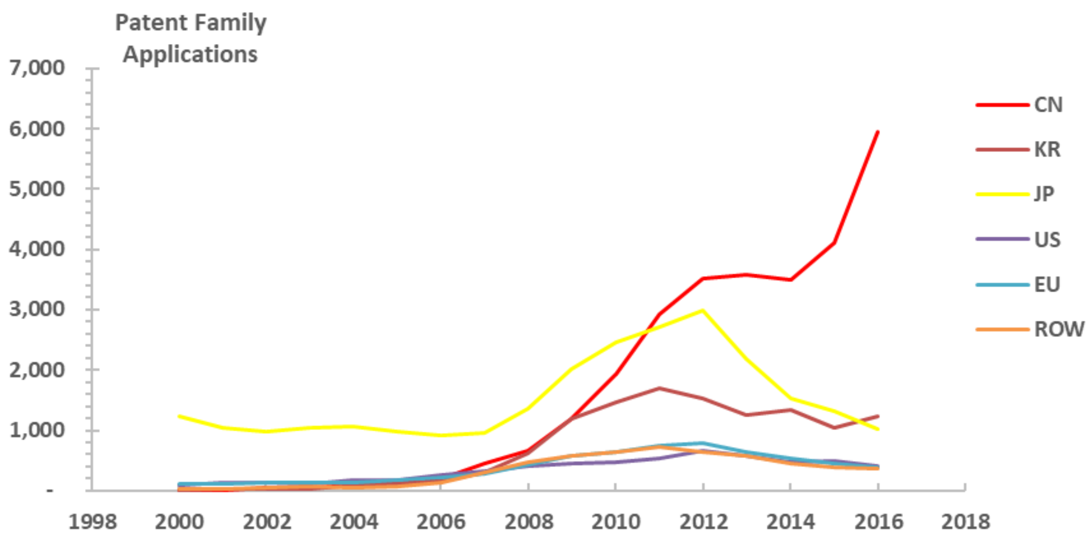


Figure 11 Regional breakdown of patent families (high value indicates applications in two or more patent offices)

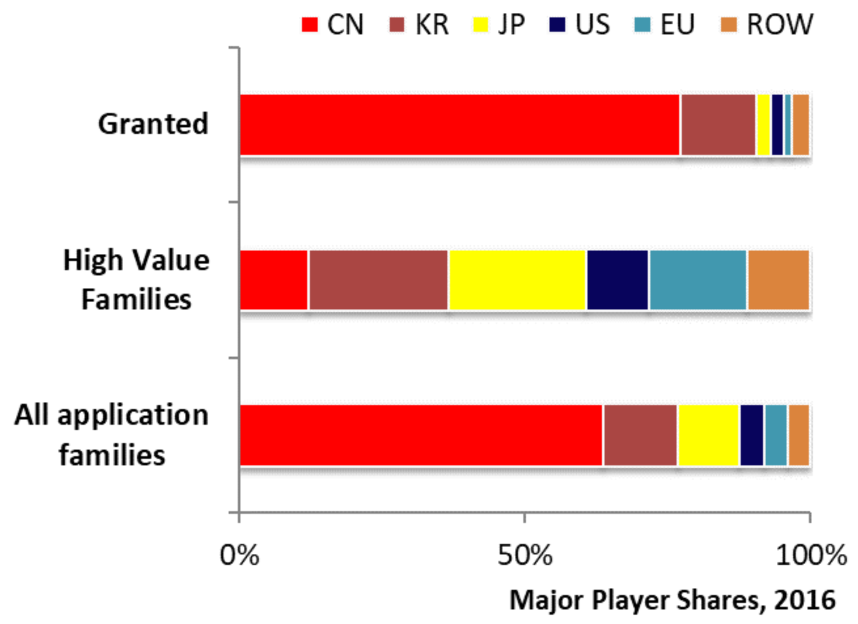


Figure 12 Trends in patenting under the three main application groups for 2000-2016

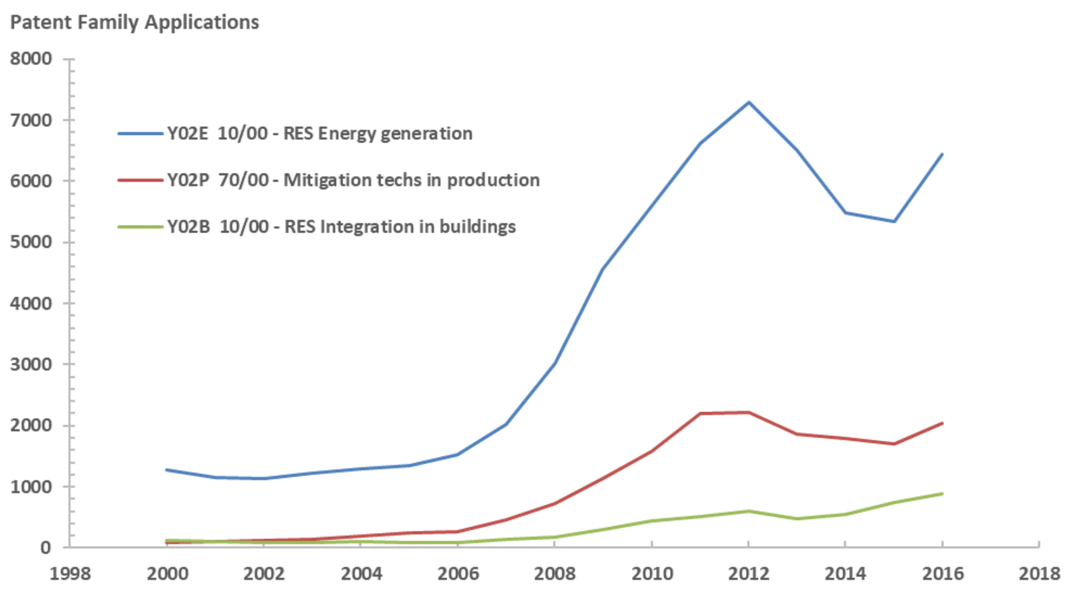


Figure 13 Trends in patenting for main PV technology groups. (NB y-axis with logarithmic scale).

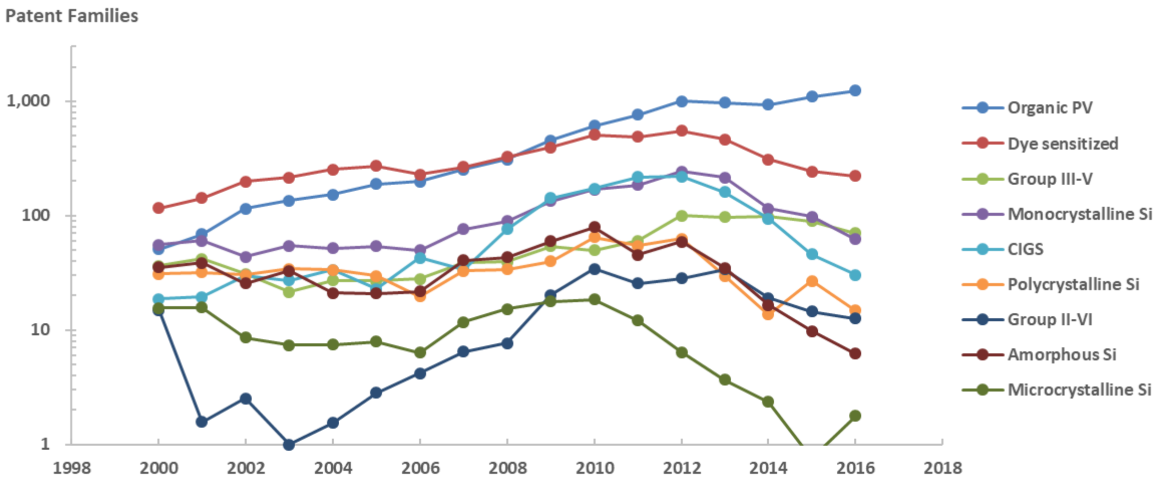
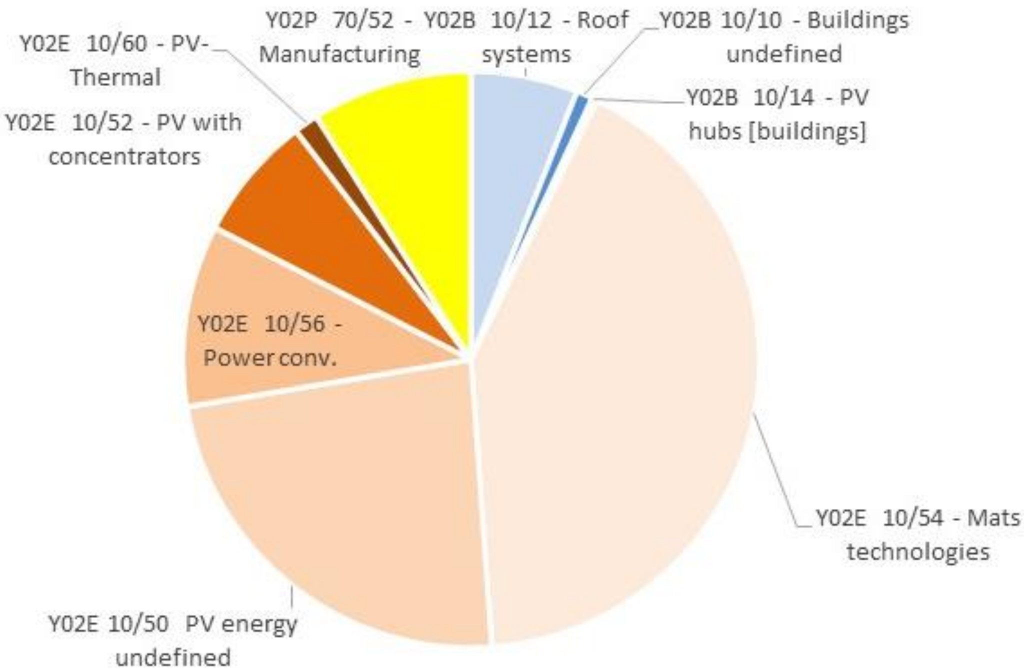


Figure 14 Sectorial breakdown of EU+UK PV patent family applications in 2016



3.2 EU 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 [50]. 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 implementation working group (IWG) on photovoltaics involves representatives of Member States, other stakeholders and the European Commission. This group issued a detailed implementation plan [8] in 2017 and are now in the process of updating it for 2020. The plan identifies six main areas:

1. PV for BIPV and similar applications
2. Technologies for silicon solar cells and modules with higher quality
3. New Technologies & Materials
4. Operation and diagnosis of photovoltaic plants
5. Manufacturing technologies
6. Cross-sectoral research at lower TRL

In 2018 the IWG started an evaluation of R&D projects of participating countries and regions, considering budget and priorities in each national program. The results will published in 2020. From the preliminary information available, the most prioritized areas were 1 (BIPV and similar applications) and 3 (new technologies & materials). However, the highest funding went to areas 2 (silicon technologies) and 5 (manufacturing technologies).

The European Technology and Innovation Platforms (ETIPs) support the implementation of the SET plan by bringing together EU countries, industry, and researchers in key areas. The photovoltaics platform, ETIP-PV[27], has the goal to help ensure that Europe maintains and improves its industrial position, in order to achieve a leadership position within the global PV market.

Also under the SET plan governance framework, 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[28] 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.

In preparation for the EU's 2021-2027 Horizon Europe research and innovation framework programme, the the Clean Energy Transition Partnership partnership is being developed strategy as Co-Funded European Partnership, meaning with Member States and Associated Countries funding, topped with EC funding. The CETP is currently developing a strategic research and innovation agenda.

3.2.2 PV in Horizon 2020

Under Horizon 2020, the EU has co-funded over 120 PV-related projects in the period 2014-2019, for a total budget of almost EUR 260 million, as part of EUR 510 million for all solar technologies (see **Table 7**). This compares with approximately EUR 360 million for wind power [51] and EUR 596 million for bioenergy [52] in the same period. **Table 8** shows the breakdown according to the various funding programmes.

Table 9 gives the distribution to the six SET plan PV priorities. The area "new technologies and materials" has received the largest single share (39%), followed by manufacturing technologies (23%) and BIPV (19%).

Figure 15a shows the breakdown in terms of applications, where the category "general" accounts for the bulk of funding, followed by buildings. The EU has also made significant grants for recycling technology. **Figure 15**b looks at the breakdown for materials technologies (here tandem concepts counted as 50% for the top and 50% for the bottom cell material). The main change compared the analysis carried out in 2017 [6] is the emergence of perovskites as a major research sector.

[27] http://www.etip-pv.eu/homepage.html

[28] https://www.eera-set.eu/eera-joint-programmes-jps/photovoltaic-solar-energy/

Table 7 H2020 funding for solar projects 2014-2019

SOLAR TECHNOLOGY	FINISHED PROJECTS	RUNNING PROJECTS	TOTAL
Photovoltaics	82,785,217	183,213,168	265,998,385
CSP	49,058,269	111,512,694	160,570,963
Solar Thermal (non-concentrating)	8,218,159	26,705,728	34,923,887
Photochemical	7,028,031	26,159,682	33,187,713
Coordination	2,980,095	14,953,181	17,933,276
Solar windows	1,264,438	995,935	2,260,372
Hybrid Technology	395,455	1,398,478	1,793,932
Total	150,718,866	360,042,340	510,761,206

(Source: JRC analysis of COMPASS data)

Table 8 Breakdown of funding for PV or PV-related projects by programme.

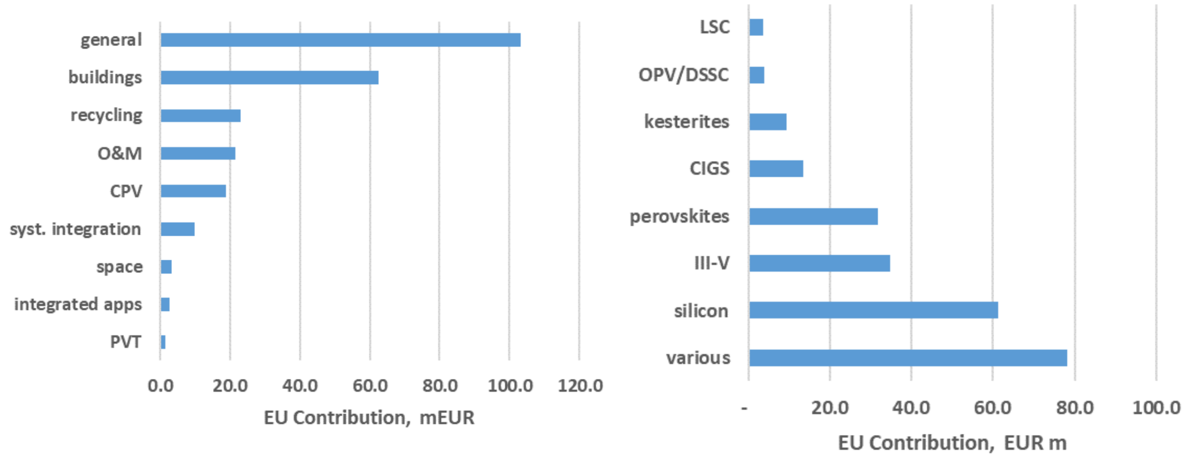
H2020 PROGRAMME	TOTAL EC FUNDING	SHARE
LCE	81,698,045	31%
LC	54,104,466	21%
ERC	20,918,767	8%
NMBP	17,203,756	7%
SME	15,264,559	6%
MSCA	14,597,783	6%
WASTE	7,844,565	3%
FITPILOT	7,633,278	3%
CIRC	7,014,893	3%
EU	6,333,425	2%
FoF	5,642,708	2%
NMP	5,516,910	2%
EEB	4,900,313	2%
COMPET	4,081,349	2%
FETOPEN	2,993,404	1%
EIC-FTI	2,419,594	1%
EE	1,355,106	1%

Table 9 Breakdown of H2020 funding to 2019 for the SET plan PV priority activities

SET PLAN ACTIVITY AREA		EU CONTRIBUTION	
		EUR	%
1	BIPV and similar applications	49,353,345	19%
2	Silicon cell and module tech.	8,900,195	3%
3	New technologies & materials	101,321,541	39%
4	Plant operation and diagnosis	31,313,868	12%
5	Manufacturing technologies	58,964,605	23%
6	Cross-sectoral R&D at lower TRL	9,669,365	4%
	Total Committed to end 2019	259,522,918	

(source: JRC analysis of COMPASS data)

Figure 15 Technology and application breakdown by EC funding for PV-related projects, H2020, 2014-2017



a) Application areas b) PV materials breakdown

3.2.3 SOLAR- ERA.NET

SOLAR-ERA.NET is a network of more than 20 European R&D programmes in the field of solar electricity technologies (mostly PV but also CSP) and itself receives funding from the EU framework programmes for coordination [53]. It was launched in 2012 under FP7 and has continued under H2020 as SOLAR-ERA.NET Cofund projects 1 and 2. Up to now over it has contributed to 40 projects, with a total budget of EUR 100 m, of which well over half came from public funding. Compared to the directly-funded EU programmes, there is more emphasis on applied research and demonstration (up to TRL 7), and less basic research. SOLAR-ERA.NET has been successful in creating complementarity between national and EU funded programmes and has demonstrated flexibility and a bottom-up nature, with no “one size fits all” approach. Appendix 3 gives a listing of completed and running projects.

3.2.4 European Metrology Programme for Innovation and Research (EMPIR)

The European Association of National Metrology Institutes (EURAMET) supports relevant research via the European Metrology Research Programme (EMRP) and the European Metrology Programme for Innovation and Research (EMPIR). In the area of PV, it has funded the Photoclass project “Towards an energy-based parameter for photovoltaic classification” (2015-2017) and its successor PV-ENERATE “Advanced PV Energy Rating“ (2017-2020).

3.2.5 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. Current or recently complete projects that involve PV technology or are relevant to PV applications include:

- TU1401 Renewable energy and landscape quality (RELY) 2014 - 2018
- MP1402 Hooking together European research in atomic layer deposition (HERALD), 2014 - 2018
- MP1307 Stable Next-Generation Photovoltaics: Unravelling degradation mechanisms of Organic and Perovskite Solar Cells by complementary characterization techniques (StableNextSol), 2014 to 2018
- MP1406 Multiscale in modelling and validation for solar photovoltaics (MultiscaleSolar), 2015 -2019
- CA16235 Performance and Reliability of Photovoltaic Systems: Evaluations of Large-Scale Monitoring Data (PEARLPV), 2017 - 2021
- CA18222 Attosecond Chemistry, 2019 to 2023

3.2.6 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) up to 2016, but no new ones since then. The most recent investment was EUR 2 million in 2017 in Nexwafe (a Fraunhofer ISE spin-off), for its kerfless wafer technology.

3.2.7 EIB InnovFin

The European Investment Bank set up the InnovFin (EU Finance for innovators) financing tool to cover a wide range of loans, guarantees and equity-type funding. Investments in PV technology innovation include:

- In 2016, 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 (an organic photovoltaic solar film for integration into building facades)
- In 2017, 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.

3.2.8 NER-300

NER 300 is a demonstration programme for CCS and RES projects involving all Member States. The only PV project selected was the Santa Luzia Solar Farm, located near Lagos, Portugal for a 20 MW plant using concentrator photovoltaics (Magsun TRK-60 modules, 23% nominal efficiency at 800x concentration). However the project was withdrawn in July 2019. For the period 2021-2030 the Commission has launched a new programme called the ETS Innovation Fund.

3.3 Other R&D Programmes

3.3.1 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 do not involve research *per se*, but focus on bringing together and analysing information from the participants [54]. There are 8 ongoing tasks:

- Task 1: Strategic PV Analysis & Outreach;
- 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;

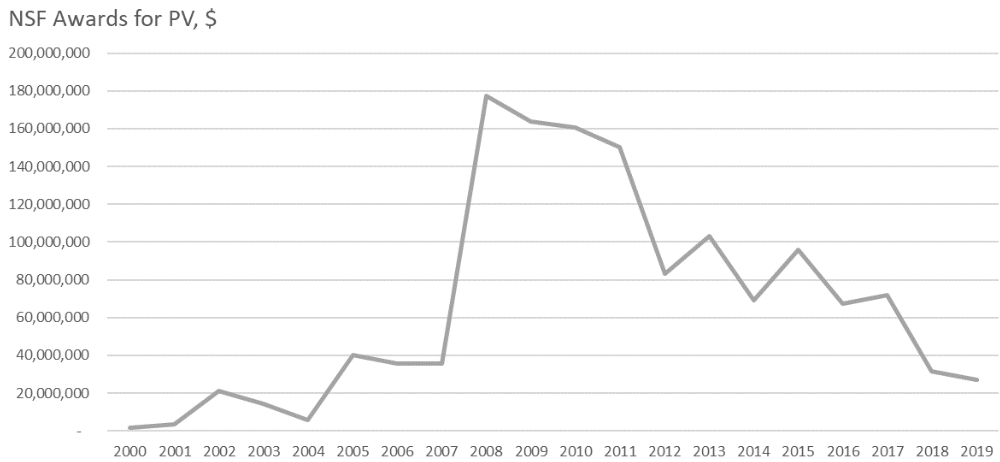
– Task 17: PV for Transport;
– Task 18: Off-Grid and Edge-of-Grid Photovoltaic Systems.

3.3.2 USA

Both the National Science Foundation and the US Department of Energy (through the Solar Energy Technology Office) fund a broad range of research activities on photovoltaics. A search of the NSF web page identified 2000 awards since 1990, amounting to USD 1.4 bn. However, after a peak in funding from 2008 to 2011, the annual total has dropped steadily (**Figure 16**).

The DOE's program (previously known as the Sunshot initiative) has an overall goal of making solar energy (PV and concentrated solar thermal) affordable for all Americans. The 2030 cost targets are USD 0.03/kWh for utility scale PV, 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.
Table 10 shows a breakdown of funding for currently active projects and programs (it includes substantial support for DOE national labs such as NREL, Sandia and Brookhaven).

Figure 16 Sum of NSF awards per year for research on photovoltaics, 2000 to 2019.



(source: JRC elaboration of search results from NSF web site section "Research Spending & Results")

Table 10 US DoE Solar Energy Technology Office, active projects as of August 2019

Sub-program	Active Projects	Gov. cost, $	Total cost, $
Systems Integration	73	171,939,833	250,377,333
Photovoltaics	103	185,757,310	206,562,787
CSP	68	125,880,840	155,003,535
Soft Costs	53	81,711,229	88,005,088
Technology to Market	28	33,927,940	50,737,601
CSP, Systems Integration	1	530,946	530,946
Grand Total	326	599,748,098	751,217,290

(Source JRC elaboration of Excel download from the SETO Solar Projects Map)

3.3.3 China

Several agencies and organisations are involved in funding R&D on photovoltaics, including:

- Chinese Academy of Sciences
- National Natural Science Foundation of China
- National Basic Research Program of China (973 Program)
- China Postdoctoral Science Foundation
- Ministry of Science and Technology of the People's Republic of China

As mentioned above, China has become a leader in PV research in terms of science publications, and is also at the forefront of crystalline silicon and thin-film (in particular perovskite) cell development with several labs challenging for record efficiency records.

China has also been effective in promoting industrial innovation, in particular through the National Energy Administration's (NEA) "Technology Top Runner Program" that was launched in 2015 to promote uptake of 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 was for installations amounting to several GW annually. This scheme provide highly successful in achieving a major shift towards products such as PERC bifacial designs for mono-crystalline silicon.

3.3.4 Japan

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 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:

AIST Renewable Energy Research Center (Fukushima)

- Crystalline Si, energy rating;
- Energy network.

AIST Research Center for Photovoltaics (Tsukuba and Koriyama (Fukujima Prefecture))

- Improvement in device performance: CIGS, CZTS, thin-film Si, Organic TFs, DSSC, Perovskite, etc.
- 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:
  1) "Development of crystal silicon PV modules using advanced multiple technologies and high performance CIS modules",

2) “Research and development of innovative new structure solar cells”,
3) “Development of common components for solar cells and modules” and
4) “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

4 Impact of R&D with EU Co-Funding

This section aims to assess the advances made by major[29] recently completed or running projects, principally in terms of technology readiness level achieved. The 45 projects considered are clustered under the headings:

- crystalline silicon devices
- thin-film devices (including CIGS, PSC, OPV and others)
- silicon wafer tandems
- building related products
- operation performance
- market uptake
- circular economy.

A series of tables (**Table 11**, **Table 12**, **Table 14**, **Table 13**, **Table 15**, **Table 16** and **Table 18**) provide an overview of the main technology goals stated in the description of work and an estimate of the final or target TRL. The following sections provide an overall summary of the progress. NB In many cases the projects set highly ambitious targets, quite justifiably for research activities.

4.1 Wafer-based crystalline silicon

Table 11 shows the projects considered and the progress assessment. AMPERE (Automated photovoltaic cell and Module industrial Production to regain and secure European Renewable Energy market) is the stand out project. In November 2019 ENEL, the coordinator, inaugurated an industrial scale (200 MW) production line for high efficiency heterojunction modules, representing the culmination of over ten years of R&D by a cluster of European labs (CEA, Fraunhofer ISE, EPFL, IMEC and others). The FP6 HETSI and FP7 HERCULES projects also contributed substantially to this development process.

H2020 is also supporting further development of HJT technology. The NEXTBASE project (ended 2019) targeted a 26% efficiency level for cells and while the cells developed did not quite reach that level, the results may provide more clarity on the path to do. The HIGHLIGHT project launched in late 2019 also addresses HJT, targeting efficiency and material usage gains for applications in building and on electric vehicles.

The DISC project focussed on innovative carrier-selective contacts with scalable manufacturing processes..

4.2 Thin film devices

Table 12 shows the details of the main projects on thin-film devices (section 4.3 covers tandems with silicon wafers).

Pervoskite devices: although now the most active area of PV research worldwide, only really emerged in 2015. Since then the area has received significant funding under H2020, targeting four aspects: efficiency, long-term stability, scalable manufacturing and sustainability (in particular to minimise or replace the lead content). The one completed project is GOTSolar (2016 to 2018) produced good results, including a 144 cm^2 module with an efficiency of 14.4% (two years on, the champion cell is 16.1% for 802 cm^2). The ESPREesSo project ended in early 2020. APOLO runs from 2018 to 2022, targeting printable PSC devices with efficiencies over 20%. While there has been substantial progress on stability, efforts so far to substitute lead have not proved successful.

<u>CIGS</u>: In H2020 the EU continued its support for European R&D on CIGS with two large projects: Sharc25 and ARCIGS-M. SHARC25 ended in 2018 having achieved important scientific results although the ultimately the targeted record efficiency levels (25%) could not be delivered. ARCIGS-M focussed on further improving sustainability of CIGS manufacturing, exploring the use of ultra-thin layers and of innovative passivation and contacting steps. Progress on getting efficiencies comparable to existing top-end CIGS devices is slower than foreseen and the project was extended to mid-2020. The OLEDSOLAR project is currently looking at roll-to-roll manufacturing processes but no results are available.

Kesterites: two projects have been completed. In SWInG the chosen technology route (Ge-based kesterite) did not bring a breakthrough in terms of efficiency (target was 15%). STARCELL (including international partners) set itself an 18% efficiency target. They achieved cell efficiencies up to 11.8% and a 50 cm^2 mini-module with

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

7% efficiency. Both projects produced important scientific insights to the challenges to improving kesterite cells, but there is no clear route to overcoming these.

4.3 Silicon wafer tandems

Tandem cell design is one of the most promising areas of photovoltaics R&D and H2020 projects address several concepts (**Table 13**).

The first is perovskite on silicon wafers. The CHEOPS project (2016-2019) included Europe's foremost groups working in this area (Oxford PV, EPFL, CHOSE etc.). They succeeded in making tandem with efficiency just over 25% on a small area (record is 29%). The partners are continuing work in this field, notably Oxford PV with its 100-MW scale manufacturing plant for PSC-Si tandems.

The other area investigated is silicon with III-V material top cells. It has already been shown that this combination can produce efficiencies well above 30%, and the challenge is to find concepts with potential to be commercially viable given the high cost of III-V materials. Nanotandem developed a template-assisted selective epitaxy (TASE) approach and produced nanowire tandem cells (InGa on Si) with efficiencies of 18%, and record III-V nanowire cells with efficiency of 16.9%. The processes developed for the Si cells interfaces (e.g. the diffraction grating back reflector approach) are broadly applicable and were used in the record GaInP/AlGaAs//Si tandem cell. AligND Systems acquired the entire IP-portfolio, but from their webpage it does not appear that the technology is being applied yet. The SME project NanoSol aimed to industrialise an existing prototype called SolFilm using an aereotaxy technique (nanowires formed in gas phase, suspended in ink and then deposited) for GaAs nanowires on silicon. The project ended prematurely and the samples produced had low efficiency even for small areas (4%, 25 mm^2). At this point it does not seem that the aereotaxy process can compete with the metalorganic vapour-phase epitaxy (MOVPE) method used by other groups working in this area. SiTaSol started in mid-2017 looking at two different epitaxial deposition/fabrication processes and no results on efficiencies are available at time of writing.

Lastly, the HIPERION project also used a III-V on silicon tandem concept but combined with a concentration optics (see also section 4.4).

4.4 Concentrating devices

Several projects have been active in H2020 (**Table 14**). The largest, CPVMatch, set itself the challenge of world record efficiency and a scalable fabrication process. It has delivered successful devices and optical systems, but there are no prospects for further development at present due to the difficulties in general of achieving competitive cost levels for concentrating PV technology.

Two SME projects have also aimed to develop CPV products. The second phase of CogemCPVT aimed to improve a prototype design. The REPHLECT project (also in phase 2) targeted an HCPV concept with a pilot line in Spain and a clone on Morocco.

Finally, the HIPERION project, which started in 2019, takes a very different approach using optical micro-tracking technology to concentrate sunlight on small (1 mm^2) multijunction solar cells, mounted on top of a conventional silicon wafer cell. The modules themselves are not on trackers, but do have a small degree of movement between the upper and lower planes to optimise optical performance. Concentration level is larger than 200 times. Efficiencies of 30% have been reported for prototypes, and project will focus on scale-up to TRL 7.

4.5 Building-related products

Table 15 lists the projects which focussed on PV products for buildings. In general these combined product development (including customised manufacturing processes) and operation demonstration on buildings:

- In Advanced-BIPV, Onyx Solar developed two full-scale (XL-format) PV glass products together with a corresponding manufacturing process, and is judged to have reached TRL 8. The company is taking part in further development and demonstrations activities in the PVSITES and TECH4WIN projects.
- STILORMADE used the iCell crystalline silicon technology to develop and certify both standard (flat plate) and innovative (curved) products. Successful demonstrations were made on a range of buildings.
- PV-SITES is a large consortium project that encompasses a number of facilitation activities (design tools, energy forecasting tools) as well as development and demonstration of products at several sites

BIPVBoost brings together a large consortium and covers both product development and demonstration, as well as addressing standards and non-technical issues. It runs to 2022. PVadapt is working on a PV-thermal hybrid system and associated building integration technology; Envision focusses on façade solutions. Both are due to end in 2022.

4.6 Operational Performance Improvement

This category has just two projects, both on coatings (Table 16). SOLARSHARC tested a previously patented paint-on coating product with silica nanoparticles. The field test data available showed a modest (+1.3%) increase in energy produced compared to uncoated systems. OPTINANOPRO was a large project looking at several applications of use of nanomaterials for packaging and coatings. The spray coating developed for OPV cells does not appear to have been successful.

4.7 Market Uptake

Three coordination and support projects are being funded (Table 17) that look at different aspects of market uptake: idistributedPV, focussing on the impact at the level of the distributed grid, EU-HEROES, with a focus on community and social enterprise projects, and lastly PV-Prosumars4Grid, looking at guidelines and best practices for prosumers and distribution system operators. All finish in 2020, and overall results are not yet available. Two observations in any case:

a) Online prosumers support tools have been developed by both idistributedPV (http://www.idistributedpv.eu/prosumer-tool/) and by PV-Prosumer4Grid (https://www.pvp4grid.eu/cmt/). It may be beneficial if all the organisations involved could concentrate efforts on a single tool to be widely publicised.
b) Broad dissemination of the projects' findings can help shape the transposition at member state level of the provisions for prosumers and renewable energy communities in the new RED-II and electricity market directives.

Lastly, this sections also include a SME project SUNNIBOX for providing an integrated solution for off-grid power, particularly in less-developed countries. A prototype of the combined PV-battery-distribution system was successfully tested and is now in commercialisation phase according to the producer. It will be competing with other "container" systems such as Mobil Watt and Solar GEM.

4.8 Circular Economy

H2020 has funded three major projects (see **Table 18**) on creating more sustainable values chains for PV products.

The CABRIS project aimed to improve high value material retrieval rates and re-manufacturing from recycled materials. The project was most successful on materials recovery. The key exploitable results included processes for recovery of indium, silver, silicon and high-quality glass (for this, in particular for thin-film modules), on recovery of silicon kerf, on purification of silicon wastes, on conductive pastes and inks with recycled silver and sputtering targets made from recycled indium. The work on reusing material for PV cells made technical advances but progress limited by quality issues with the recycled materials.

ECOSOLAR achieved most of its objectives (see details of results in Table 18) and received the "Solar Impulse Efficient Solution label" in January 2020. It demonstrated the feasibility of an encapsulant-free module design to facilitate easier disassembly and recovery of the materials, and it remains to be seen if this can be commercialised in a very competitive market for module power performance.

ELSi focussed on silicon recovery from end-of-life modules and commissioned a pilot facility in Knittingen, Germany. However commercial operation is delayed by insufficient module waste and the low price of silicon.

Table 11 Progress of major EU-funded projects under Horizon 2020: wafer-based crystalline silicon

Acronym	Title	Start/ End Date	Main Technology & Cost Objectives	TRL	EC funding, EUR
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.	4	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	4	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).	8	14 952 065
HIGHLITE	High-performance low-cost modules with excellent environmental profiles for a competitive EU PV manufacturing industry	1/10/2019 to 30/9/2022	Focus on thin (100 µm) high-efficiency HJT c-Si with passivating contacts • building-applied PV modules with η ≥ 22% and ≤ 250 kg-eq.CO2/kWp, • building-integrated PV modules with η ≥ 21% and improved shading tolerance, • vehicle-integrated curved modules with η ≥ 20% and a weight ≤ 5 kg/m2.	Target 6/7	12,870,478
SUPER-PV	Cost Reduction and Enhanced Performance of PV Systems	1/5/2018 to 30/4/2022	Module level: AR, anti-soiling and anti-heating coating based on nanomaterials; improved light harvesting; in-laminate bypass diodes, flexible encapsulation solutions. BOS component level: module-level power electronics using GaN technologies; fault-tolerant inverter topology and control architectures; low-cost meteo and soiling sensors. System level innovations: PV Information Management (PIM) platform for system design, manufacturing, installation and operation		9,907,793

Table 12 Thin-film technology - Progress of major EU-funded projects under Horizon 2020

Acronym	Title	Start/ End Date	Main Technology & Cost Objectives	TRL	EC grant EUR
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%.	4	4 563 123
ARCIGS-M	Advanced aRchitectures for ultra-thin high-efficiency CIGS solar cells with high Manufacturability	01-12-2016 31-05-2020	CIGS with 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; target cost reductions of 40%	4	4 498 700
GOTSolar	New technological advances for the third generation of Solar cells	01/01/2016 31/12/2018	Perovskites - tools to push towards 24% efficiency for cells ca. 25 mm2) and stable for 500 h under 80 °C. - lead-free light absorbers aiming at 16% efficiency also in lab-size cells. - 100 cm2 device for demonstrating a module with potential for 20 years of lifetime.	4	2 993 404
ESPResSo	Efficient Structures and Processes for Reliable Perovskite Solar Modules	01-05-2018 30-04-2020	- cell efficiency > 24% (on $1cm^2$) and < 10% degradation following IEC thermal stress cycle - modules (35 x 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.	Target 5	5 412 657
APOLO	SmArt Designed Full Printed Flexible PhotOnic-enhanced Organic HaLide PerOvskite solar cells	1/4/2018 to 30/3/2022	develop flexible & printable PSC with efficiency of 22% with at least 80% of initial performance after relevant accelerated test from standards.	Target 4 to 5	4,997,191
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. - future application in high efficiency and low cost tandem PV devices - Specifications for synthesis of Cu_2ZnXY_4 absorber with suitable back/front contacts.	3-4	3 254 755
STARCELL	Advanced strategies for substitution of critical raw materials in photovoltaics (EU-US-Japan cooperation)	01-01-2017 31-12-2019	- kesterite 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	4	4,832,189
TFQD	Thin film light-trapping enhanced quantum dot photovoltaic cells: an enabling technology for high power-to-weight ratio space	01/01/2016 31/12/2018	III-V solar cell embedding quantum dots and photonic nanogratings target efficiency higher than 30% (AM0), at least an eightfold increase of power-to-weight ratio vs. triple junction III-V solar cells and very low bending radius for rollable or inflatable solar arrays.	3	1,008,376
OLEDSOLAR	Innovative manufacturing	1/10/2018 to	(1) high yield (>15%) manufacturing processes OLEDs,	?	7,872,870

Acronym	Title	Start/ End Date	Main Technology & Cost Objectives	TRL	EC grant EUR
	processes and in-line monitoring techniques for the OLED and thin film and organic photovoltaic industries (CIGS and OPV)	30/9/2021	OPVs and CIGs solar cells in S2S and R2R environment. (2) inline system of inspection, quality control, functional testing and measurements (3) Recycling and re-use approaches (4) Automation and advance processing software for control and monitoring of manufacturing in R2R and S2S processes 5) up-scale and validation in 3 pilot lines and 4 production lines		

Table 13 Silicon Wafer Tandem technology - Progress of major EU-funded projects under Horizon 2020

Acronym	**Title**	**Start/ End Date**	**Main Technology & Cost Objectives**	**TRL**	**EC funds EUR**
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 cm^2. - Demonstrate low cost potential (<0.3€/Wp) - Develop PK-HJS tandems cells (>29% efficiency on 2x2 cm^2, at low cost (target <0.4€/Wp)	4	3 299 095
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 cm^2	3	3 561 842
NanoSol	Accelerating Commercialization of Nanowire Solar Cell Technologies	01-02-2016 31-07-2018	Basis is Sol Voltaics' SolFilm product to transfer and orient GaAS nanowires, Phase 2 goals: - integrate nanowire III-V films with Si devices - increase efficiency from 16% to 27% on tandems - prepare for la industrialization	(8)	1,740,375
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 cells to 30% using III-V top absorbers. - Prototype module 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 in a relevant environment.	4	4 298 201
HIPERION	Hybrid Photovoltaics For Efficiency Record Using Integrated Optical Technology	1/9/2019 31/8/2023	• development of an innovative optical micro-tracking technology, which concentrates sunlight on multijunction solar cells, mounted on top of a c-Si wafer (currently TRL 5-6) • module level efficiency of 29% • produce more than 100 m2 of modules	Target 7	10,590,511

Table 14 Concentrating technology - Progress of major EU-funded projects under Horizon 2020

Acronym	**Title**	**Start/ End Date**	**Main Technology & Cost Objectives**	**TRL**	**EC funds EUR**
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)	4	4 949 596
Cogem CPVTM	COGEM CPV - An innovative Ceramic Heat Spreader within HCPV	01/06/2015 31/12/2019	Develop the original HS prototype with new materials to reduce energy production costs of about 25%, and an improvement on the performance at least of 3%. - >40 year lifetime	6	2 098 456
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 optical micro-tracking technology, which concentrates sunlight on multijunction solar cells, mounted on top of a conventional silicon backplate	(8)	1,633,601
HIPERION	Hybrid Photovoltaics For Efficiency Record Using Integrated Optical Technology	1/9/2019 31/8/2023	• development of an innovative optical micro-tracking technology, which concentrates sunlight on multijunction solar cells, mounted on top of a c-Si wafer (currently TRL 5-6) • module level efficiency of 29% • produce more than 100 m2 of modules	Target 7	10,590,511

Table 15 Building Integrated PV applications - Progress of major EU-funded projects under Horizon 2020

Acronym	Title	Start/ End Date	Main Technology & Cost Objectives	TRL	EC funding, EUR
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 of 175-200€/m^2	8	1 887 121
PVSITES	Building-integrated photovoltaic technologies and systems for large-scale market deployment	01/06/2016 30/06/2020	- large BIPV market deployment by demonstrating a range building-integrated solar technologies and systems - High impact demonstration and dissemination actions for cost-effective renewable generation, reduction of energy demands and smart energy management.	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	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.	3/4	1 542 733
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 NB Based on S'Tile "iCell" concept with 4-interconnected sub-cell wafers (AL-BSF or PERC technology) and customised shapes	8	2 940 596
BIPVBoost	Bringing down costs of BIPV multifunctional solutions and processes along the value chain, enabling widespread nZEBs implementation	1/10/2018 to 30/9/2022	• flexible and automated BIPV manufacturing line • portfolio of multifunctional BIPV products for the building skin • process and energy management innovation based on digitalization • standardization and qualification activities	Target 6,7	8,844,070
PVadapt	Prefabrication, Recyclability and Modularity for cost reductions in Smart BIPV systems	1/10/2018 to 31/3/2022	• a PV/T component active energy component comprised of a sheet of flat heat pipes in a PV module • a prefabricated structural panel with multiple passive functions (thermal, resilience, stability, waterproofing etc.)	Target 7	

Acronym	Title	Start/ End Date	Main Technology & Cost Objectives	TRL	EC fund-ing, EUR
			• a Smart Envelope System, achieving critical functions such as load prediction and shifting and predictive maintenance		
Envision	ENergy harVesting by Invisible Solar IntegratiON in building skins	1/10/2017 to 30/9/2022	Develop façade solutions comprising: • panels with coloured coatings for near infrared harvesting of solar radiation • a ventilated glass concept to harvest near infrared through a glazing unit • PV solutions for glass in the façade.	Target 7 to 8	4,900,313

Table 16 Operational performance enhancement - Progress of major EU-funded projects in H2020

Acronym	Title	Start/ End Date	Main Technology & Cost Objectives	TRL	EC funds EUR
SOLARSHARC	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: - 25 year lifetime without recoating - repellent to water, dust, and bio-fouling - Cost <€10 per m2 - High transparency and anti-reflective properties	8	2 267 636
Optinanopro	Processing and control of novel nanomaterials in packaging, automotive and solar panel processing lines	1/10/2015 30/09/2018	For solar it included development of self-cleaning coatings to increase OPV effectiveness and extend the period between their maintenance and their lifetime by filtering UV light leading to material weathering.	4	6 920 685

Table 17 Market uptake - Progress of major EU-funded projects under Horizon 2020

Acronym	Title	Start/ End Date	Main Technology & Cost Objectives	TRL	EC funds EUR
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 based on 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.		2 706 940
EU HEROES	EU routes for High pEnentration of solaR PV into lOcal nEtworkS	01/09/2017 31/08/2020	- Identify at least 7 existing community energy projects that illustrate current theory and best practice for social enterprise business models - To support the implementation of at least 7 pilot projects, working in partnership with electricity network operators.	N/A	1 230 558
PVProsumers-4Grid	Development of innovative self-consumption and aggregation concepts for PV Prosumers to improve grid load and increase market value of PV		- Guidelines for Prosumers and Distributed System Operators (DSO´s), as well as policy recommendations on a regulatory framework for "prosumption". - Online tool to help prosumers to get an economic assessment of PV prosumer projects.		
SUNINBOX	Portable SolUtioN for dIstributed geNeration in a BOX (Phase 2 project)	01-02-2017 31-07-2019	- 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)	8	1 407 542

Table 18 Circular economy aspects- Progress of major EU-funded projects under Horizon 2020

Acronym	Title	Start/ End Date	Main Technology & Cost Objectives	TRL	EC funds EUR
CABRISS	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) with at least the same cells efficiency as conventional processes.	>7 for some items	7,844,565
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	(5/6)	5,642,708
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.	(8/9)	2 529 607
CIRCUSOL	Circular product-service system business models for the solar power industry	1/6/2018 to 31/5/2022	Develop sustainable product-service business models covering all sections of the value chain, including manufacturing, usage, re-use/remanufacture and recycling Product focus will be PV and batteries	N/A	7,014,893

5 Technology development Outlook

5.1 Cost Trends

The cost of PV electricity depends on several elements: the capital investment for the system, its location and the associated solar resource, its design, permitting and installation, the operational costs, the useful operation lifetime, end of life management costs and, last but not least, financing costs. Here the focus is on the investment needed for a PV system and for the modules, as the main energy conversion component.

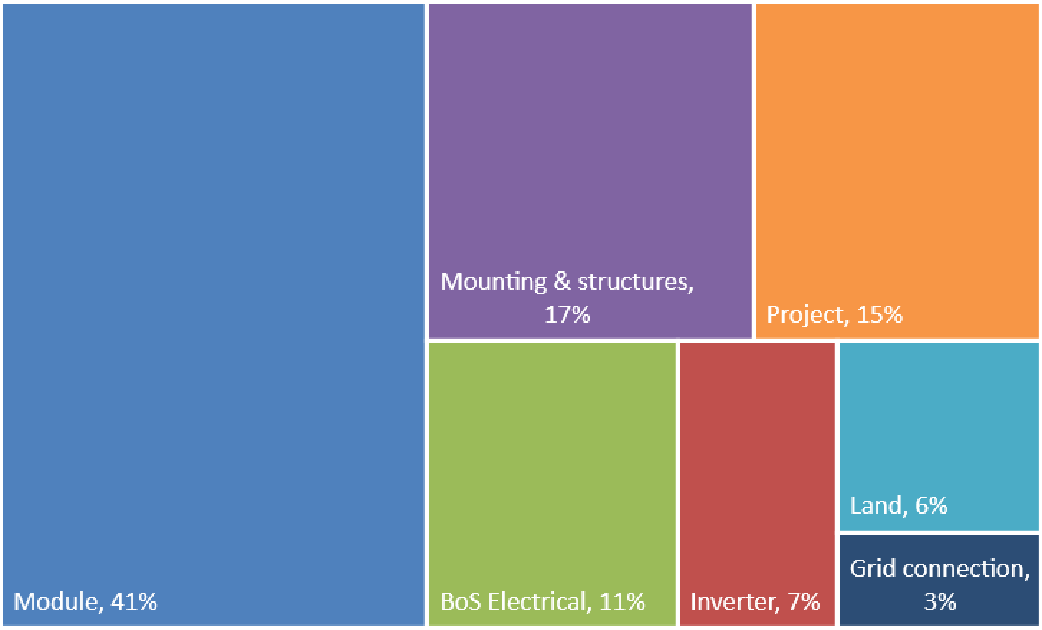
5.1.1 Modules

Modules are the largest single cost component of a system, currently accounting for approximately 40% of the total capital investment needed for utility systems (**Figure 17**), and somewhat less for residential systems where economies of scale for installation are less and soft costs are higher. Over the last four decades, solar module prices have fallen following a price-experience or 'learning' curve with an average learning rate of about 20%, i.e. the average selling price (ASP) of solar modules fell by 20% for each doubling of production volume.

Table 19 shows the April 2020 wholesale spot prices for several technologies. Some commercial products may be 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, large module sizes to reduce BoS costs, claims of improved reliability and degradation resistance, lower CO_2 footprint etc.. This cost reduction trend can continue, given the technology options in development and with further improvements in manufacturing; Hoffmann and Metz [55] have made the case for module costs reaching of 0.1 USD/W in 20 years' time.

Cost information on building integrated PV products is more difficult to evaluate both because of the wide range of products and applications and the fact that it is less commonly reported. SUPSI's 2017 survey in Europe [56] found prices from 100 to 400 EUR/m^2 – for reference a standard polysilicon module has a cost level of approximately 36 EUR/m^2.

Figure 17 PV system cost breakdown for a utility-scale system (> 100 kW)



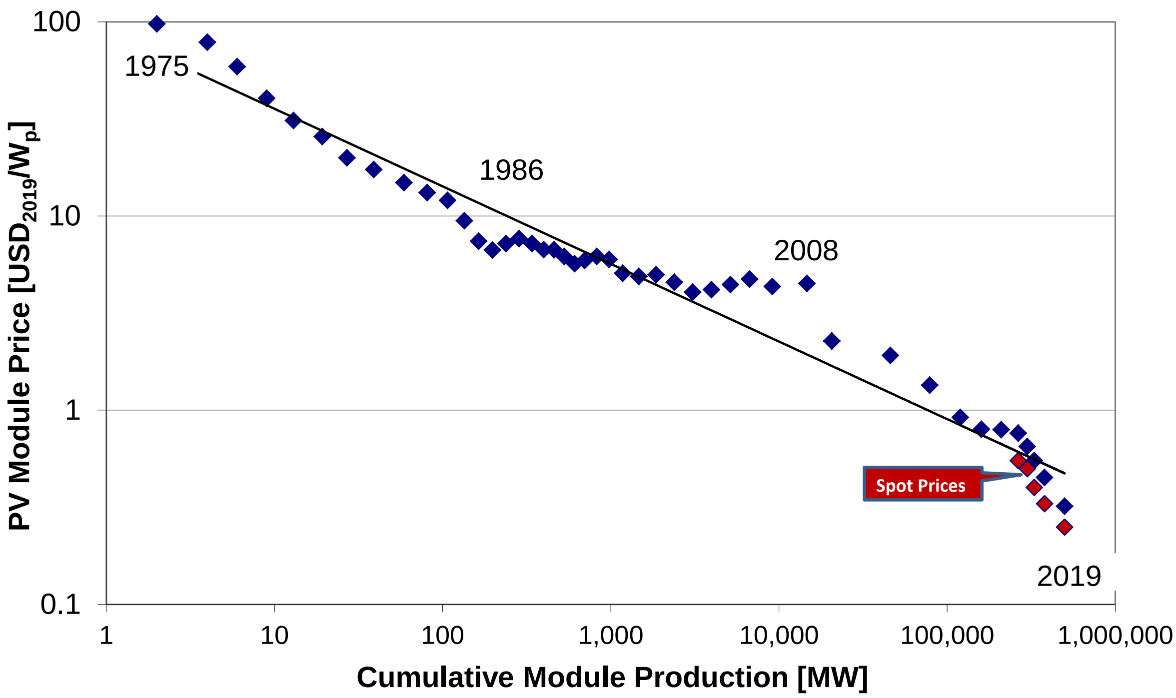
Source: JRC elaboration of ITRPV 2020 data [17]

Table 19 Wholesale spot prices for PV modules, without taxes

Technology	Average USD	High USD	Low USD
Poly Silicon Solar Module	0.177	0.290	0.160
Poly High Eff / PERC Module	0.196	0.330	0.180
Mono High Eff / PERC Module	0.200	0.380	0.185
Thin-film Solar Module	0.221	0.320	0.200

(source: PVInsights web site accessed 20/4/2020, exchange rate $/€ = 1.15)

Figure 18 Price-experience curve for solar modules [11].



Source: Bloomberg New Energy Finance (BNEF) and PV News

5.1.2 PV Systems

Over the last few years, the capital expenditures (CAPEX) for PV solar systems have converged globally. However, differences in market size and local competition can still lead to significant variations. Local factors like import taxes, local content rules, or existing tax credits have an additional influence on local prices. A global benchmark for levelized cost of electricity (LCOE) is published regularly by BNEF. For the 2nd half year (H2) 2019, this benchmark in the solar sector was USD 51 per MWh, which corresponds to a decrease of about 15% compared to of the second half 2018. With this, the LCOE for non-tracking silicon PV systems have decreased by over 77% over the last 10 years [11]. Similarly ITRTPV considers it plausible that current PV LCOE values are in a range of 25 to 61 USD/MWh for very sunny to temperature climatic conditions, and could fall to 20 to 40 USD/MWh by 2030. As part of the work of the ETIP-PV, Vartiainen et al [57] calculated PV LCOE in Europe for 2019 in a range from 24 EUR/MWh in Malaga to 42 EUR/MWh in Helsinki, and showed the potential to reduce these values by almost a half by 2030, and reduce threefold by 2050.

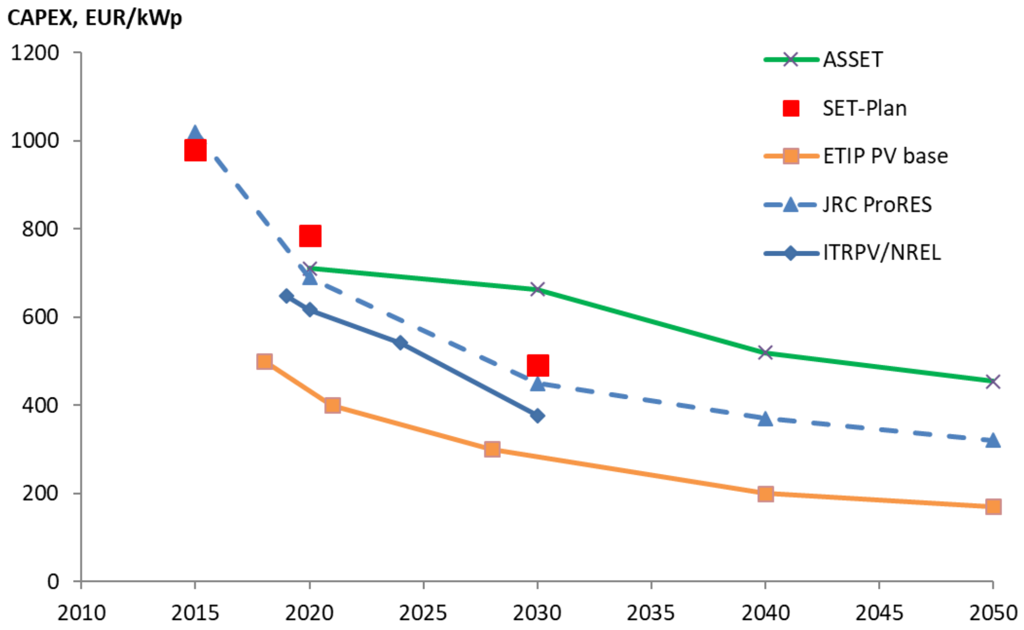
In terms of actual prices in the market, much attention is focussed on the power price agreement values obtained in auctions. A note of caution is needed as PPAs depend on the specific contractual conditions (volume, project delivery date, duration, taxes and financing). Also, project developers may be interested to bid low in order to acquire a grid connection that can be exploited for selling electricity produced outside of the PPA.

These values having been falling steadily, also in Europe. In July 2019, a Portuguese solar auction had winning bids between 14.76 and EUR 31.16 EUR/MWh for projects to be realised by June 2022.

CAPEX and OPEX trends are also important in relation to energy system modelling and the resulting scenarios used in policy assessments. Figure 19 shows projected cost trends for utility PV systems, including the ASSET data underpinning the Commission's 2018 Reference Scenarios [59], SET plan target values, JRC-EU-TIMES values for the pro-renewables scenario [60], ITRPV/NREL data from the 2020 report [17] and the baseline data from Vartiainen et al's 2019 analysis [57]. The data spread shows the difficulty to estimate PV costs for a rapidly developing technology and market, as well as a tendency to underestimate the cost reduction potential. Indeed, the fact that the two most recent analyses are on the lower end of the range points to a need to ensure that energy system models have updated cost estimates to allow them to explore the full potential of the technology.

Rooftop systems for residential or small commercial buildings have traditionally been an important market segment, particularly in Europe. Prices have seen a significant decline, and are now approximately 1000 EUR/kWp (approximately 200 EUR/m^2 or more[30]) in the well-developed and competitive German market. However, across Europe prices vary considerably and can be more than double this value [58]. Building integrated roofing systems range from 200 to 500 EUR/m^2 for standardised products and increase to 500 to 800 EUR/m2 for customised solution. BIPV facades are in the upper range [58].

Figure 19 CAPEX trends for utility PV systems



[30] The cost per unit area depends on the module efficiency and the spacing. The value quoted implies a 20% module efficiency, with 1 kW requiring 5 m^2

5.2 Future Deployment Scenarios

5.2.1 Modelling Framework

Within the LCEO project the JRC-EU-TIMES model [61] is used for assessing the possible impact of technology and cost developments. It represents the energy system of the EU27 plus UK, 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. Several scenarios were analysed, including:

Baseline:	Continuation of current trends; 48% CO_2 reduction by 2050 with respect to 1990 levels
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
SET plan	80% CO_2 reduction by 2050, with technology cost learning curves aligned to the targets identified in the various SET plan implementation plans.
Zero-Carbon	100% CO_2 reduction, underground CO_2 storage limited to 300 Mt/year.

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 [60]);

b) Environmental constraints: country specific load factor values are included to account for geographical variations in the solar resource, as well as limits on installed capacity to reflect available land and roof resources.

5.2.2 Results

Figure 20 summarises the electricity generation results for the diversified, SET plan and Zero-Carbon scenarios (the outcome of other scenarios are discussed in previous LCEO reports [6,7]). A notable feature is the large increase in electricity production in the SET plan and ZeroCarbon scenarios, reflecting a deep electrification of transport and the use of electricity to produce hydrogen, synfuels and other previously petrochemical-based products. In terms of scenario design, ZeroCarbon is comparable to the EC 2050 LTS 1.5TECH. [62], and is consistent with the new Green Deal ambition for a climate neutral Europe by 2050. The larger amount of renewables is a consequence of a higher reduction of CO_2 and because it limits underground CO_2 storage to 300 Mt/year. In all cases, the renewables contribution is dominated by wind and solar (essentially PV).

Figure 21 shows the calculated evolution of PV capacities over 2020-2050 in more detail. For the ZeroCarbon scenario the installed capacity by 2050 reaches 2.8 TW_{DC}, compared to approximately 1 TW_{DC} in the LTS 1.5TECH scenario. In terms of the type of PV installation, the model results distinguish rooftop and open field (utility) plants. While the rooftop segment grows significantly, its share of total capacity would drop from 60% in 2020 to 21% in 2050 (**Table 20**). This reflects the respective costs: the cheapest form (utility scale PV) dominates, with a smaller role for new rooftop installations.

A note regarding the 2030 timeframe: the above modelling reflects the policy situation ion 2018, aiming for 32% share of renewables. The European Commission now plans to raise the greenhouse gas (GHG) emissions reduction target from 40% towards 55% by 2030 and make Europe the first climate-neutral continent by 2050. The JRC [63] has analysed the potential role of PV by postulating an acceleration in the scenarios from the Commission's 2018 long-term strategy (LTS) for energy and climate. To reach a 55% GHG emissions reduction, it is estimated that the cumulative PV capacity in the EU and the UK would need to reach 455–605 GW_{DC}, depending on the strategic policy scenario. This implies a compound annual growth rate between 12 and 15% in the timeframe 2020–2030 to increase the annual PV market from approximately 16.5 GW_{DC} in 2019 to 50–80 GW_{DC} by 2030.

Figure 20 JRC-EU-TIMES model: distribution of power generation (TWh) by technology for the diversified (Div1), SET plan (Res4-SET) and ZeroCarbon (Res4-Near Zero carbon) scenarios for the EU28.

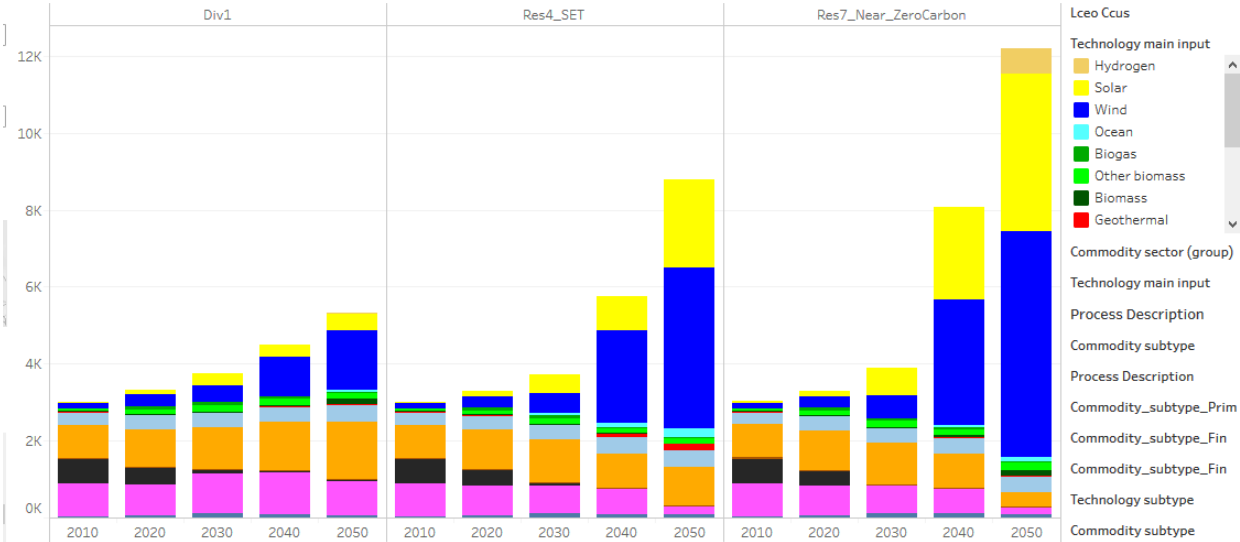


Figure 21 Growth of PV capacity (GW_{DC}) over time in selected scenarios for the EU28.

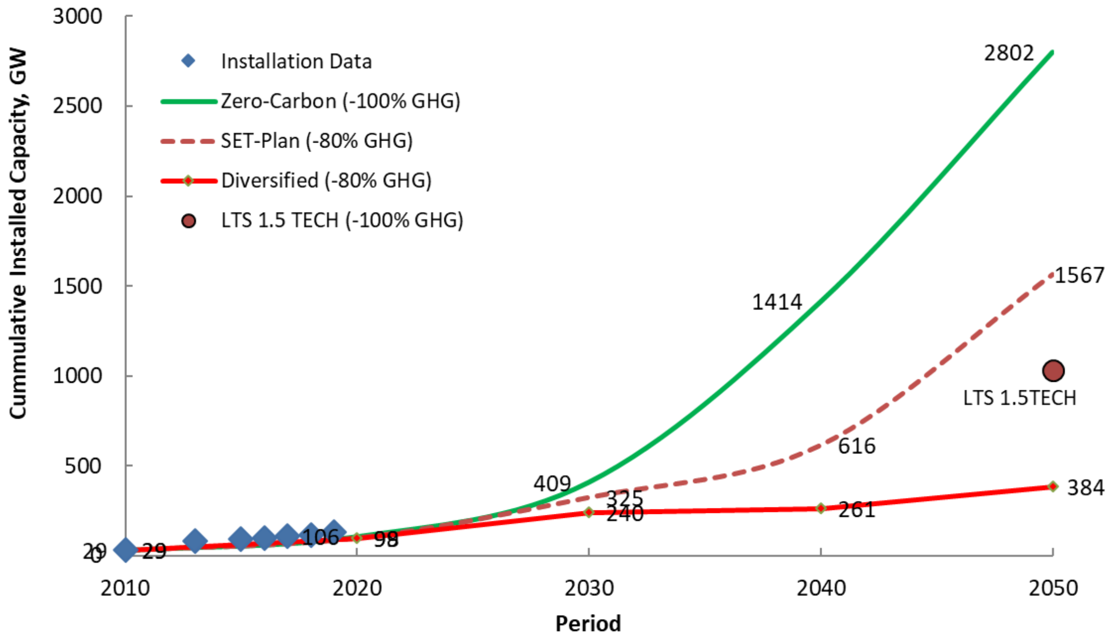


Table 20 Breakdown of solar power generation growth in the JRC-EU-TIMES ZeroCarbon scenario for the EU28.

PLANT TYPE	CAPACITY (GW_{DC})			
	2020	2030	2040	2050
PV Roof	62	100	189	602
PV Open field	42	307	1,223	2,198
PV total	104	407	1412	2802
CSP + storage	2	22	88	206

6 Conclusions

Plans for the future energy system increasingly acknowledge that wind and solar photovoltaic electricity will be the predominant energy source in the medium to long term. Europe therefore needs to continue to develop and exploit its research resources for photovoltaics and remain a global leader. The SET plan implementation plan provides a strategy for this, but needs full implementation by all the stakeholders.

6.1 R&I Resources and Programmes

- Europe retains a strong basis in research on PV technologies, but also faces stiff competition at global level. The EU is second only to China in terms of annual output of scientific articles. In terms of patents, in 2016 the EU accounted for 22% of so-called "high-value" patent family applications, although in terms of absolute numbers Asian countries lead the way. For the EU, areas of relative strength include power conversion equipment and BIPV.

- The H2020 programme is supporting a broad range of R&D projects on photovoltaics. From the results described in the body of this report, the grand majority of the projects have been successful in advancing the TRL level, even if not always reaching the ambitious goals set in the work programme.

- The innovation phase however continues to pose significant challenges. On the positive side, the AMPERE project, which includes the setting up of production of heterojunction cells and modules, is a significant step forward and exploits over 12 years' research under FP6, FP7 and H2020. The Oxford PV plant currently in development for tandem crystalline silicon and perovskite cells has benefited in part from EIB funding, with the promise of creating a commercial breakthrough for this specific technology. However in general, 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. Relatively few projects have sufficient resources to address this, particularly those requiring further technical development as well as pilot manufacturing. The new EU Green Deal and European Recovery funds could play a role in developing a new generation of PV manufacturing. Also large-scale demonstration programmes are needed, and the ETS Innovation Fund could be critical for bringing advanced concepts to commercialisation.

6.2 Technology Outlook

Wafer-based silicon technology is set to remain the predominant PV technology in the medium term. Chinese manufacturers already have module production costs as low as EUR 0.20/W. This is accompanied by a major shift in production to PERC cell architectures, bringing power conversion efficiency to the 20% level and above. Already passivated contact and heterojunction cells architectures are entering mass production and continued R&D can help push commercial cell efficiency towards 26% and the practical limits for single junction crystalline silicon. For further efficiency gains, the focus is tandem devices, mostly prominently on crystalline silicon and perovskite tandems that already have demonstrated close to 29% in the laboratory. The combination of the III-V materials with crystalline silicon offers promise but technically remains a challenge. Transversal themes such as improved contact, minimisation of reflection, improving light trapping and spectrum adjustment can also play a significant role.

For thin-films, both copper indium gallium diselenide disulphide (CIGS) and cadmium telluride technologies have established cell efficiency records of 22% or more and are confronting the technological challenge to transfer these gains to modules at competitive cost. Perovskite devices are steadily increasing in performance and lifetime but need further development for commercialisation, as well as efforts to quantify the risk (if any) of leaching of lead from damaged products. Also here tandem concepts promise high efficiency with lower environmental impact e.g. CIGS with perovskite. On the other hand, kesterites appear stalled at efficiencies around 12%, and the market outlook is not encouraging unless some fundamental technical issues can be overcome. CPV technology offers the highest absolute efficiencies 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.

Integrated PV represents an important future market opportunity and applications such as vehicle-integrated PV, agri-PV and floating PV all bring specific technical challenges. In particular, PV in buildings directly supports the objectives of a European Green Deal and the urgent need to decarbonise the EU's building stock. Technical issues include balancing product customisation and standardisation (to lower costs), integrated approaches to safety and building certification procedures, inclusion in building energy management tools, as well as methods for ensuring product durability and that these meet requirements for inspection and repair/replacement in service.

For all PV technologies, an increasing focus will be needed on circular economy aspects and to socio-economic effects associated with terawatt-scale deployment.

7 References

1. European Commission. A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. COM(2018) 773 2018:114.
2. Adoption of the Paris Agreement, United Nations Framework Convention on Climate Change, FCCC/CP/2015/L.9/Rev.1, 12/12/2015
3. European Commission. Commission proposal for a regulation: European Climate Law. Brussels, Belgium: European Commission; 2020
4. European Commission, The European Green Deal. COM(2019) 640; 2019
5. Taylor, N, Jäger-Waldau A., Photovoltaics Technology Development Report 2016, Deliverable D2.1.2 for the Low Carbon Energy Observatory, JRC 100888, 2016
6. N. Taylor, A. Jäger-Waldau, Low Carbon Energy Observatory Photovoltaics Technology Development Report 2018 – Public Version, EUR 29916 EN , European Commission, Luxemburg, 2019, ISBN 978-92-76-12541-9, doi:10.2760/373667, JRC118300.
7. N. Taylor, A. Jäger-Waldau, Low Carbon Energy Observatory Photovoltaics Technology Market Report 2018 – Public Version, EUR 29935 EN, European Commission, Luxemburg, 2019, ISBN 978-92-76-12598-3, doi:10.2760/901540, JRC118307.
8. SET plan TWP PV Implementation Plan, Final Draft, 18 October 2017
9. G.M. Wilson et al, The 2020 Photovoltaic Technologies Roadmap, Journal of Physics D: Applied Physics, https://doi.org/10.1088/1361-6463/ab9c6a, Accepted Manuscript online 12 June 2020
10. S. Peteves et al, Implementing the SET PLAN - Progress from the Implementation working groups,2019, JRC 118272
11. Jäger-Waldau A. Snapshot of photovoltaics-February 2020. Energies 2020;13. https://doi.org/10.1051/epjpv/2018004
12. IEA PVPS, 2018 Snapshot of Global Photovoltaic Markets, ISBN 978–3–906042–72-5
13. IRENA (2018), Global Energy Transformation: A roadmap to 2050, International Renewable Energy Agency, Abu Dhabi.
14. Jäger-Waldau, A., PV Status Report 2019. Luxembourg: 2019, https://doi.org/10.2760/326629
15. Jäger-Waldau et al, How photovoltaics can contribute to GHG emission reductions of 55% in the EU by 2030, Renewable and Sustainable Energy Reviews 126 (2020) 109836
16. Photovoltaics Report, Fraunhofer Institute for Solar Energy & PSE AG, Freiburg, 14 November 2019
17. International Technology Roadmap for Photovoltaics - 2019 Results, Eleventh Edition, VDMA, April 2020
18. A. De Rose, M. Buna, C. Strazza, N. Olivieri, T. Stevens, L. Peeters, D. Tawil-Jamault, Technology Readiness Level: Guidance Principles for Renewable Energy technologies, Final Report, 2017 EUR 27988 EN
19. S.K. Chunduri, M. Schmela, High Efficiency Cell Technologies 2019 Edition, Taiyang News
20. M. A. Green, E.D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, A. W.Y. Ho-Baillie, Solar cell efficiency tables (version 55),. Prog. Photovolt Res Appl. 2020; 28:3–15.
21. CIGS White Paper, 2019, https://cigs-pv.net/wortpresse/wp-content/uploads/2019/04/CIGS_White_Paper_2019_online.pdf
22. Perovskite-based photovoltaics: A unique chance for European PV-industry, A White Paper from the European Perovskite Initiative, September 2019
23. Pérez-Rodríguez, A., Thin-film photovoltaics: current status and future challenges, EMIRI Tech Talk on PV & CSP (photovoltaics & concentrated solar power) October 24th 2017, Brussels, Belgium

24. Marko Jošt, Lukas Kegelmann, Lars Korte, and Steve Albrecht, Monolithic Perovskite Tandem Solar Cells: A Review of the Present Status and Advanced Characterization Methods Toward 30% Efficiency, Adv. Energy Mater. 2020, 10, 1904102

25. Meier, J., S. Dubail, R. Platz, P. Torres, U. Kroll, J.A. Selvan, N. Pellaton Vaucher, C. Hof, D. Fischer, H. Keppner, R. Flückiger, A. Shah, S. Shklover, and K.-D. Ufert, 1997: Towards high-efficiency thin-film silicon solar cells with the "micromorph" concept. Solar Energy Materials and Solar Cells, 49(1-4), pp. 35-44

26. S. P. Philipps, A.W. Bett, K. Horowitz, S. Kurtz, Current status of concentrator photovoltaic (CPV) technology, Version 1.2, February 2016

27. Dodd, N.; Espinosa, N., Bennet, M. Preparatory study for solar photovoltaic modules, inverters and systems, Task 2 Report: Market data and trends, JRC 180611, 2018

28. SMA Solar Technology AG. Whitepaper: Maximum freedom when oversizing. Niestetal, Germany: 2019

29. Sample, T., Müllejans, H., Salis, E., Bardizza, G., Gracia Amillo, A., Kenny, R., Dunlop, ED. and Taylor, N., Photovoltaic Energy Systems: Summary of the Joint Research Centre's contribution to international and European standards in 2019, JRC Report 119538

30. Dunlop E.D., Gracia Amillo A., Salis E., Sample T., Taylor N., Standards for the assessment of the environmental performance of photovoltaic modules, power conversion equipment and photovoltaic systems, EUR 29247 EN, doi:10.2760/89830, 2019

31. Outcome of the workshop "Bringing the BIPV ecosystem together: building links between the BIPV sector, policymakers, municipalities and the construction sector", European Commission Joint Research Centre, Ispra, Italy, 30 January 2020, in cooperation with Solar Power Europe.

32. Marmier, A. et al, European Union, Horizon Scanning Alert - Agrivoltaics, shielding crops with PV panels, European Commission 2020, JRC120514

33. M. de Wild-Scholten, V. Cassagne, T. Huld, Solar resources and carbon footprint of photovoltaic power in different regions in Europe, 29th European Photovoltaic Solar Energy Conference and Exhibition, 2014.

34. M. Peh et al, Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling, Nature Energy, Vol 2, 2017, 939–945

35. R. Frischknecht, G. Heath, M. Raugei, P. Sinha, M. de Wild-Scholten IEA PVPS Task 12 - Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity 3rd Edition

36. COM(2020) 474 final Critical Raw Materials Resilience: Charting a Path towards greater Security and
37. Sustainability

38. Carrara S., Alves Dias P., Plazzotta B. and Pavel C., Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system, EUR 30095 EN,

39. A.Wade, P. Stolz, R. Frischknecht, G. Heath, P. Sinha, S. Pelland, J. Remund, J. Kleissl, T. Oozeki, K. De Brabandere,, The product environmental footprint (PRF) of photovoltaic modules – lessons learned from the environmental footprint pilot phase on the way to a single market for green products in the European Union, Proc. 33rd European Photovoltaic Solar Energy Conference and Exhibition, 2017

40. Jordan, D., Kurtz S., VanSant K and Newmiller J., 2016 Compendium of photovoltaic degradation rates Prog Photovoltaics Res Appl 24 978-89

41. Polo et al. Preliminary survey on site-adaptation techniques for satellite-derived and reanalysis solar radiation datasets. Solar Energy 2016, 132, 25-37

42. Photovoltaic and Solar Forecasting: State of the Art, IEA PVPS Task 14, Subtask 3.1 Report IEA-PVPS T14, 01/ 2013, ISBN 978-3-906042-13-8

43. Yang, D., Kleissl J., Gueymard C. Pedro HTC, Coimbra CFM. History and trends in solar irradiance and PV forecasting: A preliminary assessment and review using text mining. Solar Energy 2018, 168, 60-101

44. Blaga R, Sabadus A, Stefu N, Dughir C, Paulescu M, Badescu V. A current perspective on the accuracy of incoming solar energy forecasting. Progress in Energy and Combustion Science 2019, 70, 119-144

45. Yang et al, Verification of deterministic solar forecasts, Solar Energy, available May 2020

46. A. Fiorini, A. Georgakaki, F. Pasimeni, E. Tzimas, "Monitoring R&D in Low-Carbon Energy Technologies", EUR 28446 EN (2017), doi: 10.2760/434051,

47. Pasimeni, F., Fiorini, A., and Georgakaki, A. (2019). Assessing private R&D spending in Europe for climate change mitigation technologies via patent data. World Patent Information, 59, 101927. https://doi.org/10.1016/j.wpi.2019.101927

48. Pasimeni, F. (2019). SQL query to increase data accuracy and completeness in PATSTAT. World Patent Information, 57, 1-7. https://doi.org/10.1016/j.wpi.2019.02.001

49. N. Persat, M.-A. Le Meur, M. Boero, C. Königstein, An Overview Of Patent Application Data In Europe In The Field Of Photovoltaics, Proc. EUPVSEC 2019.

50. A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy, COM(2015)80, Brussels, 25.2.2015

51. Telsnig T, Wind Energy Technology Development Report 2020, European Commission, 2020, JRC120709.

52. N. Scarlat, F. Fahl, Heat and Power from Biomass Technology Development Report, European Commission Joint Research Centre, 2020, JRC120920.

53. S. Nowak et al, Solar-Era.Net - European Network of National and Regional Research and Innovation Programmes: Latest Developments of Transnational Cooperation, Project Results and Opportunities, Proc. EUPVSEC 2019, doi: 10.4229/EUPVSEC20192019-7DO.7.3

54. IEA Photovoltaic Power Systems Programme, Annual Report 2019, ISBN 978-3-906042-95-4 (available at http://iea-pvps.org)

55. W. Hoffmann, A. Metz, Modules at a Price of 10 $ct/Wp - Dream or Reality? New Approach for Future Cost and Price Predictions, Proc. EUPVSEC 2019, d.o.i 10.4229/EUPVSEC20192019-7EO.3.6

56. I. Zanetti, P. Bonomo, F. Frontini, E. Saretta, Building Integrated Photovoltaics: Product overview for solar building skins Status Report 2017, 2017, SUPSI-SEAC BIPV

57. E. Vartiainen et al, Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity, Prog Photovolt Res Appl. 2019; 1–15.

58. BIPVBoost H2020 Project, Competitiveness status of BIPV solutions in Europe, January 2020, https://bipvboost.eu/public-reports/

59. De Vita, A. et al. (2018) 'Technology pathways in decarbonisation scenarios', p. 62. Available at: https://ec.europa.eu/energy/sites/ener/files/documents/

60. Tsiropoulos, I., Tarvydas, D. and Zucker, A. (2018) Cost development of low carbon energy technologies - Scenario-based cost trajectories to 2050, 2017 Edition, EUR 29034 EN, JRC109894. Luxembourg. doi: 10.2760/490059.

61. Nijs, W, Ruiz, Castello P., Tarvydas, D., Tsiropoulos, I., Zucker, A., Deployment Scenarios for Low Carbon Energy Technologies, LCEO Deliverable Report D4.7, 2018

62. Capros P, Zazias G, Evangelopoulou S, Kannavou M, Fotiou T, Siskos P, et al. Energy-system modelling of the EU strategy towards climate-neutrality. Energy Policy 2019; 134. doi:10.1016/j.enpol.2019.110960.

63. Jaeger-Waldau, A., et al, How photovoltaics can contribute to GHG emission reductions of 55% in the EU by 2030, Renewable and Sustainable Energy Reviews 126 (2020) 109836

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	2014-2020 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
TRL	Technology Readiness Level

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)
CZ	Czochralski (process for mono-crystalline silicon)

DS	Directionally solidified (multicrystalline, “cast-mono” and “quasi-mono” Si ingot)
DSC	Dye-Sensitized Cell
ED	Electro-Deposition
HJT	Heterojunction Technology
ITO	Indium tin oxide (used as a transparent conductive oxide 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
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

List of figures

List of tables

Appendix 1 TRL definitions and checkpoints

RE TECHNOLOGY: PHOTOVOLTAICS	
TRL #1	**Basic principles observed**
	Description Basic research. Principles postulated and observed but no experimental proof available
	Identification of scientific concept and interfaces Starting from published research and data from literature, a promising new concept related to photovoltaic technology is identified. The system is summarily described, identifying the basic technology and the materials needed. The fundamental of the concept is investigated, and the expected barriers identified. TRL 1 is defined according the following elements and features: - identification of the new materials and technology related to the PV cells, modules and other components (i.e. wafer based-technology, thin-film PV technology or other technologies based on promising concepts, nanotechnologies and nanomaterials, substrates, glasses, encapsulant, interconnection technologies) and preliminary design.
	Checkpoints
	Once readiness level 1 is achieved, the scientific concept is observed and documented. This means: - definition of the scientific concept; - identification of adequate materials and technologies on the basis of data found in the literature; - achievement of fundamental knowledge of materials and interfaces; - Identification of expected barriers; - First guess of how much time it will take to become a technology possible applicable on the market; - evaluation of the potential benefits of the new concept over the existing ones.
TRL #2	**Technology concept formulated**
	Description Technology formulation. Concept and application have been formulated
	Proof of concept or sample prototyping approach definition and first experimental results An enhanced knowledge of the materials and the interfaces is acquired, based on scientific principles and including published papers and patents. A proof of concept or sample prototyping approach is identified and described for the individual cells or other specific PV technologies at laboratory scale. A suitable design is proposed. Functionality measuring solar energy conversion is starting to be evaluated, also based on comparison with similar devices in the literature/modelling. If other technologies are required, the integration issues are identified. TRL 2 is defined according the following elements and features: - identification of design procedures of the new PV cell or other specific PV technologies with demonstration of the photovoltaic effect and definition of the cell sample prototyping approach;

	- first evaluation of the feasibility of the technology is performed.
	Checkpoints
	Once readiness level 2 is achieved, the applied technological concept has been defined. This means: - initial empirical / numerical knowledge, understanding and identification of materials (including pros and cons), interfaces, procedures and physical characteristics; - Proof of concept or sample prototyping approach determination for test laboratory; preliminary feasibility is performed.
TRL #3	**Experimental proof of concept**
	Description Applied research. First laboratory tests complete; proof of concept
	Development of a proof-of-concept prototype, experimental evaluation and compatibility evaluation Experimental set-up is completed: this includes separate studies of independent elements of the technology at laboratory level and their integration. To better evaluate components integration at module level, characterization tests are undertaken (e.g. optoelectronic for cells) and/or simulation activities are required and the first efficiency measurements of the first prototype are made. KPIs relevant for the technology are identified. The results from laboratory studies permit the quantification of the present performance. TRL 3 is defined according the following elements and features: - Development of a proof-of-concept prototype of the new PV cell or PV technology including, at minimum, performance measurements (e.g. conversion efficiency, stability); - Confirmation that the proposed PV cell or PV technology could interface with existing surrounding components of the wider PV system (i.e. relationships with all the components of the photovoltaic system other than the photovoltaic panel: inverters, transformers, wiring, etc.) and identification of most suitable components. If the proposed PV PV cell or PV technology is unlikely to be able to interface with existing surrounding components of the wider PV system then changes to components need to be identified and the process of designing these components must start.
	Checkpoints
	Once readiness level 3 has been achieved, the applied technological concept has been defined. This means: - Prototype has been built through integration of technologies at laboratory level; - verification of compatibility between PV cell or PV technology and supporting technologies; - validation through numerical analysis (if applicable); - identification of prototype strength and weakness; - check the performances against a set of well-defined and repeatable experimental conditions; - KPIs are identified.
TRL #4	**Technology validated in lab**
	Description Small scale prototype built in a laboratory environment (“ugly” prototype)
	Validation of experimental application, manufacturability and interoperability The photovoltaic system components are integrated and their compatibility validated at laboratory level in a small scale prototype. Also the compatibility with other technologies is verified. Validation can be also made through an enhanced numerical model.

	In respect to TRL3, TRL 4 is defined according the following elements and features of the new PV cell or PV technology: - better reliability; - the device dimensions are closer to final scale (e.g. module, energy production unit, ...); - improved efficiency.
	Checkpoints
	Once readiness level 4 has been achieved, the applied technological concept is experimented and validated. This means: - the new PV cell or PV technology is reproducible and it is reliable/stable for its intended application; - device dimensions are closer to final scale; - validation with enhanced numerical model; - performances are repeatable and stable
TRL #5	**Technology validated in relevant environment**
	Description Large scale prototype tested in intended environment
	Validation of experimental application and production in simulated environment The photovoltaic components are integrated in a first complete system, with additional supporting elements (i.e. hardware and software) and auxiliaries, to be tested and validated in a (simulated) relevant working environment. It includes testing in different environmental conditions (e.g. varying irradiance levels, shading, mechanical loading, humidity levels...). TRL 5 is defined according the following elements and features: - photovoltaic module or technology large scale lab prototype is built and tested in (simulated) relevant environment, with natural or artificially simulated environmental conditions. Efficiency is calculated on testing results and matches with expected performances; - BoS components are integrated in the large scale lab prototype; - The robustness of the system is proven in the simulated environment.
	Checkpoints
	Once readiness level 5 has been achieved, the technology is ready for full-scale. This means: - Non technological parameters (environmental, social acceptance, regulatory) are defined and qualitatively assessed; - PV module or technology lab prototype completed; - testing and validation in simulated relevant environment finished matching the expected performances; - quantification of an early average performance ratio (i.e. solar yield [kWh/(kW$_p$*yr)] in function of solar irradiation level [kWh/(m^2*yr)]).
TRL #6	**Technology demonstrated in relevant environment**
	Description Prototype system tested in intended environment close to expected performance

<table>
<tr><td></td><td>Technology application functioning, manufacturing and pilot system verified
The integrated photovoltaic system (first pilot scale product) is verified in a relevant realistic environment.
The manufacturing approach is investigated: production demonstration includes prototype materials, tools, test equipment and personnel skills. Potential investors express interest in the application of technology: qualitative risk analysis and risk mitigation strategy are carried out and preliminary market analysis is performed.
The system is integrated following standardization and norms compliance; installation procedures are defined and installation authorizations and H&S issues are taken into account.
TRL 6 is defined according the following elements and features:
- photovoltaic pilot system (including all relevant mechanical, electrical components) is built and demonstrated in relevant environment, analyzing the behavior with different natural solar irradiation.
Performances are calculated based on demonstration results</td></tr>
<tr><td></td><td>Checkpoints</td></tr>
<tr><td></td><td>Once readiness level 6 is achieved, the technology is enlarged to full-scale. This means:
- technology demonstrated in relevant environment;
- conceptual design of the manufacturing line is drafted.</td></tr>
<tr><td>TRL #7</td><td>System prototype demonstration in operational environment</td></tr>
<tr><td></td><td>Description
Demonstration system operating in operational environment at pre-commercial stage</td></tr>
<tr><td></td><td>Full scale pre-commercial demonstrator integrated and demonstrated in field (operational environment)
The full scale pre-commercial photovoltaic system is demonstrated in an operational environment.
Manufacturing processes and procedures are demonstrated in an industrially relevant environment: production planning is complete. Currently the production process can be run for a limited period.
The integration of upstream and downstream technologies has been verified and validated also in an operational environment.
Control and communication systems guarantee also an independent test mode to allow long term demonstration.
The system is installed and runs following local standards and norms; installation procedures are qualified.
TRL 7 is defined according to the following elements and features:
- photovoltaic full scale pilot system (including all relevant mechanical, electrical components) is built and demonstrated in operational environment, analyzing the behavior with different natural solar irradiation and conditions. Performances are calculated based on demonstration results.</td></tr>
<tr><td></td><td>Checkpoints</td></tr>
<tr><td></td><td>Once readiness level 7 is achieved, the technology concept is validated at full-scale. This means:
- pre commercial installation demonstrated in field (operational environment);
- verification of the expected efficiency, in an operational environment;
- reliability of the integrated full scale prototype;
- manufacturing approach demonstrated;
- system stability under long-term real-time outdoor conditions is confirmed.</td></tr>
</table>

TRL #8	**System complete and qualified**
	Description First of a kind commercial system. Manufacturing issues solved
	System completed and qualified through test and demonstration The full scale photovoltaic system is tested in real world and has proven its functioning in its final form. Manufacturing process is stable enough for entering in a high-rate production and all materials are available: manufacturing processes and procedures are established, controlled and measurable to meet design key characteristics tolerances. Training and maintenance documentation are completed and available to the end users. All the standards and certifications requested are respected.
	TRL 8 is defined according the following elements and features: - the complete photovoltaic system and manufacturing process are working in a reliable and continuous way. Unexpected faults and failures may happen. Feedbacks are given to improve the system.
	Checkpoints
	Once readiness 8 is achieved, the system is incorporated in commercial design. This means: - technology in its final form and under expected conditions; - limited and stable production of the technology is demonstrated; - mandatory certifications completed;
TRL #9	**Actual system proven in operational environment**
	Description Full commercial application, technology available for consumers
	Actual system operational The PV power system is proven operational. Actual application of the technology is ready for deployment at large production rate. The integration with other supporting technologies is mature. The system is ready for full rate production: materials, manufacturing processes and procedures, test equipment are in production and controlled. Lean practices are established.
	Checkpoints
	Once readiness level 9 is achieved, the system is ready for full-scale deployment. This means: - PV power system fully operational, at optimized energy yield under field conditions; - scale-up production optimized for high volumes; - operability and maintainability of the system proven in the field.

Appendix 2 Patent codes for PV devices and systems

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[31]
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	Y02P 02/70	

[31] CPC Y02E 10/549 includes perovskites, although these are hybrid organic/inorganic materials.

Appendix 3 Listing of EU Supported R&D Projects for PV

Id	Acronym	Title	Main PV Tech.	Application	Project Type	EU Funding	Start	End
720887	ARCIGS-M	Advanced aRchitectures for ultra-thin high-efficiency CIGS solar cells with high Manufacturability	CIGS	buildings	IA	4,498,701	01/12/2016	31/05/2020
870004	Solar-Win	Next generation transparent solar windows based on customised integrated photovoltaics	CIGS	buildings	IA	2,419,594	01-10-2019	30-09-2021
856071	LUMIDUCT	Transparent PV that regulates indoor climate	III-V	buildings	SME-1	50,000	01-02-2019	31-05-2019
639760	PEDAL	Plasmonic Enhancement and Directionality of Emission for Advanced Luminescent Solar Devices	LSC	buildings	ERC-STG	1,447,410	01-04-2015	31-03-2021
818762	SPECTRACON	Materials Engineering of Integrated Hybrid Spectral Converters for Next Generation Luminescent Solar Devices	LSC	buildings	ERC-COG	2,124,593	01-05-2019	30-04-2024
774717	PanePowerSW	Transparent Solar Panel Technology for Energy Autonomous Greenhouses and Glass Buildings	OPV/DSSC	buildings	SME-1	50,000	01-05-2017	31-08-2017
804554	PanePowerSW	Transparent Solar Panel Technology for Energy Autonomous Greenhouses and Glass Buildings	OPV/DSSC	buildings	SME-2	1,491,783	01-03-2018	29-02-2020
889405	PIPER	Printing of Ultra-Thin, Flexible Perovskite Solar Cells and its Commercial Application	Peroskites	buildings	SME-1	50,000	01-12-2019	31-05-2020
717956	HyTile	Sensitive integrated Solar Hybrid Roofing for historical buildings.	Silicon	buildings	SME-1	50,000	01-03-2016	30-06-2016
726703	SolTile	A roof integrated solar tile system to develop cost-effective distributed solar power generation	Silicon	buildings	SME-2	1,542,733	01/10/2016	31/03/2019
684019	Soltile	A roof integrated solar tile system to develop cost-effective distributed solar power generation.	Silicon	buildings	SME-1	50,000	01-07-2015	31-10-2015
737884	STILORMADE	Highly efficient non-standard solar modules manufactured through an automated, reconfigurable mass production processes delivering 30% reduction in costs	Silicon	buildings	IA	2,836,035	01/01/2017	31/03/2019
857793	HighLite	High-performance low-cost modules with excellent environmental profiles for a competitive EU PV manufacturing industry	Silicon	buildings	IA	12,870,478	01-10-2019	30-09-2022
818342	PVadapt	Prefabrication, Recyclability and Modularity for cost reductions in Smart buildings systems	Silicon	buildings	IA	8,978,434	01-10-2018	31-03-2022

Id	Acronym	Title	Main PV Tech.	Application	Project Type	EU Funding	Start	End
666507	ADVANCED -buildings	New Generation of buildings glass with advanced integration properties	various	buildings	SME-2	1,887,121	01/04/2015	31/03/2017
817991	BIPVBOOST	Bringing down costs of buildings multifunctional solutions and processes along the value chain, enabling widespread nZEBs implementation	various	buildings	IA	8,844,070	01-10-2018	30-09-2022
767180	Envision	ENergy harVesting by Invisible Solar IntegratiON in building skins	various	buildings	IA	4,900,313	01-10-2017	31-03-2022
691768	PVSITES	Building-integrated photovoltaic technologies and systems for large-scale market deployment	various	buildings	IA	5,467,612	01-01-2016	30-06-2020
875870	SolMate	The world's first "Plug-in and Use-Solar PV with Storage", designed for small city apartments in the EU.	various	buildings	SME-1	50,000	01-08-2019	31-01-2020
826002	Tech4Win	Disruptive sustainable TECHnologies FOR next generation pvWINdows	various	buildings	RIA	2,877,045	01-01-2019	30-06-2022
640873	CPVMatch	Concentrating Photovoltaic modules using advanced technologies and cells for highest efficiencies	III-V	CPV	RIA	4,949,596	01/05/2015	31/10/2018
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 multijunction photovoltaic cell array	III-V	CPV	SME-1	50,000	01-05-2015	31-10-2015
683928	REPHLECT	Recovering Europe´s PHotovoltaics LEadership through high Concentration Technology	III-V	CPV	SME-2	1,633,601	01/08/2015	30/04/2018
758885	4SUNS	4-Colours/2-Junctions of III-V semiconductors on Si to use in electronics devices and solar cells	III-V	CPV	ERC-STG	1,499,719	01-02-2018	31-01-2023
857775	HIPERION	Hydrid photovoltaics for efficiency record using optical technology	III-V	CPV	IA	10,590,511	01-09-2019	31-08-2023
683876	SoHo3X	Introducing a novel concept of solar photovoltaic module in the market	Silicon	CPV	SME-1	50,000	01-07-2015	31-10-2015
641004	Sharc25	Super high efficiency Cu(In,Ga)Se2 thin-film solar cells approaching 25%	CIGS	general	RIA	4,563,123	01/05/2015	31/10/2018
715027	Uniting PV	Applying silicon solar cell technology to revolutionize the design of thin-film solar cells and enhance their efficiency, cost and stability	CIGS	general	ERC-STG	1,986,125	01-03-2017	28-02-2022

Id	Acronym	Title	Main PV Tech.	Application	Project Type	EU Funding	Start	End
655272	HISTORIC	High efficiency GaInP/GaAs Tandem wafer bonded solar cell on silicon	III-V	general	MSCA-IF-EF-ST	159,461	01-06-2015	31-05-2017
696519	NanoSol	Accelerating Commercialization of Nanowire Solar Cell Technologies	III-V	general	SME-2	1,740,375	01/02/2016	30/04/2019
641023	Nano-Tandem	Nanowire based Tandem Solar Cells	III-V	general	RIA	3,561,842	01/05/2015	30/04/2019
656208	NEXTNANOCELLS	Next generation nanowire solar cells	III-V	general	MSCA-IF-EF-ST	173,857	01-08-2015	25-04-2018
702629	R2R-3G	Towards Roll-to-Roll Production of Third Generation Solar Cells	III-V	general	MSCA-IF-EF-ST	187,420	01-06-2016	31-05-2018
687253	TFQD	Thin film light-trapping enhanced quantum dot photovoltaic cells: an enabling technology for high power-to-weight ratio space solar arrays.	III-V	general	RIA	1,008,376	01/01/2016	31/12/2018
727497	SITASOL	Application relevant validation of c-Si based tandem solar cell processes with 30% efficiency target	III-V	general	RIA	4,298,201	01/05/2017	31/10/2020
720907	STARCELL	Advanced strategies for substitution of critical raw materials in photovoltaics	Kesterites	general	RIA	4,832,185	01/01/2017	31/12/2019
640868	SWInG	Development of thin film Solar cells based on WIde band Gap kesterite absorbers	Kesterites	general	RIA	3,254,755	01/06/2015	31/05/2018
777968	INFINITE-CELL	International cooperation for the development of cost-efficient kesterite/c-Si thin film next generation tandem solar cells	Kesterites	general	MSCA-RISE	1,318,500	01-11-2017	31-10-2021
747734	Hy-solFullGraph	New hybrid-nanocarbon allotropes based on soluble fullerene derivatives in combination with carbon nanotubes and graphene. Application in organic solar cells and biomaterials.	OPV/DSSC	general	MSCA-IF-EF-ST	159,461	01-05-2017	30-04-2019
656658	NanoCuI	Nano-Copper Iodide: A New Material for High Performance P-Type Dye-Sensitized Solar Cells	OPV/DSSC	general	MSCA-IF-EF-ST	195,455	03-09-2015	02-09-2017
715354	p-TYPE	Transparent p-type semiconductors for efficient solar energy capture, conversion and storage.	OPV/DSSC	general	ERC-STG	1,499,840	01-01-2017	31-12-2022
844655	SMOLAC	Theoretical design of non-fullerene small molecule acceptors for organic solar cells with improved efficiency.	OPV/DSSC	general	MSCA-IF-EF-ST	174,806	01-12-2019	31-01-2022

Id	Acronym	Title	Main PV Tech.	Application	Project Type	EU Funding	Start	End
793424	TRIBOSC	Towards Radically Innovative Materials for Better and Sustainable Organic Solar Cells	OPV/DSSC	general	MSCA-IF-EF-ST	183,455	01-10-2018	16-12-2020
843872	WONDER	Low-Bandgap Fused Ring Electron Acceptors towards High-Efficiency Organic Solar Cells	OPV/DSSC	general	MSCA-IF-EF-ST	203,852	01-06-2019	31-05-2021
774686	AlbaSolar	Developing perovskite-based solar panels	Peroskites	general	SME-1	50,000	01-05-2017	30-09-2017
653296	CHEOPS	Production technology to achieve low Cost and Highly Efficient phOtovoltaic Perovskite Solar cells	Peroskites	general	RIA	3,299,095	01/02/2016	31/01/2019
699935	Crystal Tandem Solar	Single-Crystal Perovskite Tandem Solar Cells For High Efficiency and Low Cost	Peroskites	general	MSCA-IF-GF	269,858	01-01-2017	31-12-2019
687008	GOTSolar	New technological advances for the third generation of Solar cells	Peroskites	general	RIA	2,993,404	01/01/2016	31/12/2018
707168	MatchForSolar	Mechanochemical Approach to Inorganic-Organic Hybrid Materials for Perovskite Solar Cells	Peroskites	general	MSCA-IF-EF-ST	131,565	01-09-2016	28-02-2018
653184	MPerS	Sustainable Mixed-ion Layered Perovskite Solar Cells	Peroskites	general	MSCA-IF-EF-ST	195,455	01-04-2015	31-03-2017
659237	PerovskiteHTM	New Hole-Transport Materials to Enhance Perovskite Solar Cells	Peroskites	general	MSCA-IF-EF-ST	195,455	01-02-2016	31-01-2018
661480	PlasmaPerovSol	A full plasma and vacuum integrated process for the synthesis of high efficiency planar and 1D conformal perovskite solar cells	Peroskites	general	MSCA-IF-EF-ST	158,122	01-01-2016	31-12-2017
747221	POSITS	High Performance Wide Bandgap and Stable Perovskite-on-Silicon Tandem Solar Cells	Peroskites	general	MSCA-IF-EF-ST	175,420	01-06-2017	31-05-2019
727722	PRINTSolar	Printable Perovskite Solar Cells with High Efficiency and Stable Performance	Peroskites	general	ERC-POC	150,000	01-09-2016	28-02-2018
706094	TONSOPS	Titanium Oxide Nanocomposites for Scalable Optimized Perovskite Solar cells	Peroskites	general	MSCA-IF-EF-ST	170,122	16-03-2016	15-03-2018
763989	APOLO	SmArt Designed Full Printed Flexible RObust Efficient Organic HaLide PerOvskite solar cells	Peroskites	general	RIA	4,997,191	01-04-2018	31-03-2022

Id	Acronym	Title	Main PV Tech.	Application	Project Type	EU Funding	Start	End
764047	ESPResSo	Efficient Structures and Processes for Reliable Perovskite Solar Modules	Peroskites	general	RIA	5,412,658	01-04-2018	31-03-2021
797546	FASTEST	Fully Air-Processable and Air-Stable Perovskite Solar Cells Based on Inorganic Metal Halide Perovskite Nanocrystals	Peroskites	general	MSCA-IF-EF-ST	180,277	01-09-2018	31-08-2020
804519	FREENERGY	Lead-free halide perovskites for the highest efficient solar energy conversion	Peroskites	general	ERC-STG	1,500,000	01-02-2019	31-01-2024
839136	HES-PSC-FCTL	High efficiency and stability perovskite solar cells based on the functionalized charge transport layers	Peroskites	general	MSCA-IF-EF-ST	224,934	01-08-2019	31-07-2021
795716	HYBRICYL	Organic-Inorganic Hybrid Heterojunctions in Extremely Thin Absorber Solar Cells Based on Arrays of Parallel Cylindrical Nanochannels	Peroskites	general	MSCA-IF-EF-ST	159,461	01-07-2018	30-06-2020
756962	HYPERION	HYbrid PERovskites for Next GeneratION Solar Cells and Lighting	Peroskites	general	ERC-STG	1,759,733	01-11-2017	31-10-2022
826013	IMPRESSIVE	ground-breakIng tandeM of transPaRent dyE SenSitIsed and peroVskite solar cEIls	Peroskites	general	RIA	2,929,050	01-01-2019	31-12-2021
841265	LOVETandemSola r	Local Optoelectronic Visualisation for Enhancing Tandem Perovskite/Silicon Solar Cells	Peroskites	general	MSCA-IF-EF-ST	212,934	01-10-2019	30-09-2021
764787	MAESTRO	MAking pErovskiteS TRuly explOitable	Peroskites	general	MSCA-ITN-ETN	3,829,217	01-11-2017	31-10-2021
726360	MOLEMAT	Molecularly Engineered Materials and process for Perovskite solar cell technology	Peroskites	general	ERC-COG	1,878,085	01-11-2017	31-10-2022
841005	PerSiSTanCe	Low-cost and Large-Area Perovskite-Silicon Solar Tandem Cells	Peroskites	general	MSCA-IF-EF-ST	203,149	01-05-2019	30-04-2021
745776	PHOTOPEROVSKI TES	Photoexcitation Dynamics and Direct Monitoring of Photovoltaic Processes of Solid-State Hybrid Organic-Inorganic Perovskite Solar Cells	Peroskites	general	MSCA-IF-EF-ST	195,455	01-09-2017	29-02-2020
843453	STARS	STable perovskite solar cells via interfacial engineering of 2D/3D mixed-dimensional Absorbers and Robust dopant-free hole transporting materialS	Peroskites	general	MSCA-IF-EF-ST	191,149	01-09-2019	31-08-2021
751375	TinPSC	Towards Stable and Highly Efficient Tin-based Perovskite Solar Cells	Peroskites	general	MSCA-IF-EF-ST	185,857	01-08-2018	31-07-2020

Id	Acronym	Title	Main PV Tech.	Application	Project Type	EU Funding	Start	End
727529	DISC	Double side contacted cells with innovative carrier-selective contacts	Silicon	general	RIA	4,743,519	01/10/2016	30/09/2019
657270	EpiSil-IBC	Epitaxial silicon foil solar cells with interdigitated back contacts	Silicon	general	MSCA-IF-EF-ST	160,800	01-11-2015	31-10-2017
658391	NeutronOPV	New neutron techniques to probe bulk heterojunction solar cells with graded morphologies – understanding the link between processing, nanostructure and device performance	Silicon	general	MSCA-IF-EF-ST	195,455	01-07-2015	30-06-2017
727523	NextBase	Next-generation interdigitated back-contacted silicon heterojunction solar cells and modules by design and process innovations	Silicon	general	RIA	3,800,421	01/10/2016	30/09/2019
684528	PVFINAL	Photo Voltaic Fully Integrated and Automated Line	Silicon	general	SME-1	50,000	01-07-2015	31-12-2015
745601	AMPERE	Automated photovoltaic cell and Module industrial Production to regain and secure European Renewable Energy market	Silicon	general	IA	14,952,065	01/05/2017	30/04/2020
701254	GreenChalcoCell	Green and sustainable chalcopyrite and kesterite nanocrystals for inorganic solar cells	various	general	MSCA-IF-EF-ST	171,461	11-07-2016	17-07-2018
655039	NANOSOLAR	HYBRID QUANTUM-DOT/TWO-DIMENSIONAL MATERIALS PHOTOVOLTAIC CELLS	various	general	MSCA-IF-EF-ST	158,122	02-06-2015	01-06-2017
655852	Quokka Maturation	A mature Quokka for everyone – advancing the capabilities and accessibility of numerical solar cell simulations	various	general	MSCA-IF-EF-ST	171,461	01-02-2016	31-01-2018
743419	SpinSolar	Characterisation method for spin-dependent processes in solar energy technology	various	general	MSCA-IF-EF-ST	159,461	01-11-2017	31-10-2019
881226	ETC Solarshade	Invisible metal contacts for solar cells – boosting power output while cutting costs	various	general	SME-2	2,032,343	01-10-2019	30-09-2021
725165	HEINSOL	Hierarchically Engineered Inorganic Nanomaterials from the atomic to supra-nanocrystalline level as a novel platform for SOLution Processed SOLar cells	various	general	ERC-COG	2,486,865	01-02-2017	31-01-2022
795206	MolDesign	Molecule design for next generation solar cells using machine learning approaches trained on large scale screening databases	various	general	MSCA-IF-GF	227,166	01-04-2018	31-03-2021
820789	OLEDSOLAR	Innovative manufacturing processes and in-line monitoring techniques for the OLED and thin film and organic photovoltaic industries (CIGS and OPV)	various	general	RIA	7,872,870	01-10-2018	30-09-2021

Id	Acronym	Title	Main PV Tech.	Application	Project Type	EU Funding	Start	End
795079	PhotSol	Towards the Photonic Solar Cell - In-Situ Defect Characterization in Metal-Halide Perovskites	various	general	MSCA-IF-EF-ST	159,461	01-07-2019	30-06-2021
832606	PISCO	Photochromic Solar Cells: Towards Photovoltaic Devices with Variable and Self-Adaptable Optical Transmission	various	general	ERC-ADG	2,497,742	01-09-2019	31-08-2024
647281	SOLACYLIN	A preparative approach to geometric effects in innovative solar cell types based on a nanocylindrical structure	various	general	ERC-COG	1,938,655	01-09-2015	31-08-2020
825142	ZeroR	Resistance-free charge spreading for LEDs and solar cells	various	general	ERC-POC	150,000	01-01-2019	30-06-2020
674502	HySolarKit	Converting conventional cars into hybrid and solar vehicles	Silicon	integrated apps	SME-1	50,000	01-05-2015	31-10-2015
762726	PLATIO	Innovative outdoor solar and kinetic energy harvesting pavement system	silicon	integrated apps	SME-1	50,000	01-01-2017	30-04-2017
718003	SolardeSaLt	A Renewable Approach for Industrial Water Desalination by using Hybrid Photovolt	Silicon	integrated apps	SME-1	50,000	01-02-2016	31-05-2016
878182	ESMOS	Efficient, Safe and Multi-Functional Operation of Solar-Roads	Silicon	integrated apps	SME-1	50,000	01-08-2019	31-01-2020
850275	HORIZON	Redefining solar technology with retractable solar power folding roofs. Unlocking photovoltaics for waste water treatment plants towards self-sufficient plants.	Silicon	integrated apps	SME-2	2,488,125	01-03-2019	28-02-2021
728894	CDRONE	Towards un-subsidised solar power – Cleandrone, the inspection and cleaning solution	N/A	O&M	SME-1	50,000	01-06-2016	30-11-2016
790316	DeepSolar	Artificial Intelligence-based diagnostic system for Solar PV Plants	N/A	O&M	SME-1	50,000	01-12-2017	31-03-2018
886287	SecureTracker	New-generation bifacial solar tracker with integrated wind protection system for large scale photovoltaic arrays	Silicon	O&M	SME-1	50,000	01-11-2019	31-03-2020
686116	OptiNanoPro	Processing and control of novel nanomaterials in packaging, automotive and solar panel processing lines	various	O&M	IA	5,516,910	01/10/2015	30/09/2018
651970	POLYSOLAR	A light weight, recyclable, tracking support system, for solar photovoltaic modules based on inflatable polymer membranes	various	O&M	SME-1	50,000	01-10-2014	31-03-2015

Id	Acronym	Title	Main PV Tech.	Application	Project Type	EU Funding	Start	End
760311	SolarSharc	SOLARSHARC - a durable self-clean costing for solar panels to improve PV energy generation efficiency	various	O&M	IA	2,267,636	01/05/2017	30/04/2019
721452	SOLAR-TRAIN	Photovoltaic module life time forecast and evaluation	various	O&M	MSCA-ITN-ETN	3,576,248	01-09-2016	31-08-2020
792245	SUPER PV	CoSt redUction and enhanced PERformance of PV systems	various	O&M	IA	9,907,793	01-05-2018	30-04-2022
736217	SOcool	SunOyster cooling (SOcool)	III-V	PVT	SME-1	50,000	01/08/2016	31/01/2017
778106	SOcool	SunOyster cooling (SOcool)	III-V	PVT	SME-2	1,398,478	01/09/2017	31/08/2020
876320	LightCatcher	Scalable energy efficiency modules integrating both energy recovery and passive cooling systems for the solar photovoltaic industry	Silicon	PVT	SME-1	50,000	01-08-2019	31-01-2020
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	Silicon	recycling	RIA	5,642,708	01/10/2015	30/09/2018
701104	ELSi	Industrial scale recovery and reuse of all materials from end of life silicon-based photovoltaic modules	Silicon	recycling	IA	2,529,607	01/05/2016	30/04/2018
641972	CABRISS	Implementation of a CirculAr economy Based on Recycled, reused and recovered Indium, Silicon and Silver materials for photovoltaic and other applications	various	recycling	IA	7,844,565	01/06/2015	31/05/2018
776680	CIRCUSOL	Circular business models for the solar power industry	various	recycling	IA	7,014,893	01-06-2018	31-05-2022
657359	PVFIFTY	TOWARDS A 50% EFFICIENT CONCENTRATOR SOLAR CELL AND A 40% EFFICIENT SPACE SOLAR CELL	III-V	space	MSCA-IF-EF-ST	183,455	01-05-2015	30-04-2017
776362	RadHard	Ultra High Efficiency Radiation Hard Space Solar Cells on Large Area Substrates	III-V	space	RIA	3,072,973	01-01-2018	30-06-2021
646554	PV FINANCING	PV FINANCING	N/A	system integration	CSA	2,050,939	01/01/2015	30/06/2017
815019	Solar Bank	Virtual Energy Trading IT System to couple photovoltaic production and electric vehicles charging.	N/A	system integration	SME-1	50,000	01-06-2018	30-11-2018

Id	Acronym	Title	Main PV Tech.	Application	Project Type	EU Funding	Start	End
649997	Solar Bankability	Improving the Financeability and Attractiveness of Sustainable Energy Investments in Photovolatics: Quantifying and Managing the Technical Risk for Current and New Business Models	N/A	system integration	CSA	1,355,106	01/03/2015	28/02/2017
764805	EU HEROES	EU routes for High pEnentration of solaR PV into lOcal nEtworkS	N/A	system integration	CSA	1,230,558	01-09-2017	31-08-2020
764452	iDistributedPV	Solar PV on the Distribution Grid: Smart Integrated Solutions of Distributed Generation based on Solar PV, Energy Storage Devices and Active Demand Management	N/A	system integration	CSA	2,706,940	01-09-2017	29-02-2020
764786	PV-Prosumers-4Grid	Development of innovative self-consumption and aggregation concepts for PV Prosumers to improve grid load and increase market value of PV	N/A	system integration	CSA	2,501,739	01-10-2017	31-03-2020

Appendix 4 Listing of SOLAR-ERANET Projects (status 2019)

ACRONYM & TITLE	COORDINATOR	STATUS
ACCESS-CIGS - Atmospheric Cost Competitive Elemental Sulpho-Selenisation for CIGS	Helmholtz-Zentrum Berlin für Materialien und Energie (DE)	Completed
AER II - Industrialization and System Integration of the Aesthetic Energy Roof Concept	AERspire B.V. (NL)	Completed
ALCHEMI - A Low Cost, High Efficiency, Optoelectronic HCPV Module for 1000 Sun Operation	IQE plc (UK)	Running (2019)
APPI - Atmospheric Pressure Processing for Industrial Solar Cells	Fraunhofer Institut für Solare Energiesysteme (DE)	Completed
Bifalo - Bifacial PV modules for lowest levelized cost of energy	International Solar Energy Research Center (ISC) Konstanz e.V. (DE)	Running (2019)
BIPVpod - Building Integrated Photovoltaics panels on demand	DLR-Institut für Vernetzte Energiesysteme e. V. (DE)	Running (2019)
BLACK - Black Silicon and Defect Engineering for Highly Efficient Solar Cells and Modules	Aalto University (Aalto) (FI)	Completed
CNT-PV - Carbon Nanotube Hole-Transporting and Collecting Layers for Semi-Transparent, Flexible and Low-Cost Solid-State Photovoltaic Cells	Uppsala University (SE)	Completed
Cost-Effective Moisture Protection	Empa – Swiss Federal Laboratories for Materials Science and Technology (CH)	Completed
DINAMIC - Dilute Nitride Based Concentrator Multijunction Solar Cells, with Efficiencies Over 47%	IQE plc (UK)	Running (2019)
DURACIS - Advanced Global Encapsulation Solutions for Long Term Stability in Industrial Flexible Cu(In,Ga)Se2 Photovoltaic Technology	Fundació Institut de Recerca de l'Energia de Catalunya (ES)	Running (2019)
Enhance - Enhanced Rooftop PV Integration through Kinetic Storage and Wide Erea Monitoring	University of Cyprus (CY)	Running (2019)
FrontCIGS - Re-Designing Front Window in Flexible CIGS Modules for	Empa – Swiss Federal Laboratories for Materials Science and Technology (CH)	Completed
FunGlass – Multi-Functional Glass for PV Application	Fraunhofer Center for Silicon-Photovoltaics CSP (DE)	Completed
HESiTSC - High efficiency silicon based tandem solar cell PV module	Royal Institute of Technology-KTH (SE)	Completed
HESTPV - High-Efficiency and Stable Tin-Based Perovskite Solar Cells	Universitat de València Estudi General (ES)	Running (2019)
HighCast - High Performance Silicon Casting and Wafering	Karlstad University (SE)	Completed
HIPER - High-Efficiency Si Perovskite Tandem Solar Cells	Universitat de València Estudi General (ES)	Completed
HIPPO - High-Efficiency Poly-Si Passivated Contact Solar Cells and Modules	Fraunhofer Institute for Solar Energy Systems ISE (DE)	Running (2019)
Hvolt-PV - High voltage IBC photovoltaic i-Cells and modules	S'Tile SA (FR)	Completed

ACRONYM & TITLE	COORDINATOR	STATUS
INFORPV - Innovative Forecasting PV Energy Yield Solution for Sustainable Large Scale Deployment	M.G.Lightning Electrical Engineering (MGL) (IL)	Completed
InGrid -High efficiency PV modules based on back-contact cells and novel interconnecting grid	Specialized Technology Resources España, S.A. (ES)	Completed
InnoModu - Lead free modules with low silver content and innovative bus less cell grid	AIT Austrian Institute of Technology GmbH (AT)	Completed
INTESEM - Intelligent Solar Energy Management Pipeline from Cell to Grid	Fortum Oyj (FI)	Completed
IPERMON - Innovative Performance Monitoring System for Improved Reliability and Optimized Levelized Cost of Electricity	Gantner Instruments Test & Measurement GmbH (AT)	Completed
LIMES - Light Innovative Materials for Enhanced Solar Efficiency	RISE Research Institutes of Sweden AB (former Glafo AB) (SE)	Completed
Liquid Si 2.0 - Liquid Phase Deposition of Functional Silicon Layers for Cost-Effective High Efficiency Solar Cells	Evonik Creavis GmbH (DE)	Running (2019)
Monoscribe - Roll-to-Roll Monolithic Interconnection of Customizable Thin-film Solar Modules	Sunplugged GmbH (AT)	Completed
NOVACOST - Non Vacuum Based Strategies for Cost Efficient Low Weight Chalcogenide Photovoltaics	Advanced Coatings & Construction Solutions sàrl (BE)	Completed
NovaZOlar - All-non-Vacuum Processed ZnO-based Buffer and Window Layers for CIGS Solar Cell Technology	Empa - Swiss Federal Laboratories for Materials Science and Technology (CH)	Completed
PEARL TF-PV - Performance and Electroluminescence Analysis on Reliability and Lifetime of Thin-Film Photovoltaics	Forschungszentrum Jülich GmbH (DE)	Running (2019)
PRooF - Competitive Industrialized Photovoltaic Roofing	SP Technical Research Institute of Sweden (SE)	Completed
PV me - Organic Photovoltaic Systems Integrated in Manufactured Building Elements	ECN (NL)	Completed
PV2GRID - A next generation grid side converter with advanced control and power quality capabilities	University of Cyprus (CY)	Completed
PV4FACADES - Photovoltaics for High-Performance Building-Integrated Electricity Production Using High-Efficiency Back-Contact Silicon Modules	ECN (NL)	Completed
Refined PV - Reduction of Losses by Ultra Fine Metallization and Interconnection	International Solar Energy Research Center Konstanz e.V. (DE)	Running (2019)
SNOOPI - Smart Network Control with Coordinated PV Infeed	Energynautics GmbH (DE)	Completed
SPRINTCELL - Sulfide-based Ink for Printable Earth-Abundant Solar Cell	AIT Austrian Institute of Technology GmbH (AT)	Completed
THESEUS - Tandem High Efficiency Solar Cells Utilizing III-V Semiconductors on Silicon	IQE plc (UK)	Running (2019)

Appendix 5 PV-Related Projects supported by KIC-Innoenergy

Acronym	Title	Partners
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
EFFIC	A back-end interconnection system for thin-films CIGS	Meyer Burger, Centre for Concept in Mechatronics (CCM), TNO, ECN, Avancis
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
Epicomm	NEXWAFE's kerfless wafer technology aims for a drop-in replacement for Cz silicon wafers	NexWafe, Fraunhofer ISE, ISC Konstanz, Ecosolifer
FASCOM	Advanced concept of solar streetlight.	SIARQ, Sunplugged, Tecnalia, SECE
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

KJ-BK-21-005-EN-N

The European Commission's science and knowledge service
Joint Research Centre

JRC Mission
As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

EU Science, Research and Innovation

EU Science Hub

Publications Office
of the European Union

doi:10.2760/827685
ISBN 978-92-76-27274-8