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Contents

Foreword

This report is an output of the Clean Energy Technology Observatory (CETO). CETO's objective is to provide an evidence-based analysis feeding the policy making process and hence increasing the effectiveness of R&I policies for clean energy technologies and solutions. It monitors EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal; and assesses the competitiveness of the EU clean energy sector and its positioning in the global energy market.

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Executive Summary

As part of the Clean Energy Technology Observatory (CETO), this report on Photovoltaics is built on three sections: the technology state of the art, future developments and trends, the value chain analysis and the EU position and global competitiveness of Photovoltaics. Photovoltaics is the fastest-growing source of electricity production from renewable energies and a pillar for the EU's energy transition and the accomplishment of the European Green Deal (EGD).

The global cumulative PV installed capacity exceeded the 1TW in March 2022. The EU alone reached a cumulative installed PV capacity of 170 GW at the end of 2021 and a cumulative electricity generation of 158 TWh from PV. The average PV module efficiency has increased from 9 % in 1980 to 14.7 % in 2010 and 20.9 % in 2021. Silicon-based photovoltaic technology remains the predominant technology (efficiency of 24 % and over) but research regarding performance, integration and sustainability is still essential. As far as thin-film technologies are concerned, the way forward for Copper Indium (Gallium) Selenide (CIGS) and Cadmium Telluride (CdTe) technologies is mass production to benefit from scaling effects by considering at the same time the supply of potentially critical materials for their production. Depending on the learning curve, perovskite module (current module efficiency 17.9 % while the record cell efficiency is 25.7 %) manufacturing could quickly achieve comparable costs compared to current technologies while the multi-junction technology, silicon-based tandems with III-V top material (32.65 % module efficiency) together with perovskite-silicon tandem devices (31.25 % module efficiency) are the two most promising and efficient technologies.

Current technological advancement and market orientation are moving towards the replacement of Passivated Emitter and Rear Contact (PERC) architecture (~21 % module efficiency with projections reaching ~22.5 % in 2032) by n-type Tunnel Oxide Passivated Contact (TOPCon) (~21.3 % module efficiency with projections reaching ~24 % in 2032) that will further increase efficiency. Bifacial modules are emerging in the market. Ideal for applications that allow the absorption/exploitation of light from both sides of the module (front and rear), for different orientations and needs, like in the case of emerging innovative PV applications like Agri-Photovoltaics (AgriPV).

Solar PV costs have fallen significantly since 2010, mainly due to the large-scale manufacturing and also the intense Research & Development (R&D) efforts of the past decades and the significant amounts of funding. Both PV module prices and the Levelised Cost of Electricity (LCoE) have decreased considerably and further decrease is foreseen in the next years. The global weighted average LCoE for utility-scale projects fell by 88 % between 2010 and 2021. Projections for the EU indicate that in 2050 it will further decrease by approximately 60 % compared to 2020. The relevant regulatory and economic schemes, such as feed-in tariffs and minimum targets for generation from renewables in electricity systems, together with the above-mentioned cost reductions have rendered PV a competitive technology.

EU's public Research & Innovation (R&I) funding is not always reported for all member states and for this reason caution in the interpretation of the results is advised. EU's public R&I funding in solar was 30 % of the global public R&I funding solar in 2010 as well as in 2020. As far as public R&I funding in PV is concerned, in 2010 EU's funding was 36 % of the global public R&I funding and it grew to 64 % in 2020. The compound growth of public R&I funding on PV between 2010 and 2020 in the EU decreased by only 0.5 % whereas at a global level it decreased by 6 %. The EU's share in the global private Research & Development (R&D) funding in PV remained constant at 18 % for each year from 2010 until 2018. EU's private R&D funding in PV suffered a compound decrease of 6 % in the period 2010-2018. The global private R&D funding in PV followed a similar compound decrease of 5 %. The EU is in 4th position in terms of the total number of patents after China (1st), South Korea (2nd), and Japan (3rd) but ranks 1st in high-value patents above the US (2nd) and Japan (3rd). The publications regarding PV technologies, systems, and applications generated in the EU are found to be significantly fewer than those of other countries (mainly China) but significantly more highly-cited (as are also publications from the US). The H2020 funding programme (2014-2020) has contributed EUR 329 million to projects related to the 6 priorities defined in the SET-Plan TWP PV Implementation Plan. Most funding from the H2020 was received for projects regarding new technologies and materials (around EUR 108 million). The Innovation Fund (IF), launched in 2020 has contributed EUR 126 million in total to two small-scale and one large-scale PV project. The large-scale TANGO project, is targeting the manufacturing technologies priority and has received EUR 118 million, paving the way forward for the up-scaling of EU manufacturing facilities. Horizon Europe (2021-2027), H2020's successor, is expected to boost the EU's innovation and demonstration activities in PV.

The Energy Payback Time (EPBT) of a PV system in Southern Europe is one year, whereas in Northern Europe less than a year and a half. Nonetheless, it is also important that the PV sector further reduces its environmental footprint and becomes more sustainable and circular along the entire PV value chain.

EU's PV estimated turnover in 2020 slightly decreased compared to 2019 from EUR 23 billion to EUR 21 billion but this is a result of cost reductions rather than a decrease in turnover since the installed capacity between 2019 and 2020 actually increased. The compound growth between 2015 and 2020 is estimated to be 18 % with Germany and the Netherlands accounting for almost half of the EU's turnover in 2020. Germany together with the US, Japan, China and South Korea host almost 70 % of identified innovators. The EU as a total hosts 23 % of innovators in the field of PV. In particular, Germany holds the 4th position behind the US, Japan and China among the world's leading countries in terms of innovation. The EU has significantly increased job creation in PV in recent years mainly due to the large-scale deployment of PV systems, thus limited to the downstream and not the upstream value chain (i.e. manufacturing). The compound growth of PV employment in the EU is estimated to be around 17 % in the period between 2015 and 2020 based on the most conservative data source. As expected (due to their strong presence in both the downstream as well as the upstream value chain), at global level, the number of PV-related jobs created in China is more than 10 times higher than that of the EU.

Between 2011 and 2020, the compound decrease in production value in the EU was 17 %. However, the EU slightly recovered in 2021 reaching EUR 1 920 million, resulting in an overall compound decrease of 13 % between 2011 and 2021. China has a leading market in PV and exhibits minimal dependence on the EU as far as imports are concerned. Most of the leading solar cell and module production companies are Chinese and they dominate the PV module shipments. In 2020, Chinese companies have produced 67 % of the total c-Si PV modules and in 2019 accounted for 62 % of the global shipments of PV modules. Additionally, the costs for PV manufacturing in China are considerably lower than in Europe. According to the IEA, costs in China are 10 % lower than in India, 20 % lower than in the United States, and 35 % lower than in Europe. The EU is aiming at strengthening its position in the global market with several manufacturing capacities being announced and realised in the next years. The 3 GW and 1 GW plants of Heterojunction (HJT) PV modules manufacturing announced in Italy and Germany are expected to boost the EU PV market. After a three year period of having a considerable share in the inverter market, SMA (Germany) and Power Electronics (Spain) have grown less than other companies from China and therefore did not maintain their competitiveness in 2021. The above-mentioned European companies reduced their market share from 14 % in 2018 to 11 % in 2021. The EU as a total but also each member state (MS) individually exhibited a negative relative trade balance between 2019 and 2021. The EU's extra-EU imports have increased by 14 % between 2015 and 2021, while for the same period, its exports decreased by 6 %.

The EU is not directly affected by a high-risk supply of critical raw materials since, for now, it is importing final products and not the primary raw materials. The use of silver for connections has been identified as a potential concern due to the expected large-scale manufacturing activity in the next few years and therefore there is continuous R&D for the minimisation of silver use as well as raw materials substitution like copper. Particular attention is needed also regarding PV glass that is lacking in the EU and has to be imported, mainly from China, which, due to environmental restrictions on some plants, is experiencing a shortage.

Therefore, the promising advancements in photovoltaics are crucial for the next years, both to reach EGD targets and to favour the emergence of competitive new European industrial players and clusters producing higher value products with the ability to relocate an increased share of the photovoltaics value chain into Europe.

1 Introduction

1.1 Context

Over the past decade, photovoltaics has become a mature technology and the fastest-growing source of electricity production from renewable energies. Photovoltaics (PV) is the technology that converts light into electricity using semiconductors (special type of materials) exploiting the photo-electric effect. The main types of photovoltaic cell and module technologies are the crystalline silicon (mono and poly), the thin-film (Copper Indium (Gallium) Selenide, Cadmium Telluride, amorphous silicon, perovskite), and the multi-junction (multiple p-n junctions of different semiconductor materials absorbing different wavelengths of light) modules. The photovoltaic systems can be ground-mounted, building-mounted or building-integrated. According to how the produced electricity is handled, the systems can be grid-connected, stand-alone or grid-connected with battery backup. There are different main types of photovoltaic systems: residential, commercial or utility-scale systems. The main components of a photovoltaic system are the photovoltaic modules, the tracking system, the balance of system and the inverter.

The photovoltaic sector reached its first TW milestone in the spring of 2022 – 1 Terra Watt power (TW_p) of cumulative installed PV capacity with an annual production of solar cells and modules in the range of 200 to 230 GW_p. The next TW milestone, 1 TW_p of annual production is expected to be reached within the next 5 to 7 years and reach even 2 TW_p by the beginning of the next decade, to reduce worldwide Greenhouse Gas (GHG) emissions in order to remain compliant with the objective to minimise the global temperature increase to 1.5 °C by the mid of this century as stipulated in the Paris Agreement of 2016.

A fivefold increase in annual solar cell production within the next 5 to 7 years and a 10 fold increase by the beginning of the next decade has severe consequences for the PV industry and the research needed to enable it. Even though technological improvements in the solar system hardware will still be at the core to achieve this increase, additional issues have to be resolved, which require the attention of researchers and solid scientific work.

Along the whole PV value chain – from raw material extraction to the recycling or re-use of solar system components – the PV sector has to reduce its environmental footprint and become truly sustainable and circular.

In addition, the build-up of such an industry as well as the deployment of such big PV capacities require huge financial means and must be with the consent of societal stakeholders.

The recent European Solar Strategy communication calls for about 450 GW_{ac} of new photovoltaic system capacity between 2021 and 2030. Given the current trend of installing 1.25 to 1.3 times the AC capacity in DC, this would bring the total nominal photovoltaic (PV) capacity in the European Union (EU) to approximately 720 GW_p. Compared to 2021, this would require an annual market volume increase to over 100 GW_p annually by 2030, which is achievable if the current market trend is maintained.

However, the ramp-up of the annual market in the European Union requires a focus on material efficiency as well as risk-hedging to avoid disruption of the international value chain, such as those which could be observed during the Covid-19 pandemic over the last two years. To realise this, the revival of a European value chain capable to supply between a quarter and a third of the annual European market is necessary.

This is only the case so far for polysilicon manufacturing, backsheets, contact materials, inverters and balance of system components. The build-up of the missing capacities for wafers, cells and solar glass production needs to be monitored carefully.

In parallel, the research in photovoltaics has advanced rapidly: the industry has expanded significantly, becoming the world's fastest-growing energy technology, and its applications are continuously growing in numbers, thus rendering it the most competitive option for electricity generation. Photovoltaics constitute one of the main technologies for the EU's energy transition and the accomplishment of the European Green Deal (EGD) targets to tackle climate change. According to projections, an even broader deployment of photovoltaic systems is required to achieve the goals set in the EGD. Therefore, the promising advancements in photovoltaics are crucial for the next years, both to reach EGD targets and to favour the emergence of competitive new European industrial players and clusters producing higher-value products with the ability to relocate an increased share of the photovoltaics value chain into Europe.

1.2 Methodology and Data Sources

The present report follows the general structure of all CETO technology reports and is divided into three sections with several indicators aiming to present and evaluate the EU PV technology along its value chain:

- Technology State of the art and future developments and trends;
- Value chain analysis;
- EU position and global competitiveness.

The *technology state-of-the-art and future developments and trends* section builds on the:

- PV technology readiness level;
- Installed capacity and electricity production;
- Technology costs;
- Public and private R&I funding;
- Patenting trends;
- Scientific publication trends;
- Impact of EU R&I.

The *value chain analysis* maps the situation of the PV technology with regard to the:

- Turnover;
- Gross Value Added;
- Environmental and socio-economic sustainability;
- EU companies;
- Employment;
- Energy intensity and labour productivity;
- EU production.

The *EU position and global competitiveness* analyses the EU position in the global market according to the:

- Global and EU market leaders;
- Trade, imports and exports;
- Resources efficiency and dependence.

The report uses the following information sources:

- Existing studies and reviews published by the European Commission and international organisations;
- Information from EU-funded research projects;
- EU and international databases;
- EU trade data, trade reports, market research reports and others;
- JRC own review and data compilation;
- Stakeholders' input.

Details of specific sources can be found in the corresponding sections.

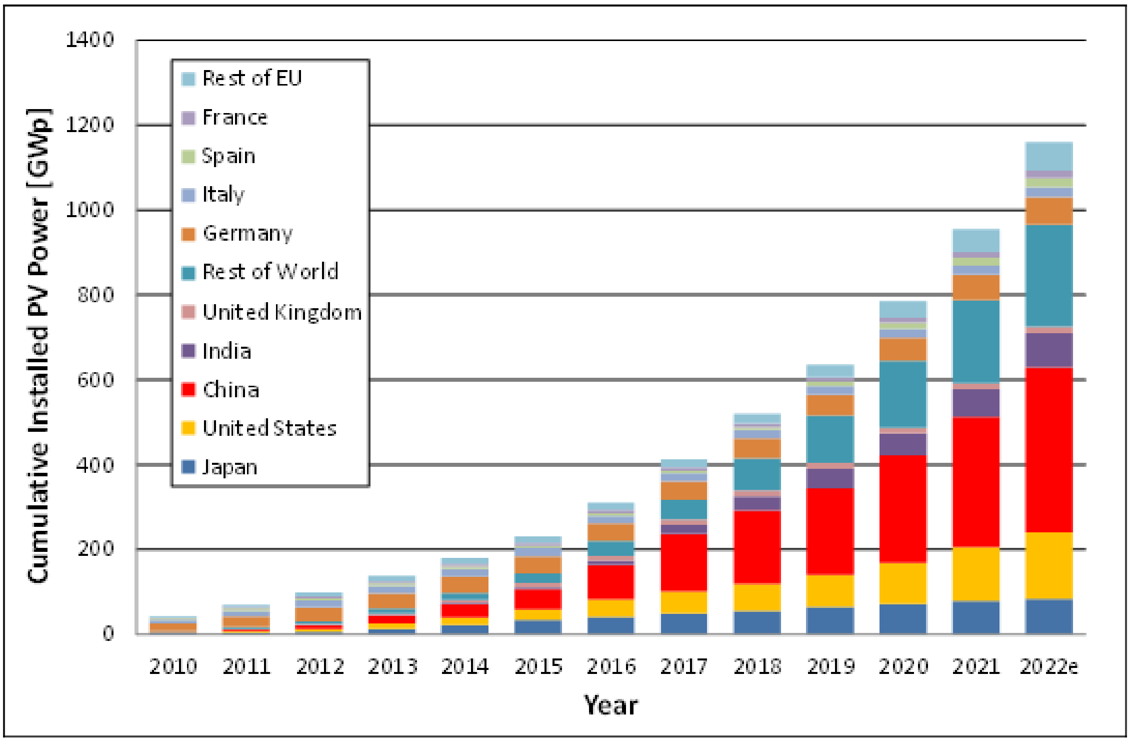
2 Technology State of the art and future developments and trends

2.1 Technology readiness level (TRL)

The global compound annual growth rate of PV installations was 32.5 % in the period 2010 to 2021 (Jäger-Waldau, 2022) .

During 2021, the 2nd year of the ongoing Covid-19 pandemic, global investments in renewable energy increased by 12 % to USD 417 billion (BloombergNEF, 2022b). Investments into new solar capacity increased by 19 %, reaching USD 205 billion. Data from April 2022 show that the new PV capacity increased by about 15 % to over 180 GW in 2021. For 2022, market forecasts are considerably higher, with an annual new installed capacity above 200 GW, which would bring the total cumulative installed PV capacity to about 1.15 TW (Figure 1). In March 2022 the cumulative worldwide capacity exceeded 1TW.

Figure 1. Global cumulative Photovoltaic Installations from 2010 to 2021 with an estimate for 2022.



Source: (Jäger-Waldau, 2022)

In 2021, the photovoltaic market in the European Union (EU) grew by more than 25 % to over 26 GW_p and reached a cumulative installed capacity of over 165 GW_p. Seven countries installed more than 1 GW_p, namely Germany (5.4 to 5.5 GW_p), Spain (4.6 to 4.8 GW_p), Poland (3.7 to 3.8 GW_p), the Netherlands (3.2 to 3.4 GW_p), France (2.7 to 2.9 GW_p), Greece (1.1to 1.2 GW_p) and Denmark (1.1 to 1.3 GW_p). The EU is a leading installer of PV per capita with 400 W_p/capita on average, having ten EU members in the first 15 countries in this ranking (with Australia, Japan, S Korea, Taiwan and US from outside the EU)[1].

This growth is due to the decreasing cost of the PV modules and systems (EUR/W), and the increasingly competitive cost of the electricity generated (in EUR/MWh). Analysing the global evolution of module price vs cumulative production, the Learning Curve suggests a price decrease of 26 % for each doubling of cumulative production in the last 40 years (Fraunhofer ISE, 2022b).

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[1] https://www.statista.com/statistics/612412/installed-solar-photovoltaics-capacity-eu/#:~:text=Solar %20photovoltaics %20capacity %20installed %20per,EU %2D27 %202021 %2C %20by %20country&text=At %20815 %20watts %20per %20inhabitant,545 %20watts %20per %20inhabitant %2C %20respectively

In Germany, at the end of 2020 the price for a typical 10 to 100kW$_p$ PV rooftop system is only 7.4 % of the price in 1990, thus a net-price regression of about 92 % in 30 years (Fraunhofer ISE, 2022b).

Photovoltaic (PV) module technologies

According to the International Technology Roadmap for Photovoltaic (ITRPV) 13th edition (VDMA, 2022), the yearly learning for module efficiency for the past 10 years is presented in Table 1.

Table 1. Yearly average module efficiencies for the period 2010-2021.

Year	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Aver. module efficiency [%]	14.7	15.2	15.4	16.0	16.3	17.0	17.5	17.7	18.4	19.2	20.0	20.9

Source: (VDMA, 2022)

The above-mentioned module efficiencies, between 2010 and 2019, were calculated, based on average module powers of p-type polycrystalline (poly c-Si) and monocrystalline (mono c-Si) silicon modules reported by ITRPV (3rd to 11th edition) for a standardised module size of about 1.64m^2 with 60 cells. After 2019 an average module area of 1.7m^2 is considered. Average module efficiencies for Passivated Emitter and Rear Contact (PERC) modules in 2020 and 2021 are assumed to be 20 % based on the ITRPV 12th edition and 20.9 % respectively. For a better comprehension of the evolution of PV module efficiencies, the 1980 average PV module efficiency is reported to be 9 % (VDMA, 2022).

Crystalline silicon

The crystalline silicon technology accounts for 95 % (143.9 GW$_p$) of global PV module production. Of these, 80 % are monocrystalline (mono c-Si) modules and the remaining are polycrystalline (poly c-Si) modules. The record efficiency of mono c-Si and poly c-Si cells is 26.7 % (Kaneka, n-type rear IBC) and 24.4 % (Jinko Solar, n-type) respectively, whereas the efficiency of the modules is 24.4 % (Kaneka (108 cells)) for the monocrystalline and 20.4 % (Hanwha Q cells (60 cells)) for the polycrystalline (Green *et al.*, 2022). The efficiency of average commercial wafer-based silicon modules increased from 15 % to over 20 % over the last 10 years (Fraunhofer ISE, 2022b).

The European Strategic Research and Innovation Agenda for PV (SRIA) (SNETP, 2013) identifies that further R&D support in the EU in the field of silicon PV technology is needed and it should focus on achieving multi-GW$_p$ of silicon cell and module manufacturing capability with low carbon footprint and circularity in the EU, further lowering the Levelized Cost of Electricity (LCoE) of both utility-scale PV and integrated PV and maintaining and reinforcing EU's leading position in silicon PV technology in terms of high performance and lower costs, while at the same time achieving sustainability and integration in the environment.

Research and innovation regarding performance, integration and sustainability are still essential in order to reach large-scale deployment. This also includes high-efficiency silicon technology being used for multi-junction devices (efficiencies may reach 30 % for hybrid tandems and 40 % for multi-junctions[2]).

The technology targets and research priorities for silicon PV modules as they were identified in SRIA (SNETP, 2013) are presented in Figure 2.

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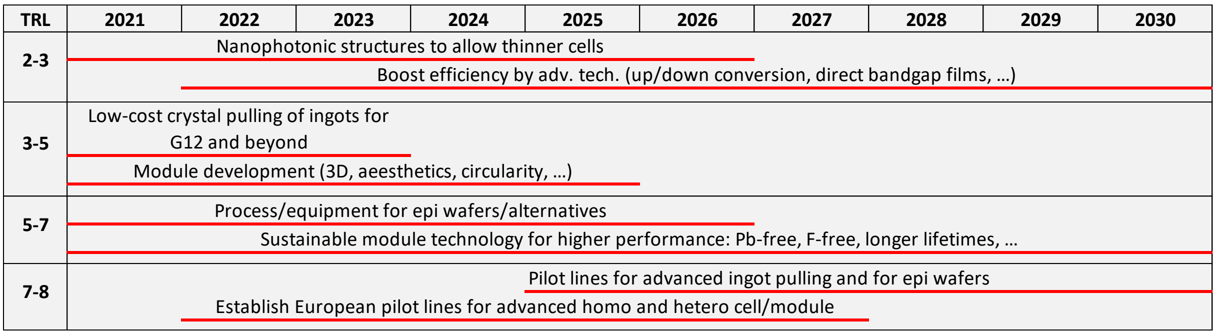
[2] Tandem devices consist of two junctions whereas multi-junction devices consist of more than two (i.e. multiple) junctions.

Figure 2. Technology targets, research priorities and respective TRLs for the monocrystalline and polycrystalline silicon PV modules.



Source: (SNETP, 2013)

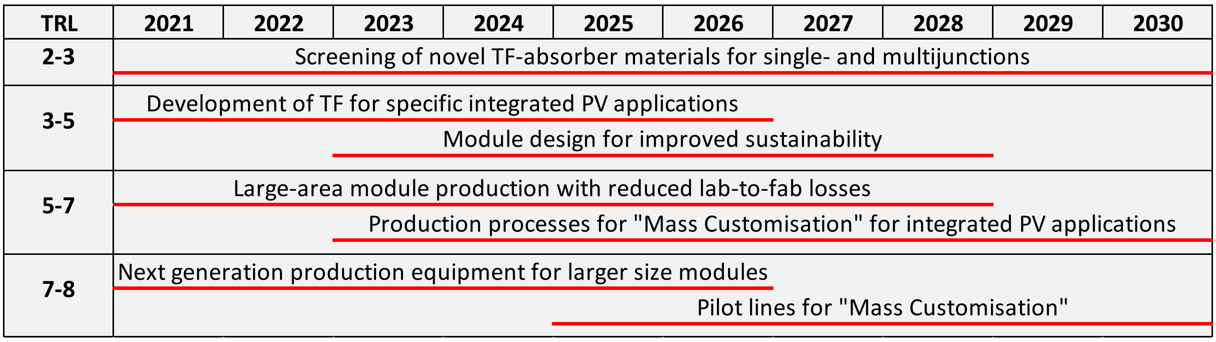
Thin-film

The thin-film share of global production is only 5 % corresponding to 7.8 GW_p of the total PV module global production. Of these 7.8 GW_p, 78 % is CdTe, 19 % CI(G)S and 3 % is amorphous silicon. The record cell efficiencies of CdTe and CIGS are 21 % (First Solar, on glass) and 23.4 % (Solar Frontier) respectively and for the modules, CdTe modules exhibit an efficiency of 19.5 % (First Solar) and CI(G)S 19.2 % (Solar Frontier (70 cells)) (Green *et al.*, 2022). The CdTe module efficiency has increased from 9 % to 19 % in the last 10 years (Fraunhofer ISE, 2022b).

As far as the CIGS technology is concerned, there are only a few European producers (mostly branches of Asian companies), whereas CdTe modules are produced only by First Solar in the USA. The efficiencies of commercial CIGS and CdTe modules need to increase and reach those reached in the laboratory. Only this way can they compete with crystalline silicon modules. The way forward for these two thin-film technologies is mass production in order to benefit from scaling effects, but a remaining issue is the supply of critical materials for their production (indium, tellurium, etc.).

The technology targets and research priorities for the thin-film PV modules as they were identified in SRIA (SNETP, 2013) are presented in Figure 3.

Figure 3. Technology targets, research priorities and respective TRLs for the thin-film PV modules.



Source: (SNETP, 2013)

Perovskites

Perovskites (Pks) are currently a very promising thin-film technology and for this reason, justify a separate treatment within this report. Perovskites' power conversion efficiency in a single-junction cell has increased from 3.8 % at their discovery in 2009 to an impressive 25.7 % (UNIST Ulsan) in 2020 whereas the perovskite module record efficiency is 17.9 %. (Panasonic (55 cells)) (Green *et al.*, 2022). It is expected that module efficiencies will be comparable to current existing PV technologies within the next 5 years.

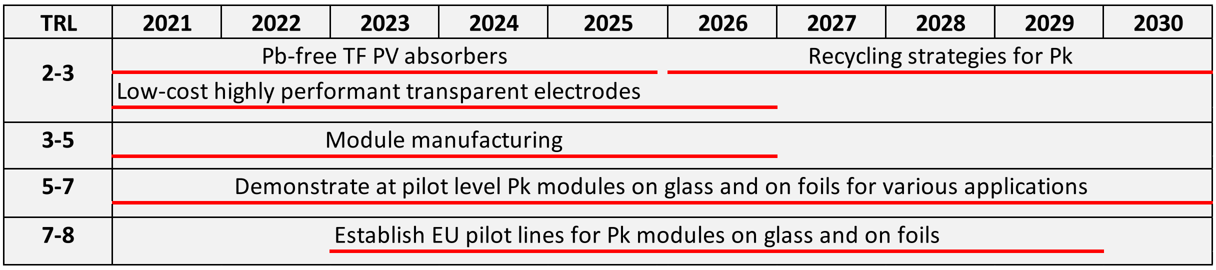
The EU has remarkable expertise in perovskite PV modules and may be considered a leader. At the moment, several companies are starting pilot lines of production. Some of these companies, reported in (SNETP, 2013), are Evolar (focusing on semi-transparent perovskite on glass as an upgrade for existing PV modules like crystalline or CIGS with the 4-terminal approach, where current PV module top glass can be replaced by a glass containing the semi-transparent Pk-PV module), Saule Technologies (focusing on flexible Pk-PV made by ink jet printing, with sheet-to-sheet processes today, but with the intention of moving to roll-to-roll production) and Solaronix (producing opaque Pk-PV on glass).

China is also producing a producer of this technology. In particular, the company GCL New Energy has a 10 MW line (soon to be joined by a 100 MW pilot line) producing semi-transparent and hence bifacial perovskite modules with non-certified efficiencies of 16 % on 40 x 60 cm^2 glass. The company has plans for a 1 GW production line in 2022 (SNETP, 2013).

Depending on the learning curve, perovskite module manufacturing could quickly achieve costs comparable to current commercial technologies. The industry anticipates that perovskites will become a low-cost, highly efficient and stable technology that may incorporate different characteristics (level of flexibility, transparency, etc.). This way, perovskites could become an ideal technology for many different photovoltaic applications in infrastructure, buildings, vehicles, etc.

The technology targets and research priorities for the perovskite PV modules as they were identified in SRIA (SNETP, 2013) are presented in Figure 4.

Figure 4. Technology targets, research priorities and respective TRLs for the perovskite PV modules.



TRL	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
2-3	Pb-free TF PV absorbers					Recycling strategies for Pk				
	Low-cost highly performant transparent electrodes									
3-5	Module manufacturing									
5-7	Demonstrate at pilot level Pk modules on glass and on foils for various applications									
7-8			Establish EU pilot lines for Pk modules on glass and on foils							

Source: (SNETP, 2013)

Multi-junction

The multi-junction technology consists in incorporating multiple p-n junctions made of different semiconductor materials within the same cell. This technology allows reaching the highest efficiency levels among all technologies. The silicon-based tandems with III-V top material are the most efficient technology, with a record efficiency of 47.1 % for a multi-junction cell (NREL, 6J inv. Metamorph, AlGaInP/AlGaAs/GaAs/GaInAs(3)) and 32.65 % for a module (Sharp, 40 cells; 8 series, InGaP/GaAs/InGaAs) (Green *et al.*, 2022).

In particular, perovskite-silicon tandem devices reach high efficiencies and benefit from lower manufacturing costs as well. The 29.8 % accomplished efficiency by Oxford PV in November 2021 (Green *et al.*, 2022), has been recently overcome. EPFL and CSEM have announced a world record efficiency of 31.25 %, breaking the 30 % efficiency barrier (EPFL, 2022). According to SRIA, tandem technologies should reach a market share of more than 5 % while successfully transitioning from niche to mass market applications by 2030.

The technology targets and research priorities for multi-junction PV modules as they were identified in SRIA (SNETP, 2013) are presented in Figure 5.

Bifacial modules[3] represent another field of technological advances. Even though they have been in the market for many years now, they have recently attracted increased interest. They are used for ground-mounted applications with or without a tracker but can also be vertically mounted. N-type Passivated Emitter Rear Totally diffused (PERT) or Tunnel Oxide Passivated Contact (TOPCon) solar cells can reach considerably higher bifaciality[4] than p-type Passivated Emitter and Rear Contact (PERC) solar cells. Rear contact of modules represent another major advance (Wilson *et al.*, 2020). With PERC modules being near their upper-efficiency limit (currently 21 % efficiency with projections reaching 22.5 % in 2032), the industry is investing in n-type technology with major manufacturers switching to TOPCon technology (currently 21.8 % efficiency with projections reaching 24 % in 2032) (VDMA, 2022). The n-type TOPCon manufacturing capacity already increased

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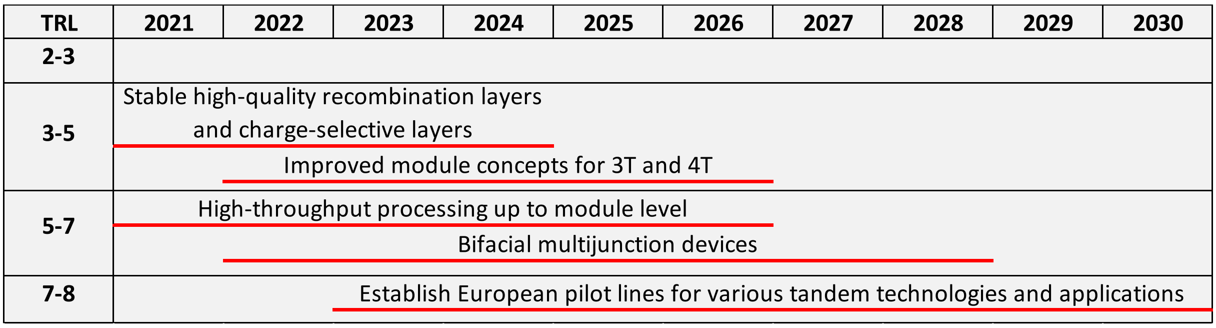
[3] Bifacial modules are PV modules that can produce electrical energy when illuminated on both its sides (front and rear).

[4] Bifaciality refers to the ratio of rear efficiency in relation to the front efficiency subject to the same irradiance.

considerably in the 2nd half of 2021. Some projections suggest that it could represent the 2nd highest production capacity in 2022 and become dominant by 2023 due to new additions based on this technology. However, at the moment, the manufacturing costs of the TOPCon technology are higher than those of PERC (PV Magazine, 2021).

Figure 5. Technology targets, research priorities and respective TRLs for the multi-junction PV modules.



Source: (SNETP, 2013)

Emerging innovative PV deployment applications

In recent years, apart from the traditional ground-mounted, rooftop and Building Integrated Photovoltaics (BIPV), other innovative applications are emerging. A few of them are presented in Box 1.

Box 1. Emerging innovative PV deployment applications.

Agricultural photovoltaics (Agri-PV): The optimisation of agricultural land use for the simultaneous production of food and generation of electricity. The agriculture yield can increase under certain conditions and the electricity can either be used locally or sold for extra revenue.

Closed landfill sites: The use of PV plants in landfills will not alter sensitive ecosystems as they are brownfields. In addition, closed landfills are often connected to the grid and in the case of landfill gas use, the load factor of the plant can be improved by the PV system.

Building envelopes: The use of PV installed on façades and roofs as a power source and as a shading element at the same time can reduce the building's heat load and cooling demand.

Hydro dams: PV can protect the surface of earthen dams and act as a protective element against erosion caused by the rain.

Irrigation channels and floating PV: Minimise water evaporation in arid climate regions and may contribute to the limitation of critical water scarcity.

Parking lots: PV is used as sun protection for parked vehicles and at the same time generates electricity for the electric vehicle charging.

Sound barriers: PV on sound barriers on motorways can generate electricity to be used either in the neighbouring cities or at service areas for electric vehicle charging stations. The use of bifacial PV technology eliminates the necessity of a south oriented surface and also east- and west- oriented surfaces can be used. PV along train line may generate electricity that can be used directly to power trains.

Vehicle integrated PV (VIPV): Trucks and passenger cars with integrated PV technology integrated are being developed in the past few years for providing on-board electricity, thus contributing to a more sustainable mobility.

Source: (Jäger-Waldau, 2020; Chatzipanagi *et al.*, 2022)

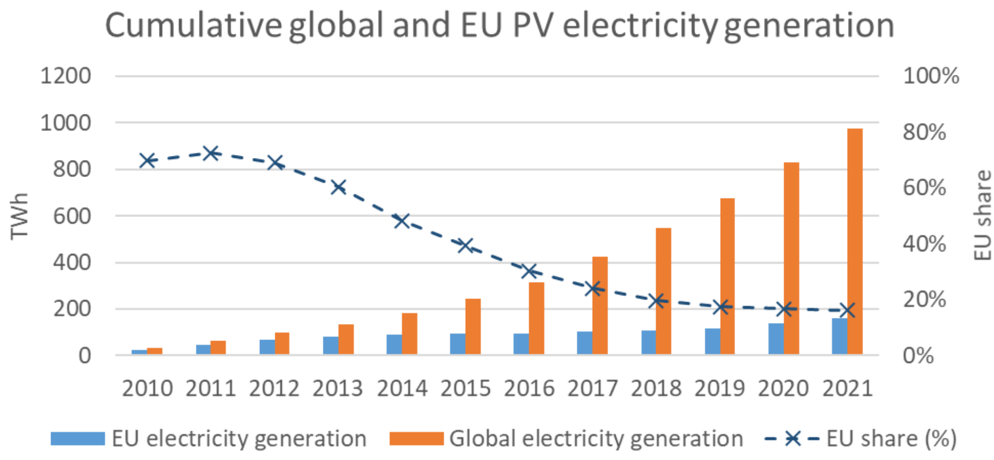
2.2 Installed energy Capacity[5], Generation/Production

As depicted in Figure 6, the global cumulative PV electricity production increased in the past years from 32 TWh in 2010 to 976 TWh in 2021 (IEA, 2021). The EU generated approximately 22.5 TWh from PV in 2010, corresponding to a share of 70 % of the global PV electricity production. From 2010 to 2021, the EU's share decreased gradually to 16 % of the global cumulative PV electricity production, with a cumulative EU PV electricity production of 158 TWh in 2021. A proper and straightforward comparison between the EU Member States is however not possible as there are several factors impacting these statistics (Box 2).

Box 2. Uncertainties in Market Statistics.

- Not all countries report standard nominal power capacity for solar PV systems (DC – W_p under standard test conditions), but especially for larger scale system the utility peak AC capacity relevant for the transmission operator.
- Some statistics only count the capacity which is actually connected or commissioned in the respective year for the annual statistics, irrespective of when it was actually installed. This can lead to short term differences in which year the installations are counted. This can lead to differences in the annual statistics, but levels out in the long-run, if no double counting occurs. E.g.:
    - In Italy about 3.5 GW of solar PV systems were reported under the 2nd *conto energia* and installed in 2010, but only connected in 2011.
    - The construction period of some large solar farms spread over two or more years. Depending on the regulations – whether or not the installation can be connected to the grid in phases and whether or not it can be commissioned in phases, the capacity count is different.
- Some countries don't have official statistics on the capacity of solar PV system installations or sales statistics of the relevant components.

Figure 6. Global and EU PV electricity production with EU share for the period 2010-2021.



Source: JRC analysis based on Eurostat and IRENA

A bit less than three-quarters of the EU's cumulative PV electricity in 2021 (70 %) was produced in only four of the twenty-seven countries. These are Germany, Italy, Spain and France (Figure 7). The same countries, in

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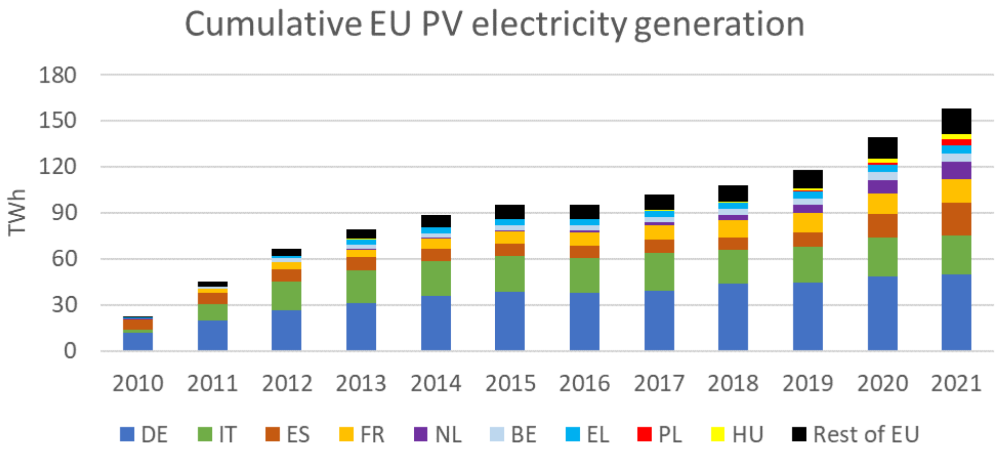
[5] Please note that the PV scenarios use AC capacities, which are relevant for the grid operators. The installed peak capacity (DC), relevant for the material demand can be 25 to 30 % higher (Kougias *et al.*, 2021).

2010 produced over 90 % of the EU's cumulative PV electricity. The Member State (MS) coding can be found in Annex 1.

Figure 7. EU PV electricity generation per country for the period 2010-2021.



Source: JRC analysis based on Eurostat

The summer of 2022 was particularly interesting for the EU (Box 3) as 12 % of its electricity production was generated by solar energy.

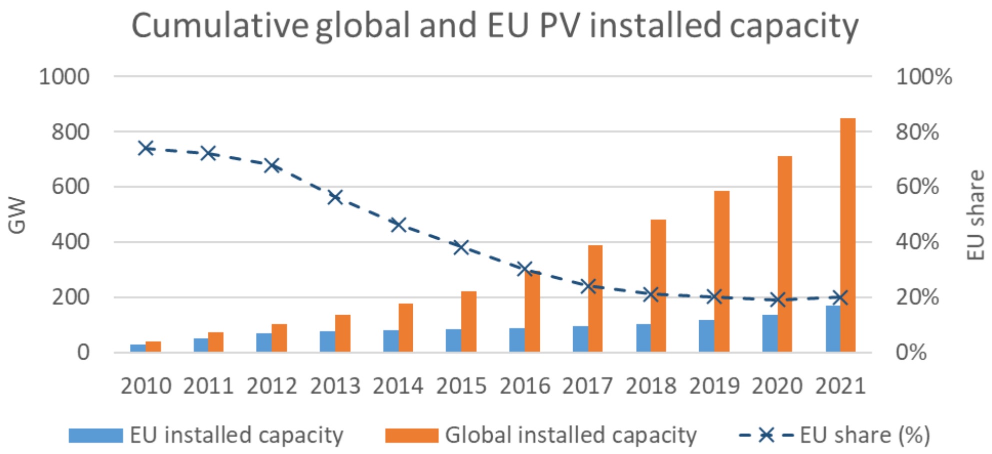
Box 3. Record of solar share in the EU's electricity generation between May and August 2022.

- Between May and August 2022 the EU generated 99.4 TWh of solar electricity. One year ago, for the same period the electricity generation from solar was 77.7 TWh. This translates to a 28 % increase.
- The above mentioned electricity generation saved the EU from importing 20 bcm of gas. Eighteen EU countries have increased their solar share for electricity generation to substantially high levels.
- Most notable is the case of Netherlands with approximately 23 % of its electricity generation being produced from solar. Germany's solar share was around 19 % and Spain's 17 %. Greece, Italy and Hungary produced around 15 % of their electricity from solar. A share of over 10 % was accomplished also in Estonia, Cyprus, Denmark and Belgium (approximately 13 %).

Source: (EMBER, 2022)

Regarding the PV installed capacity, the EU installed 30 GW, 85 GW and 170 GW in 2010, 2015 and 2021 respectively, while globally there were installed 40 GW, 223 GW and 848 GW in the respective years. This means that the EU's share in global PV installed capacity decreased from 74 % in 2010 to 38 % in 2015 and ultimately to 20 % in 2021 Figure 8.

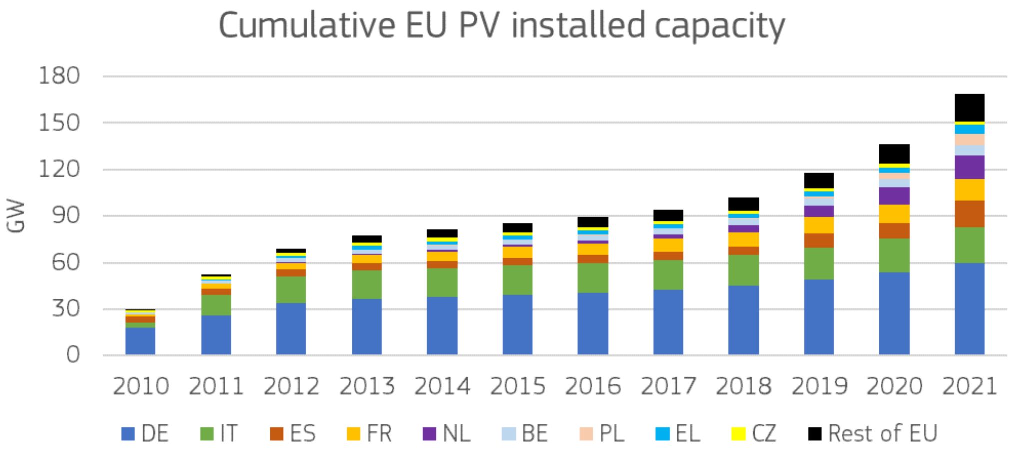
Figure 8. Cumulative global and EU PV installed capacity with EU share for the period 2010-2021.



Source: JRC analysis based on Eurostat, IRENA and (Jäger-Waldau, 2022)

Figure 9 shows the evolution of the EU's cumulative PV installed capacity from 2010 until 2020 per country. The countries contributing less to the EU installed capacity are shown as rest of EU. At EU level, Germany, Italy, Spain and France installed 67 % of the total EU installed capacity in 2021 from 82 % in 2015 and 89 % in 2010.

Figure 9. EU PV installed capacity per country for the period 2010-2021.



Source: JRC analysis based on Eurostat and (Jäger-Waldau, 2022)

SolarPower Europe (SPE) is reporting a cumulative EU capacity of 165 GW in 2021 (SolarPower Europe, 2021b). In 2025 the cumulative PV installed capacity in the EU will increase to 328 GW (SolarPower Europe, 2021b) in a business-as-usual scenario. In 2030 according to the business-as-usual scenario, the PV capacity will reach 672 GW and according to the accelerated scenario, it will exceed 1 TW, by also taking into consideration the current geopolitical risks (SolarPower Europe, 2022b). The ambition for 2050 is to reach 7-8.8 TW of PV installed capacity and 10-12 TWh of PV electricity production (Manish *et al.*, 2020). Others project an installed capacity of 500 GW by 2030 (EurObserv'ER, 2022b).

For the global cumulative PV installed capacity 22 TW are projected in 2050 for the base growth scenario and over 60 TW for the fast growth scenario (Vartiainen *et al.*, 2020).

2.3 Technology Cost – Present and Potential Future Trends

Solar PV system costs have fallen by over 80 % since 2010. This is due to significant technology improvements made possible by the intense R&D efforts of the past decades combined with the industrialisation of the manufacturing process and massive expansion of the market. This development was additionally supported by the introduction of public support schemes like feed-in tariffs or minimum targets for renewable electricity generation, combined with the introduction of relevant regulatory frameworks to enable the integration of renewable energy sources in the electricity system (IRENA, 2020a). The above-mentioned measures promoted PV awareness and acceptance thus acting as indirect influencing parameters that increased PV deployment hence also the demand for PV production.

It is important to note that technological progress and industrial learning are the two key ingredients for a further decrease in PV investment costs as well as operation and maintenance costs. However, this can only be ensured with steady and predictable R&D funding, both from the public and the private sector. Increased attention should be paid to the soft costs, including regulatory, planning and permitting costs, which in the past have not followed the same radical decrease as other technology-related factors.

CAPEX

The capital investment in a photovoltaic system can be divided into three components: the photovoltaic modules, the Balance of System (BoS) (support structure, tracking system, cabling, inverter, etc.) and the soft costs (permitting, marketing, etc.).

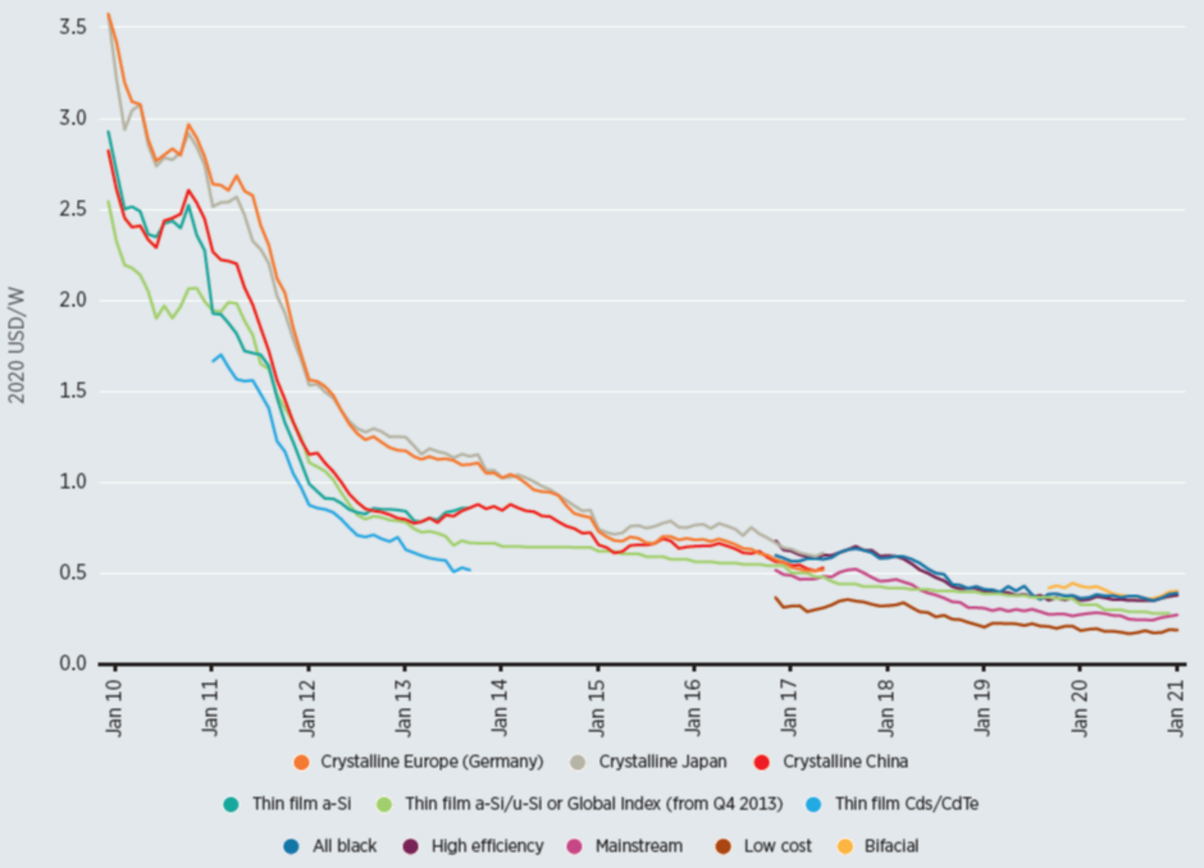
The reduction in PV module prices has been remarkable. Between 2010 and 2021 the price of c-Si modules decreased by 92 % while the cumulative installed capacity increased by 803 GW reaching 843 GW in 2021 (IRENA, 2022c). The PV module price reduction is mainly due to the higher efficiencies achieved over years, *i.e.* less active area needed for the same wattage production. Apart from the material and area-related cost reduction, BoS costs are reducing simultaneously as racking/mounting structures and cabling costs are also reduced. The land area requirement has decreased from 2.7 hectares/megawatt (MW) in 2010 to 1.9 hectares/MW in 2020 (IRENA, 2020c). Further land requirement reductions may be achieved with the application of bifacial modules that exploit both sides for the conversion of light into electricity, and agri-photovoltaic systems that combine food and electricity production on the same land without changing the land use and without having them compete with each other.

Figure 10 presents the evolution of the price of different PV module technologies from 2010 until 2021.

The cost of crystalline technology PV modules decreased from USD 0.27/W in the summer of 2010 to USD 0.2/W in the summer of 2020 (23 % reduction). USD 0.2/W represents a minimum price since in mid-2020, prices started going up against stakeholders' expectations (IRENA, 2020b). Between 2020 and 2021, the price of c-Si modules increased between 4 % and 7 %, from a range of USD 0.19-0.41/W to a range of USD 0.20-0.43/W (IRENA, 2022c). The global market price of mono c-Si PERC modules increased by 42 % between August 2020 and November 2021. There was in particular a significant increase in the price of polysilicon, from USD 6.8/kg in July 2020 to USD 11.0/kg at the beginning of 2021 and then to USD 30.0/kg at the end of 2021, arriving up to USD 45.4/kg in August 2022 (PV Magazine, 2022a) This increase in the price of polysilicon is attributed (i) to the fact that several polysilicon factories ceased their production in China, (ii) to cost inputs like electricity and other energy prices as well as (iii) to the Covid-19 related disruptions to logistics and shipments (IRENA, 2020c, 2022c). The polysilicon price increase together with the mismatch between supply and demand, as PV technologies are becoming more and more indispensable for decarbonisation targets, are the main reasons behind the increase in PV module prices (JMK Research and Analytics, 2022).

The most dramatic reduction of cost occurred for the thin-film technologies and more in particular for the a-Si and CdTe. The former experienced a decrease in cost of 35 % in five years, whereas the latter experienced a 46 % decrease in only 3 years. Thin-film PV modules in December 2020 were sold at USD 0.28/W, following a price drop of 22 % between December 2019 and December 2020 (IRENA, 2020b). In December 2021 the price of thin-film modules dropped to USD 0.26/W (IRENA, 2022c).

Figure 10. Module spot prices for different PV technologies for the period 2010-2021.



Source: (IRENA, 2022c)

The mainstream modules followed an average 13 % reduction (between 2017 and 2021), resulting in an average cost of USD 0.30/W in 2021 and USD 0.31/W in the 1st quarter of 2022, depending on the module technology considered. Over the same period, all black[6] and high-efficiency PV modules reduced their cost by 10 % and 11 % respectively. In the 1st quarter of 2022, they maintained their price at USD 0.42/W and USD 0.40/W respectively (IRENA, 2020b, 2022c). Even though low-cost PV modules started with a relatively low price (USD 0.34/W in 2017), their price managed to further decrease by 12 % in the course of the next five years (IRENA, 2020b, 2022c). The lowest decrease in price is identified for the bifacial technology but the technology has a recent presence in the market as bifacial module prices were only introduced at the end of 2019 when they were sold at a 21 % higher price than the high-efficiency monofacial c-Si modules. Starting in 2019 at USD 0.45/W with an 8 % share in the market, bifacial modules reduced their price to USD 0.41/W in 2020 by increasing their market to 27 % (IRENA, 2020b, 2022c). Bifacial c-Si modules are still sold at higher prices than monofacial c-Si technologies because the costs for the former are driven by the cost of cell architectures types used to build them, rather than by the bifacial design itself (IRENA, 2020b, 2022c).

Analysis performed in March 2022 projects that the global price of modules will decrease to USD 0.15/W in 2032 (VDMA, 2022).

The prices for the different PV module technologies, in April/September 2022 for the EU are presented in Table 2.

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[6] All black PV modules are monocrystalline PV modules that are visually black. Differently from blue polycrystalline PV modules, they are made from a single, high-quality (purity) silicon crystal.

Table 2. EU spot market module prices by technology in April / September 2022.

PV module technology	**EUR/W$_p$**
Bifacial	0.40 (April 2022)
All black	0.39 (April 2022)
High efficiency	0.43 (September 2022)
Mainstream	0.34 (September 2022)
Low cost	0.21 (September 2022)

Source: (Pvxchange, 2022a, 2022b)

Inverters account for approximately 10 % of the capital costs of a PV installation and they are foreseen to be replaced at least once over the course of the plant's lifetime. Table 3 presents the forecasted prices of inverters according to IHS Markit.

According to Table 3, the forecasted inverter price for 2021 was USD 0.066/W and in fact, the actual inverter price for 2021 was USD 0.050/W (forecasted price for 2022) thus proving that the reduction in inverter price came earlier than expected. ITRPV projects a further decrease in inverter prices to USD 0.025/W in 2032 (VDMA, 2022).

Table 3. Inverter prices.

Year	**USD/W**
2018	0.076
2019	0.066
2020	0.060
2021	0.066
2022	0.050
2023	0.047

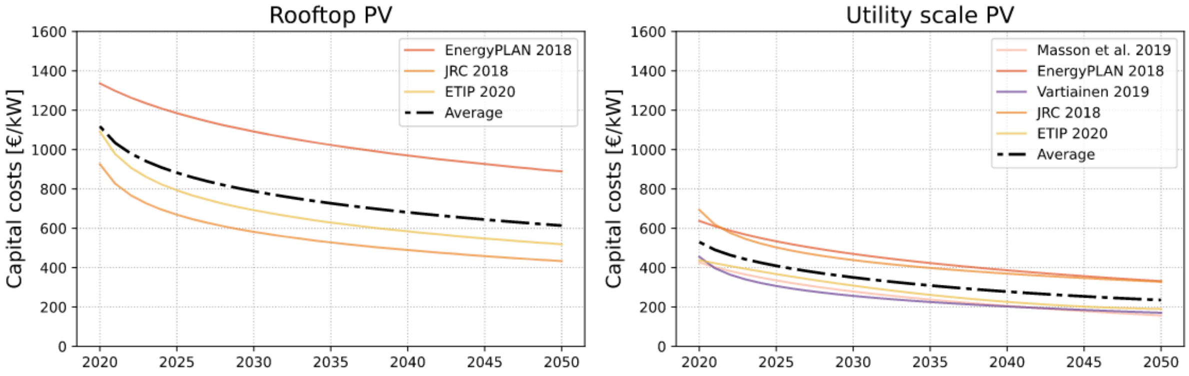
Source: (Ribeyron, 2020)

As module and inverter costs have significantly decreased, nowadays the other BoS costs account for a larger share of the system's total costs (IRENA, 2020b). This is because the learning rate of modules proved to be higher than that of BoS and OPEX In 2020, the BoS costs accounted for 57 % of the total installed costs (without the consideration of inverters) (IRENA, 2022c).

The global weighted-average total installation costs for newly commissioned utility-scale projects fell by 81 % between 2010 and 2020, from USD 4.731/W to USD 0.883/W (IRENA, 2020c). From 2020 to 2021 it further decreased by 6 % resulting in USD 0.857/W (IRENA, 2022c).

The future projections regarding the capital cost in Europe are shown in Figure 11. For rooftop installations, the capital costs may fall to an average value of EUR 0.8/W in 2030 from approximately EUR 1.1/W in 2020, while the prediction for 2050 is a compound average decrease of 6 % over the 2020-2050 period (from EUR 1.1/W to EUR 0.6/W). For utility-scale installations, the compound decrease is predicted to be 4 % and 7 % for the period 2020-2030 and 2020-2050 respectively.

Figure 11. Capital cost projections for rooftop and utility-scale PV installations for the period 2020-2050.



Source: (Prina *et al.*, 2019; Moser, 2021)

OPEX

The O&M benchmark costs in the US in 2020 are reported to be USD 18.7/kW/year for commercial ground-mounted installations, USD 18.6/kW/year for commercial roof-mounted installations, USD 28.9/kW/year for residential installations, USD 16.3/kW/year for fixed utility-scale installations and USD 17.5/kW/year for 1-axis tracking utility-scale installations (IRENA, 2020c).

According to IRENA, average utility-scale O&M costs in the Europe (instead of EU dealt in the present report) are around USD 10/kW/year, and in Germany at USD 9/kW/year, (suggesting an 85 % decrease between 2005 and 2017). This reflects in a 16 % - 18 % reduction with every doubling of cumulative installed capacity (IRENA, 2020b, 2022c).

An evaluation of the solar energy costs at EU level revealed that the average EU O&M costs[7] for utility-scale installations are between EUR 6.8/kW/year and EUR 14.8/kW/year. The lowest O&M costs are in Bulgaria in the range of EUR 5.2-11.2/kW/year and the highest in Germany between EUR 8.7/kW/year and EUR 18.9/kW/year (Lugo-laguna, Arcos-Vargas and Nuñez-hernandez, 2021). The low range value refers to a fixed system and the high range value to a 2-axis tracking system. The O&M costs for each EU country can be seen in Table 4.

Analysis performed in March 2022 projects that in the next ten years, the total system costs will decrease by approximately 35 % because of the technology improvements that will take place (VDMA, 2022).

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[7] O&M costs are calculated as a percentage of the initial investment (I_0). For fixed angle PV systems: 1 % of I_0 and for 2-axis tracking system: 1.5 % of I_0.

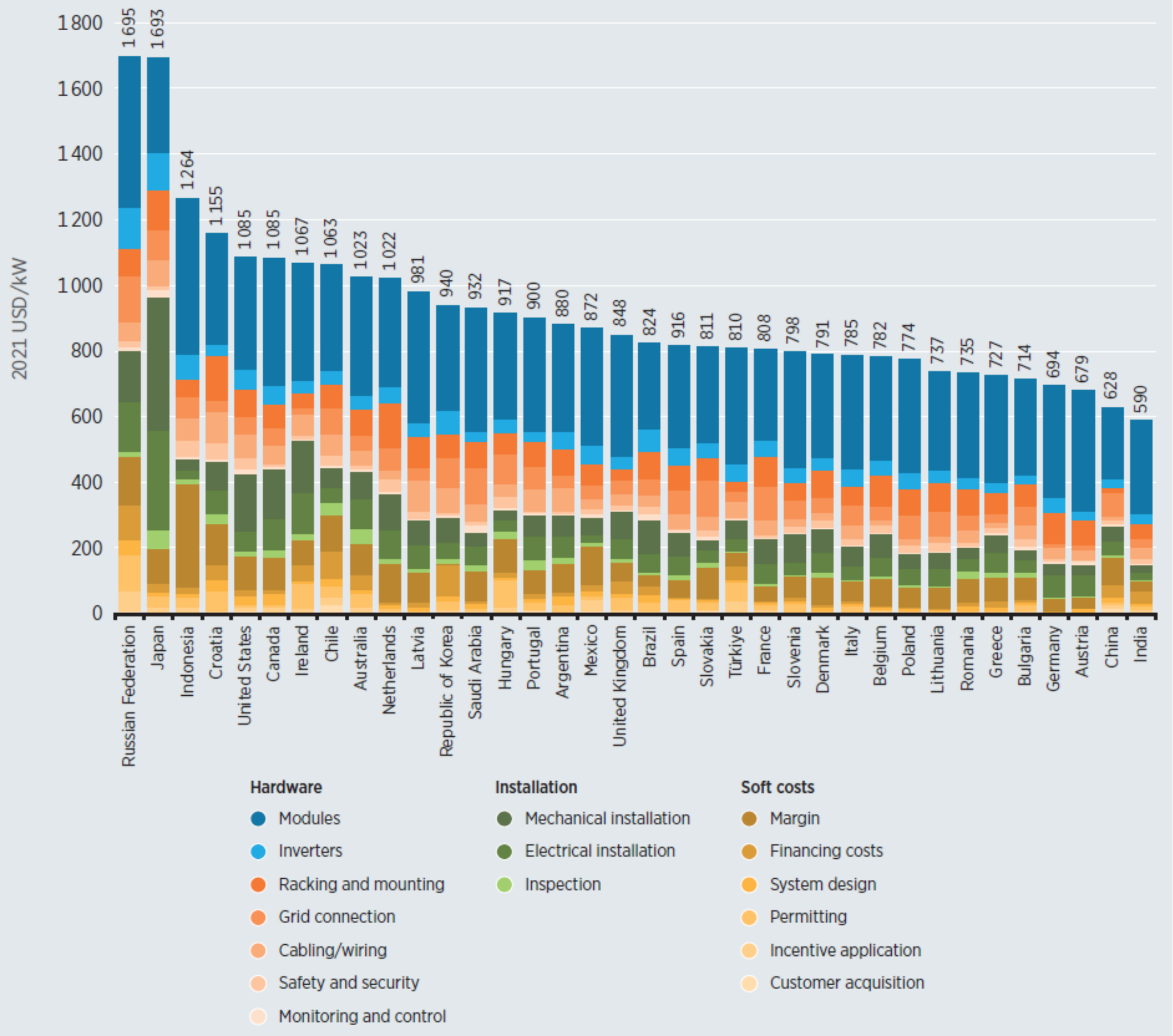
Table 4. Operation and Maintenance (O&M) costs for utility-scale installations for the EU.

Country	EUR/kW/year
Austria	8.42-18.29
Belgium, Luxembourg, Netherlands	8.54-18.54
Bulgaria	5.18-11.24
Croatia, Slovenia	5.64-12.24
Cyprus	6.47-14.04
Czech Republic	5.82-12.64
Finland	8.17-17.74
France	7.80-16.94
Germany	8.70-18.89
Greece	6.33-13.74
Hungary, Slovakia	5.66-12.29
Ireland	8.40-18.24
Italy, Malta	7.13-15.49
Latvia, Lithuania, Estonia	5.57-12.09
Poland	5.64-12.24
Portugal	6.10-13.24
Romania	5.36-11.64
Spain	6.79-14.74
Sweden, Denmark	8.19-17.79

Source: (Lugo-laguna, Arcos-Vargas and Nuñez-hernandez, 2021)

The total installed costs vary depending on the location. The hardware, the installation, as well as the soft costs, show a non-negligible variation even among the different member states of the EU. The differences in total installed costs are mostly due to the installation and the soft costs. Figure 12 presents the different total installed costs for utility-scale PV installations.

Figure 12. Detailed breakdown of total installed costs for utility-scale PV installations for different countries in 2021.



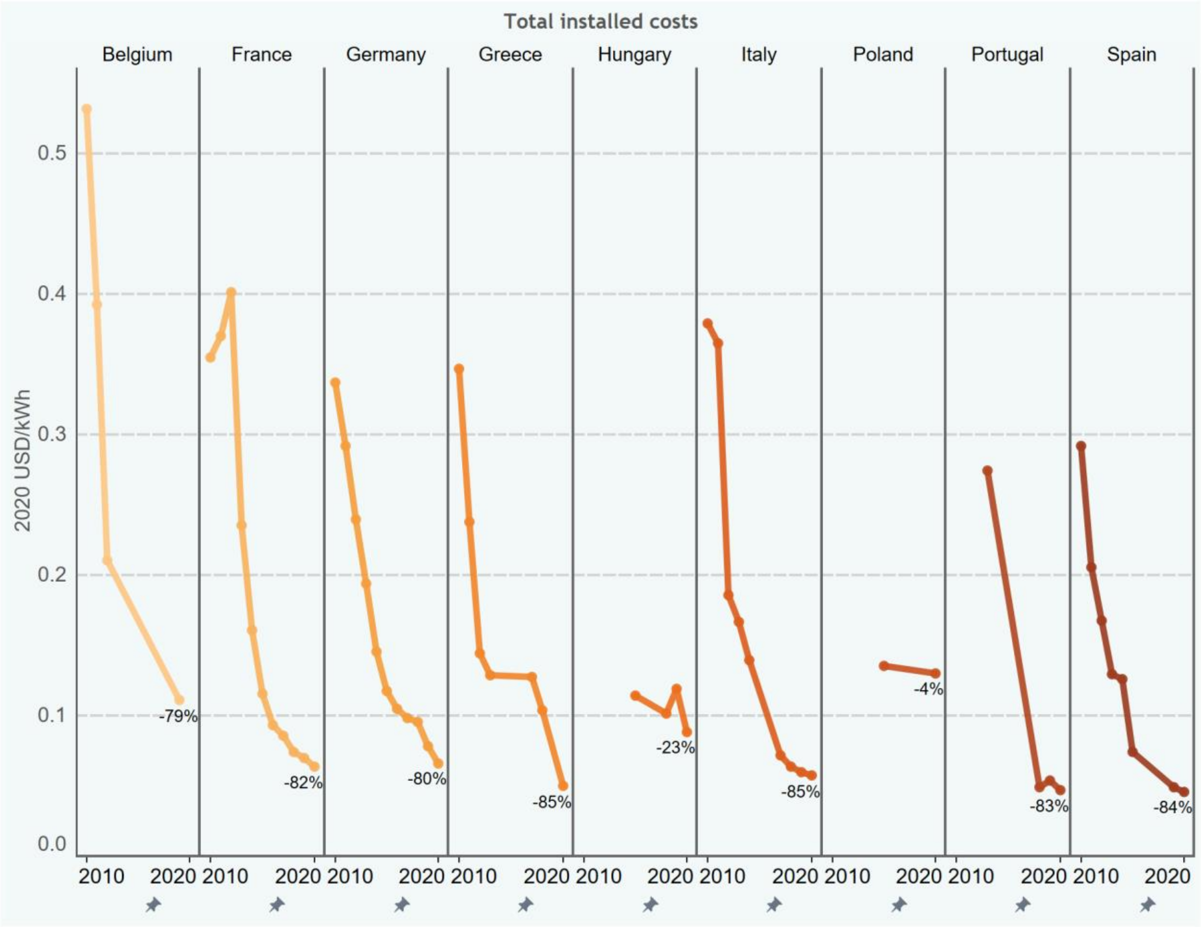
Source: (IRENA, 2022c)

Predictions for large installations (>100kW$_p$) based on European, Asian and US systems, report that the total system costs in 2032 will decrease by 34 % in comparison to 2021 (VDMA, 2022). This reduction of costs is attributed mainly to the expected reduction of module costs by 18 % and project costs including tax and contingencies by 7 % (VDMA, 2022).

LCoE

The global weighted-average LCoE for utility-scale projects fell by 88 % between 2010 and 2021 from USD 0.4170/kWh to USD 0.0448/kWh (IRENA, 2022c). The main contributors to this cost-reduction were: (i) the 45 % reduction of module costs, (ii) the 17 % reduction of inverters, racking and mounting and other BoS costs, (iii) the 26 % reduction of installation, engineering, procurement and construction (EPC), development costs and other soft costs and (iv) the better financial conditions, reduced O&M costs and increased capacity factor (IRENA, 2022c). Figure 13 presents the LCoE of different European countries for utility-scale installations (IRENA, 2020c).

Figure 13. Levelised cost of electricity (LCoE) for utility-scale installations in nine European countries.

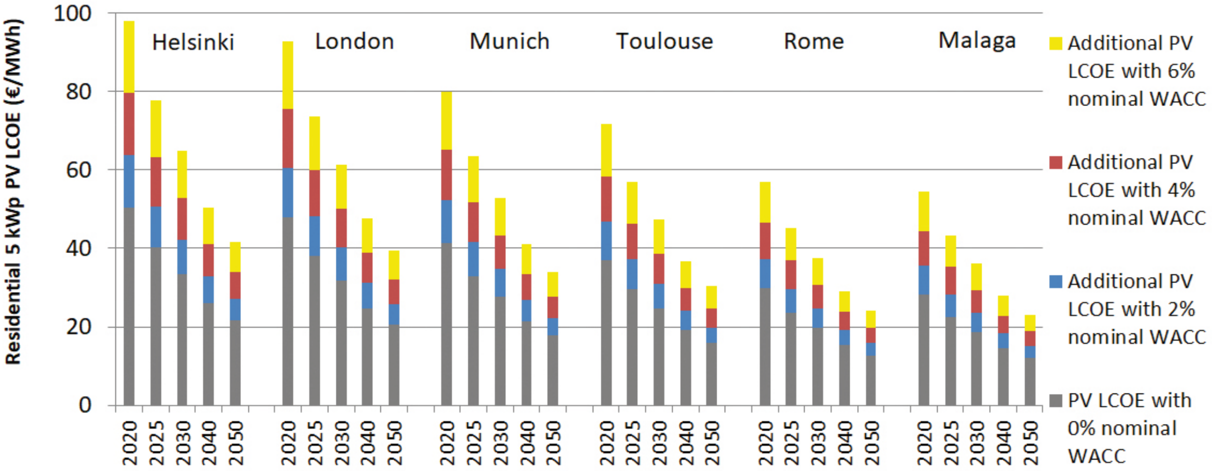


Source: (IRENA, 2020c)

According to the Bloomberg New Energy Finance (BNEF)'s global benchmark for the levelised cost of electricity (LCoE) (BloombergNEF, 2021) reports that for non-tracking utility-scale systems, the LCoE was USD 0.043/kWh while for the tracking utility-scale systems it was USD 0.040/kWh in the 2nd half of 2021. These values are around 10 % higher than the 1st half of 2021 due to the increased price of polysilicon. However, even as such, the above LCoE values are still lower by 30 % than the ones for coal and gas without carbon capture and sequestration (CCS) and by 85 % than LCoE for coal and gas with CCS (Jäger-Waldau, 2022).

A comparative analysis of calculated LCoE values at different EU locations and with different Weighted Average Costs of Capital (WACC) rates (ETIP-PV, 2020) has shown that for a residential rooftop installation (Figure 14) when applying a 6 % WACC, the EUR 0.100/kWh of LCoE in 2020 will decrease to EUR 0.040/kWh of LCoE in 2050 in Finland. For southern locations, like in Spain, for the same conditions, the 2020 LCoE of EUR 0.055/kWh will be reduced to EUR 0.022/kWh in 2050. Indicatively, LCoE values for residential rooftop installations are expected to be higher than utility-scale installations by a factor of roughly 2 (Vartiainen *et al.*, 2020).

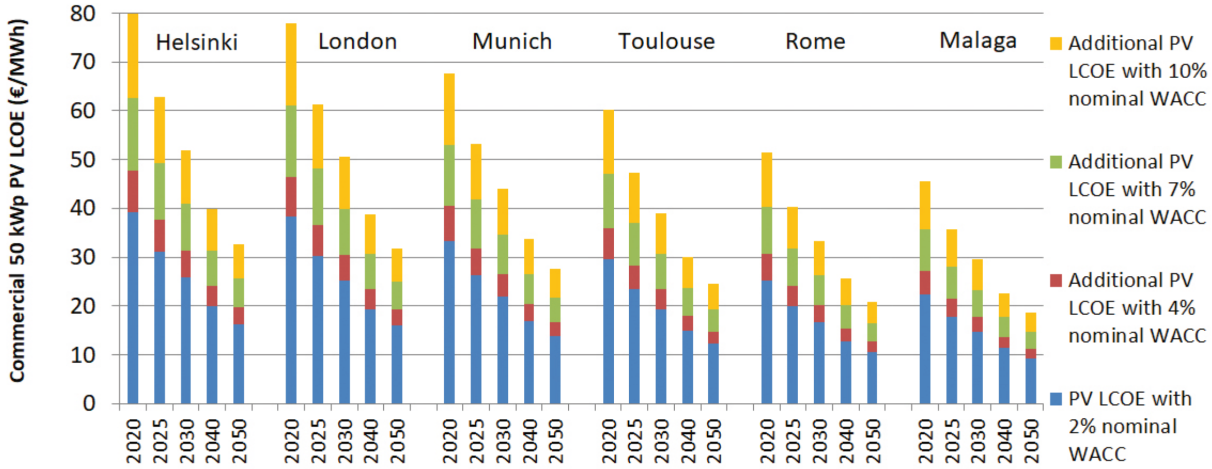
Figure 14. PV LCoE at six European locations with different nominal WACCs for 5 kW$_p$ residential rooftop PV installation.



Source: (ETIP-PV, 2020)

The relevant LCoE values for a commercial rooftop installation presented in Figure 15 are lower than for the residential installation in Figure 14. In Finland from EUR 0.080/kWh in 2020 the LCoE will decrease to EUR 0.034/kWh in 2050, whereas in Spain in 2050 it will drop by EUR 0.028/kwh from EUR 0.046/kWh.

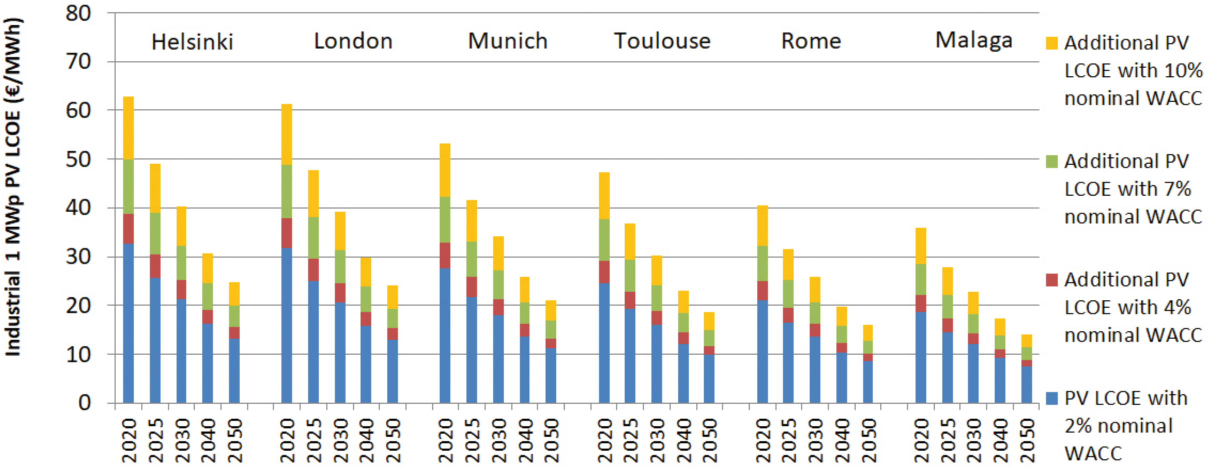
Figure 15. PV LCoE at six European locations with different nominal WACCs for 50 kW$_p$ commercial rooftop PV installation.



Source: (ETIP-PV, 2020)

A decrease of EUR 0.038/kWh between 2020 and 2050 (from EUR 0.063/kWh to EUR 0.025/kWh) is predicted for the LCoE of industrial installations in Finland. In Spain, the LCoE will drop by EUR 0.022/kWh in 2050 in comparison to 2020 (EUR 0.015/kWh) (Figure 16).

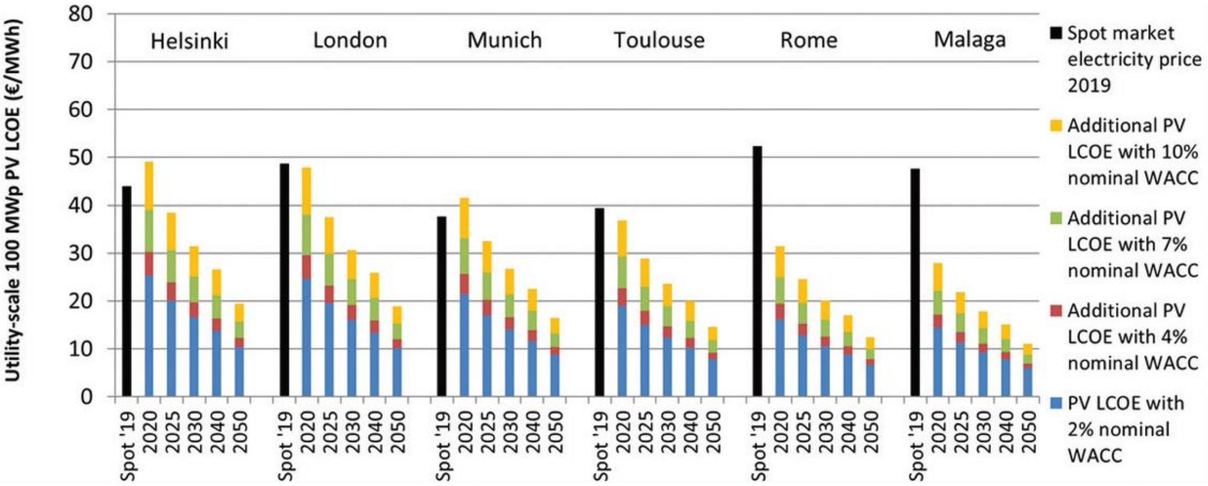
Figure 16. PV LCoE at six European locations with different nominal WACCs for 1 MW$_p$ industrial PV installation.



Source: (ETIP-PV, 2020)

In the case of utility-scale installations and by taking into consideration the wholesale electricity prices, the cost of electricity produced from PV was already competitive in Munich and Helsinki even when applying a WACC of 7 % and in London, Toulouse, Rome and Malaga when applying a WACC of even over 10 % (Figure 17).

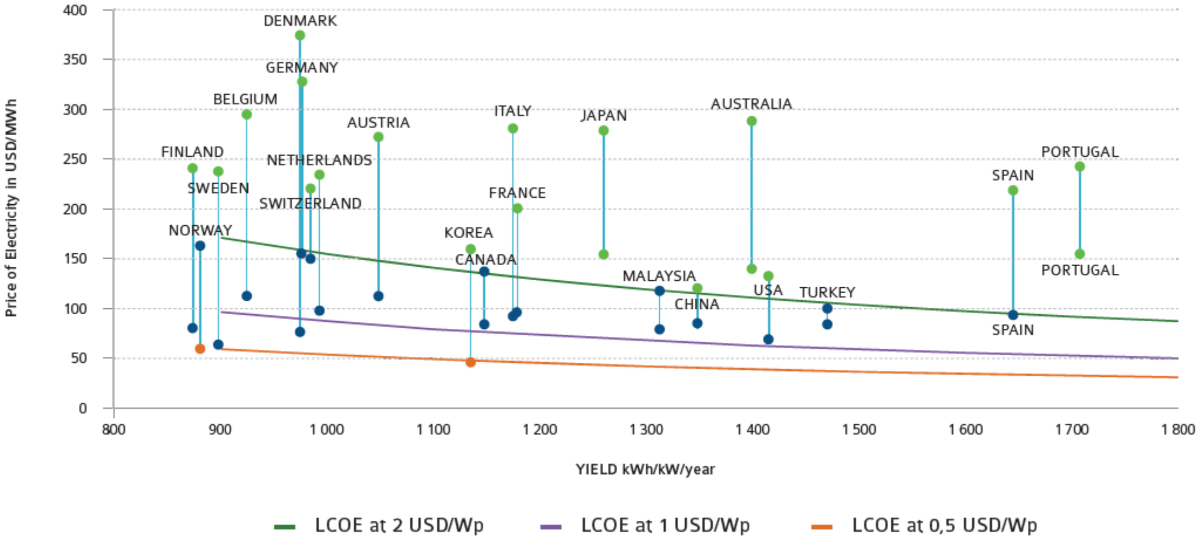
Figure 17. PV LCoE six European locations with different nominal WACCs for 100 MW$_p$ utility-scale PV installation compared and average spot market electricity price in 2019.



Source: (ETIP-PV, 2020)

According to Figure 18 grid parity is already a reality in various countries and for many others costs are decreasing to such levels that PV electricity is becoming competitive and expected to be even more so in the years to come. The figure shows the price of electricity for several countries, for three different system prices depending also on each country's solar resource. The green points on the figure represent the cases where PV is competitive, while the blue points are the cases where PV competitiveness depends on the system prices and the retail prices of electricity. Orange points need special circumstances to be competitive. (IEA-PVPS, 2021).

Figure 18. LCoE as a function of solar irradiance and retail prices in key markets.



Source: IEA-PVPS, TRENDS IN PHOTOVOLTAIC APPLICATIONS 2021

2.4 Public R&I funding

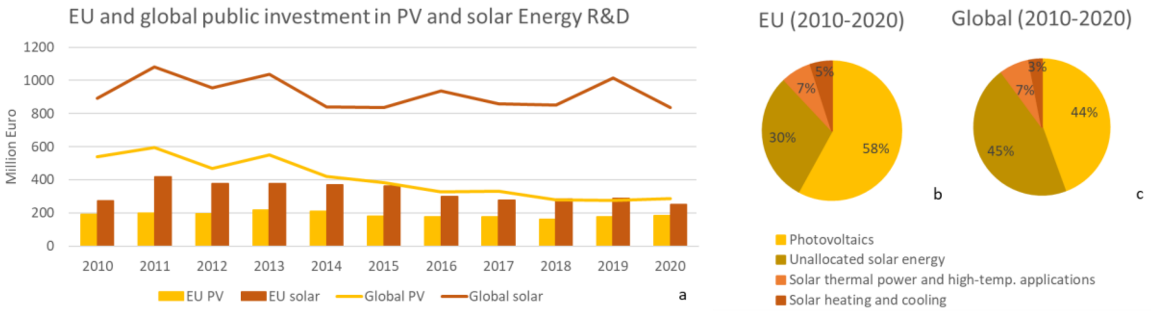
The public investment in solar energy and PV (treated as a sub-category) at EU and global level from 2010 until 2020 is illustrated in Figure 19a. It must be noted that the 2020 values do not include funding reported from Italy thus an artificial decline is created for the specific year.

Overall, public investments in solar increased by 5 % and 14 % at EU and global levels respectively between 2010 and 2019. On the contrary, over the same period, it is observed that global public funding in PV has significantly decreased by 54 % (from EUR 595 million in 2010 to EUR 275 million in 2019). EU has experienced a decrease itself but much lower (10 %).

Over the last 10 years, EU public investments in solar energy increased in 2011 (EUR 420 million) to then stabilise to around EUR 370 million each year until 2015 and started decreasing thereafter down to EUR 280 million in 2017. In the years to follow (from 2018 until 2020) a slight increase is observed. It should be noted that the global public investment in research into solar energy R&D suffered its lowest budget in 2015 (approximately EUR 835 million) and its highest in 2011 with approximately EUR 1 100 million.

As far as the PV sector is concerned, at EU level, public investment remained between EUR 164 million and EUR 220 million from 2010 to 2020 even without Italy's contribution, whereas the global public investment in PV suffered a significant decrease from a maximum of EUR 600 million in 2011 to EUR 285 million in 2020.

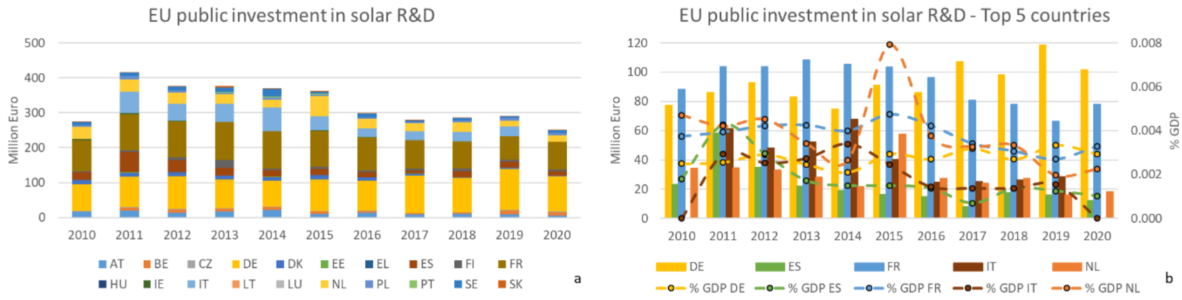
Figure 19. (a) EU and global public investment in Solar and PV R&D, (b) EU and (c) global allocation of solar energy technologies for the period 2010-2019.



Source: JRC analysis based on (IEA, 2022a)

In fact, while 58 % of the total solar energy sector public investment was attributed to PV in the EU, the respective percentage at global level was 44 % for the period between 2010 and 2020 (Figure 19b and Figure 19c). The total cumulative EU public investments in PV accounted for 47 % of the total cumulative global public investments in PV during the period 2010-2020, while in the case of the total cumulative public investments in solar, the EU accounted for 35 % of the global total cumulative public investments. The above-mentioned percentages are lower than expected since Italy is not included in the dataset for the year 2020.

Figure 20. (a) EU public investment per MS and (b) EU public investment and % of GDP in Solar and R&D for the top 5 MS.

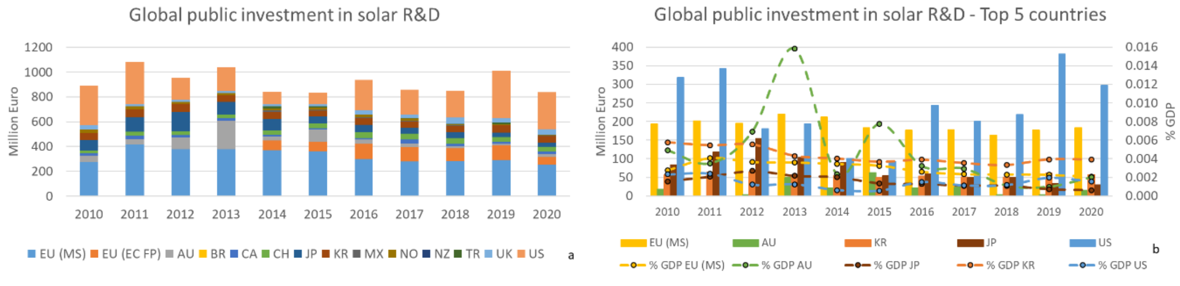


Source: JRC analysis based on (IEA, 2022a)

Data on PV public investments (IEA codes: 312 Solar photovoltaics) are not always reported from the EU MS and therefore are considered incomplete. For this reason, Figure 20a and Figure 20b present MS' and the rest of the world countries' public investments in the broader technology group of solar energy rather than the specific technology of PV. This enables a more direct and fair comparison.

Germany, France, Italy, Netherlands and Spain are the top 5 EU countries with the highest public investment in solar energy technologies. Germany and France have kept a nearly constant solar energy public investment as a percentage of their GDP, between 0.0021 and 0.0033 and between 0.0027 and 0.0047 respectively. Spain shows a peak in 2011 (0.0043) and a decrease in the following years. The same applies also to Italy but its peak (0.0034) is in 2014. In the case of the Netherlands, the public investment as a percentage of the country's GDP is rather unstable ranging from 0.0019 to 0.0048 with a distinct peak in 2015 (0.0080).

Figure 21. (a) Global public investment per country and (b) global public investment and % of GDP in Solar and R&D for the top 5 countries.



Source: JRC analysis based on (IEA, 2022a)

The top 5 regions in the world with the highest public investments in solar energy are the EU, the US, Japan, South Korea and Australia (Figure 21a and Figure 21b). The investments in the EU for 2012 and 2013 are comparable to those of the US. From 2012 until 2015 a decrease in the US and a stable course in the EU has put the EU in the 1st place among public investors globally. After 2015, the US is surpassing again the EU and becomes a leading public investor in 2019 and 2020. In terms of percentage of the GDP, the US has a lower level of public investment in comparison to the EU. Korea, which had a 0.0060 public investment as a percentage of its GDP in 2010 has experienced a gradual decrease, down to 0.0039 in 2020. Australia, similarly to the Netherlands in Figure 20b exhibits a less stable course with two peaks of 0.0160 in 2013 and 0.0080 in 2015.

In Figure 21a and Figure 21b, 'EU (MS)' denotes the sum of the Member States' national investments, while 'EU (EC FP)' denotes funding from EU framework programmes (H2020) and is only available from 2014 onwards.

According to the 2021 annual report of the European Climate Neutral Industry Competitiveness Scoreboard (CIndECS), whose objective is to establish a scoreboard to assess the EU's competitive position in carbon-neutral solutions across important industrial ecosystems related to the energy transition, the EU has medium competitiveness in public R&D for PV (Kuokkanen *et al.*, 2022).

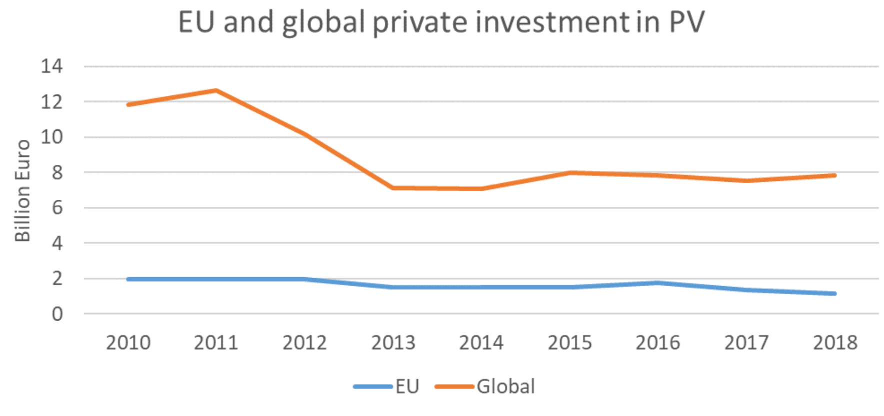
2.5 Private R&D funding

Retrieving as well as evaluating information on private funding for PV is difficult as private companies do not have the obligation to disclose their financial and Research & Development (R&D) details. According to the results of an analysis performed regarding the PV R&D funding from 2014 to 2020 (Moser *et al.*, 2021), a substantial portion of funding is coming from the private sector. In particular, the analysis showed that approximately two-thirds of the R&D funding comes from the private sector and the remaining one-third from the public sector.

The following tentative analysis is based on the use of patenting output as a proxy for private funding (Fiorini *et al.*, 2017; Pasimeni, Fiorini and Georgakaki, 2019) and the results should therefore be interpreted with caution (especially in the case of China). Unlike public investments, the analysis is performed from 2010 until 2018, since 2019 data is incomplete.

According to the collected data for public R&I funding in the previous chapter and the data for private R&D funding in this chapter, the relationship between public and private funding is different from that presented in (Moser *et al.*, 2021). While the public investments for the EU and globally ranged from EUR 164 to EUR 220 million and from EUR 279 to EUR 595 million respectively for the period 2010-2018, the private investments in the EU and globally ranged from EUR 1.2 to EUR 2 billion and from EUR 7.1 to EUR 12.6 billion respectively for the same period (Figure 22). Analysing the relationship between public and private funding from 2010 until 2018, it is observed that public R&D funding was between 9 % and 13 % of the total R&D funding. This suggests a much higher contribution of the private sector to the PV R&D funding (87 %-91 %).

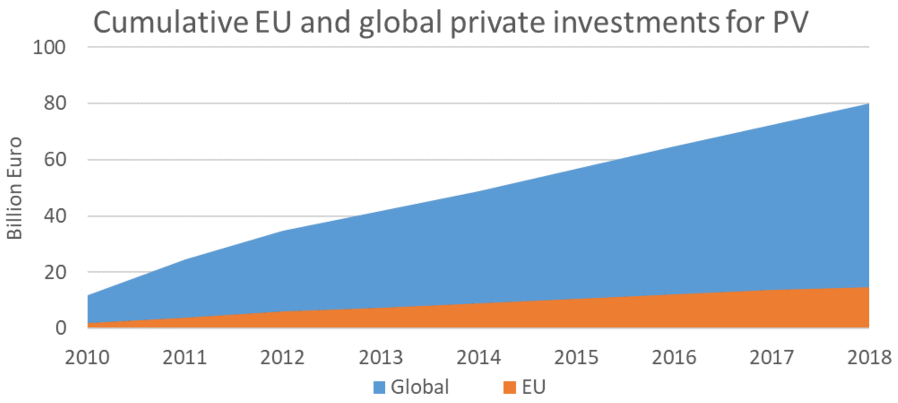
Figure 22. EU and global private investment in PV for the period 2010-2018.



Source: JRC analysis based on (Fiorini *et al.*, 2017; Pasimeni, Fiorini and Georgakaki, 2019)

Between 2010 and 2018, as far as PV is concerned, the indication is that the EU exhibits a more extended decrease in private than in public investments, while over the same period, private investments at global level suffered a smaller decrease than public investments. Regardless of the public or private nature of the investment, investments have suffered significant decreases both in the EU and globally. However, there is an indication that, unlike the EU, the rest of the world is more and more benefitting from private rather than public investments.

Figure 23. EU and global cumulative private investment in PV for the period 2010-2018.

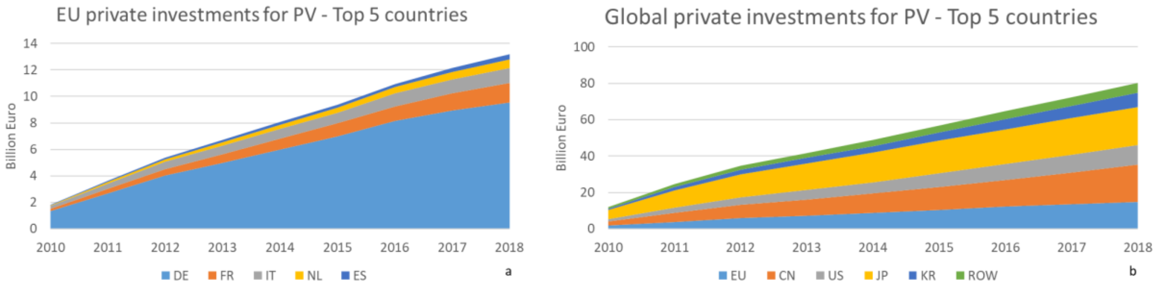


Source: JRC analysis based on (Fiorini *et al.*, 2017; Pasimeni, Fiorini and Georgakaki, 2019)

As shown in Figure 23, at global level, cumulated private investments in PV reached EUR 80 billion in 2018. In the same year, the EU private investments amounted to EUR 15 billion (18 % of the cumulated private investments at global level).

Figure 24a presents the five EU countries with the highest levels of cumulated private investment in the EU. These five countries account for 90 % of the total cumulated private investments in the EU from 2010 to 2018. Germany had the highest level of private investment in PV, accounting for 67 % of the cumulative investments (2010-2018), followed by France with 9 % and Italy with 8 %.

Figure 24. (a) EU cumulative private investment in PV per MS and (b) global cumulative private investment in PV EU and top 5 countries for the period 2010-2018.



Source: JRC analysis based on (Fiorini *et al.*, 2017; Pasimeni, Fiorini and Georgakaki, 2019)

Globally (Figure 24b), the cumulated private investments in PV from China (26 %) and Japan (26 %) represent more than half of the global cumulated private investments. The EU represents 18 % of the total cumulated private investments from 2010 to 2018, representing approximately EUR 15 billion out of a total of approximately EUR 88 billion. The next two regions are the US (13 %) and Korea (10 %).

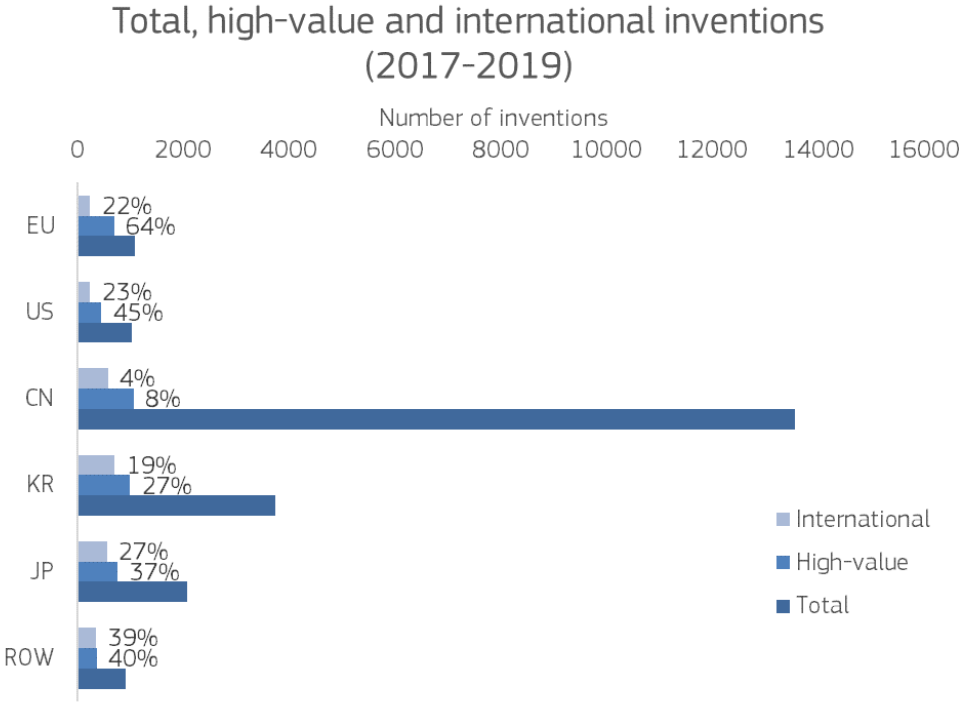
2.6 Patenting trends

Patenting trends are a valuable tool to analyse research trends in concepts that have market value. They are essentially using R&D knowledge to translate it into commercialised products. It must be noted though that in no way they may be used for R&D analysis but they can provide an insight into innovation.

The dataset used for the creation of the patent indicators (Fiorini *et al.*, 2017; Pasimeni, 2019; Pasimeni, Fiorini and Georgakaki, 2019, 2021; Pasimeni and Georgakaki, 2020) is based on the following Cooperative Patent Classification (CPC) codes: Y02B 10/10, Y02E 10/50, Y02E 10/52, Y02E 10/541, Y02E 10/542, Y02E 10/543, Y02E 10/544, Y02E 10/545, Y02E 10/546, Y02E 10/547, Y02E 10/548, Y02E 10/549 (European Patent Office, 2022). Since the last PV Technology Development report of the Low Carbon Energy Observatory (LCEO) (Taylor and Jaeger-Waldau, 2020), there has been a reclassification of the CPC codes and therefore the dataset used in the present report is different depicting a lower number of inventions, mainly affecting inventions patented after 2009 and mainly with regard to China.

As depicted in Figure 25, China has the largest number of patents with more than 13 567 inventions, followed by South Korea and Japan. The EU is in 4th position with 1 093 inventions in total between 2017 and 2019. However, when only the high-value inventions[8] are taken into consideration, the EU moves 1st with 64 % of its total inventions being high-value inventions and China results into the last position, thus suggesting that the EU, unlike China, is generally filing to more than one patent office. The same trend is evident also as far as international inventions are concerned. The EU is aiming for patent applications outside while China appears to be concentrated on applying mainly within the country rather than internationally.

Figure 25. Number of inventions and share of high-value and international activity for the period 2017-2019.



Source: JRC analysis based on EPO PATSTAT

While Figure 25 shows the high-value inventions as a percentage of the total number of inventions, Figure 26a presents the number of high-value inventions in absolute numbers for each year from 2009 until 2019. A decreasing trend is observed for most countries apart from South Korea and China. Germany, France, Netherlands and Italy are among the top 10 countries with the highest number of high-value inventions between 2017 and 2019 appear (Figure 26b). In fact, from 2009 until 2019, Germany has had 1535, France 702, Netherlands 219 and Italy 195 high-value inventions.

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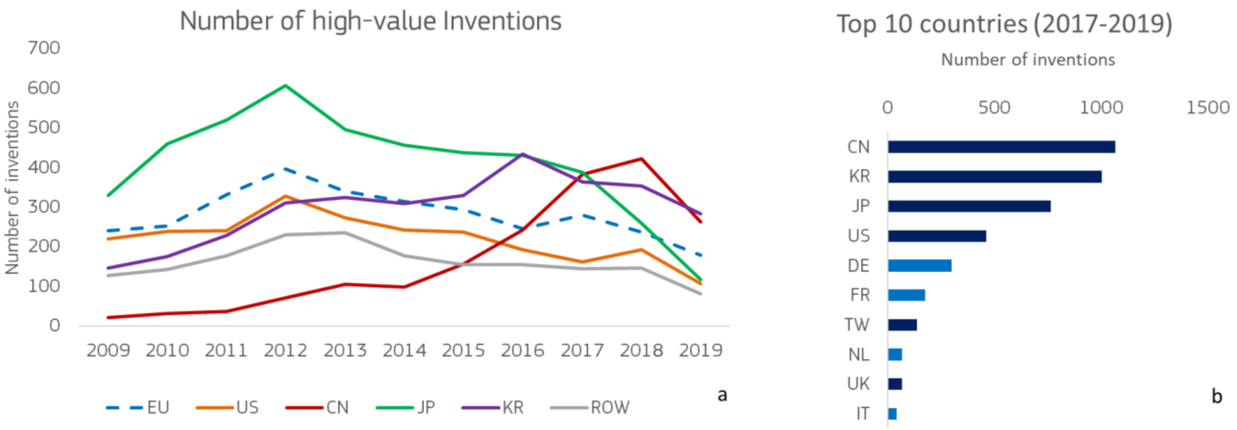
[8] High-value inventions (or high-value patent families) refer to patent families that include patent applications filed in more than one patent office, while international inventions include patent applications protected in a country different to the residence of the applicant. Note that high-value considers EU countries separately, while for international inventions European countries are viewed as one macro category.

Figure 26. (a) Global number of high-value inventions for the period 2009-2019 and (b) top 10 countries of high-value inventions for the period 2017-2019.



Source: JRC analysis based on EPO PATSTAT

Table 5 and Table 6 respectively present the top 10 entities globally and in the EU which filed the highest number of inventions in PV between 2017 and 2019. At global level, South Korea is featured in Table 5 through four of its entities, China with three and Japan with two. Cynora GmbH, a German company holds the 9th position in this ranking and is the only EU entity in the list.

Table 5. Global top 10 entities with high-value inventions in PV for the period 2017-2019.

Entities	Number of high-value inventions	Country
Samsung Display Co Ltd	348	KR
Boe Technology Group Co Ltd	181	CN
Lg Philips Lcd Co Ltd	138	KR
Wuhan China Star Optoelectronics Semiconductor Display Technology Co Ltd	126	CN
Lg Electronics Inc	89	KR
Samsung Electronics Co Ltd	85	KR
Sharp Kabushiki Kaisha	65	JP
Japan Display Inc	56	JP
Cynora Gmbh	**54**	**DE**
Beijing Apollo Ding Rong Solar Technology Co Ltd	42	CN

Source: JRC analysis based on EPO PATSTAT

At EU level, six of the entities are based in Germany, three are in France and there is only one Italian company in the top 10 entities with high-value inventions in PV (Table 6).

Table 6. EU top 10 entities with high-value inventions in PV for the period 2017-2019.

Entities	Number of high-value inventions	Country
Cynora Gmbh	54	DE
Merck Patent Gmbh	35	DE
Hanwha Q Cells Gmbh	22	DE
Novaled Gmbh	21	DE
Azur Space Solar Power Gmbh	19	DE
Total Sa	14	FR
Eni Spa	11	IT
Heliatek Gmbh	9	DE
Electricite De France	8	FR
Isorg	8	FR

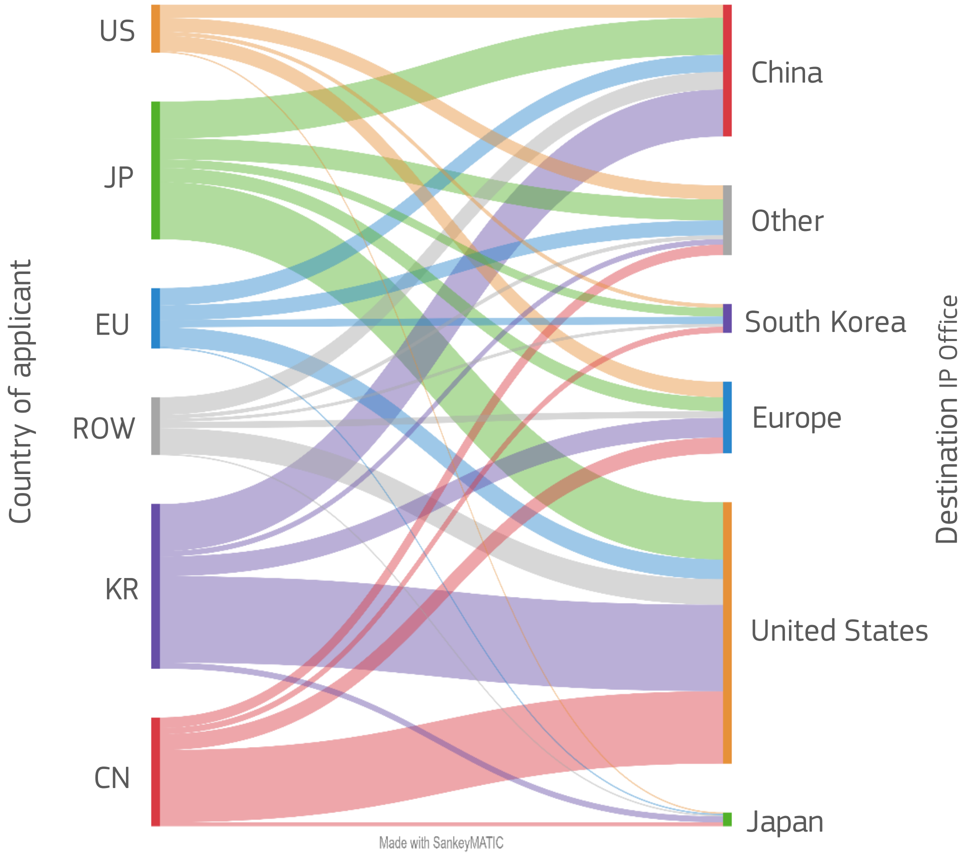
Source: JRC analysis based on EPO PATSTAT

Figure 27 presents the countries in which patents for high-value inventions were submitted, and subsequently enjoyed patent protection, from 2017 to 2019. Chinese applicants have mainly chosen to patent their inventions in the US. The number of patent applications in the EU and other countries is very small. The US applicant has split their patent applications evenly between China, Europe and others. The same applies also for the EU, where patent applications are split evenly between China, US and others. Applicants from South Korea are mainly applying in the US and to a lesser extent in China. In conclusion, the US is receiving the largest number of high-value invention applications. The EU is 2nd to last as far as the reception of patent applications is concerned.

A more detailed evaluation of the high-value patenting activity for the single CPC codes for CIS, dye-sensitised, II-VI group, III-V group, micro c-Si, mono c-Si, poly c-Si, a-Si and organic PV cells from 2009 until 2019 reveals a decreasing trend that for all PV technologies, except for organic PV cells patents. In this case, the high-value patenting activity increased between 2009 and 2017 and started decreasing thereafter. Japan is leading in the field of dye-sensitised, mono c-Si and a-Si PV cell patents. The US is the country with the highest number of patents on II-VI group and III-V group PV cells and South Korea patented inventions mostly relating to organic PV cells, with China equalling South Korea's number of high-value patents in 2018. The EU has significantly increased the number of high-value patents related to III-V group PV cells and surpassed the US to reach the leading position in this domain in 2019.

The EU's competitiveness as far as patenting in PV is concerned, is low according to the CIndECS scoreboard for 2021 (Kuokkanen *et al.*, 2022).

Figure 27. International protection of high-value inventions for the period 2017-2019.

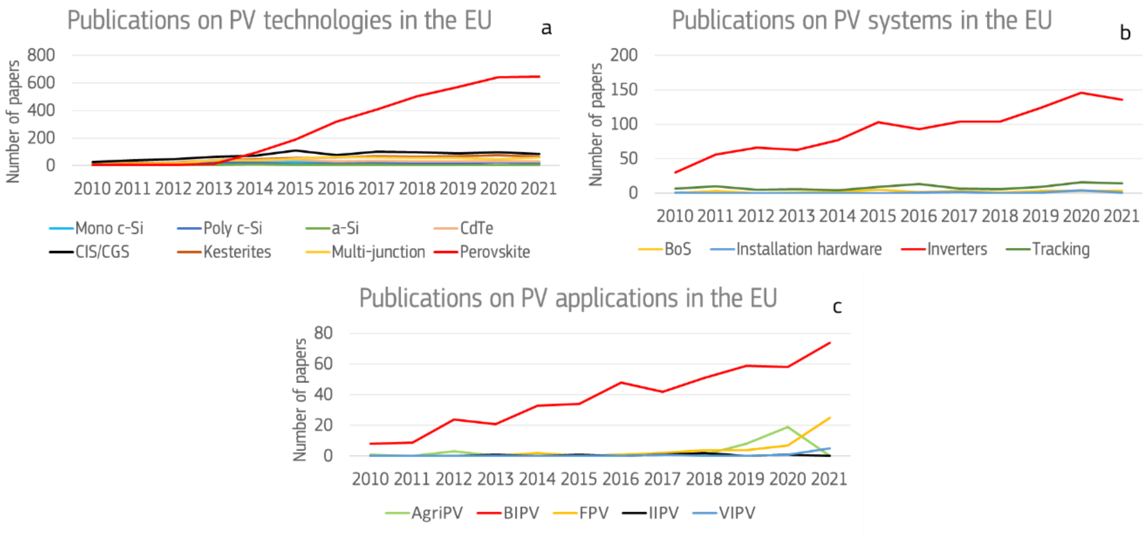


Source: JRC analysis based on EPO PATSTAT

2.7 Bibliometric trends/Level of scientific publications

In the EU, the number of publications on PV technologies has increased steadily from 2010 to 2021 for all technologies apart from perovskites. For this later particular PV technology, there has been a rapid increase in the number of papers published from 2013 onwards (Figure 28), due to the promising outlooks of this technology. It is because of this intense research activity that the perovskites technology has reached high efficiencies in recent years. The analysis of PV technologies publications at global level depicts the same trends as at EU level.

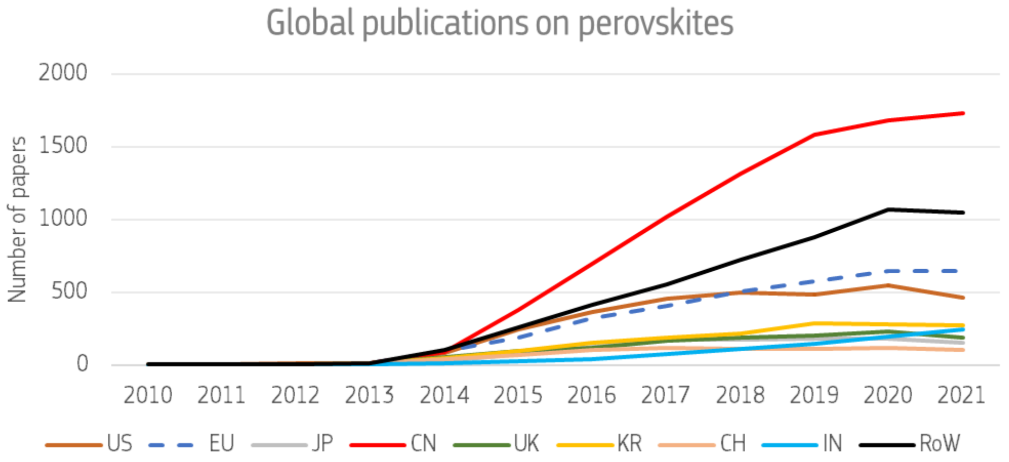
Figure 28. EU publications on (a) PV technologies, (b) systems and (c) applications for the period 2010-2021.



Source: JRC analysis

The number of publications on mono c-Si, poly c-Si and kesterite technologies has been comparable for the EU and China from 2010 until 2021. However, the number of publications on these technologies has remained very limited compared to the rest of the technologies in the above-mentioned period. On a-Si, CIS/CGS and multi-junction technologies, the EU has had more publications than other countries, whereas, for the CdTe technology, the leading country in publications is the US for the period 2010-2021 (also the dominating country in the CdTe production and market). For the perovskite technology, which is the highest-trending topic, China has the highest number of papers from 2010 until 2021 (Figure 29).

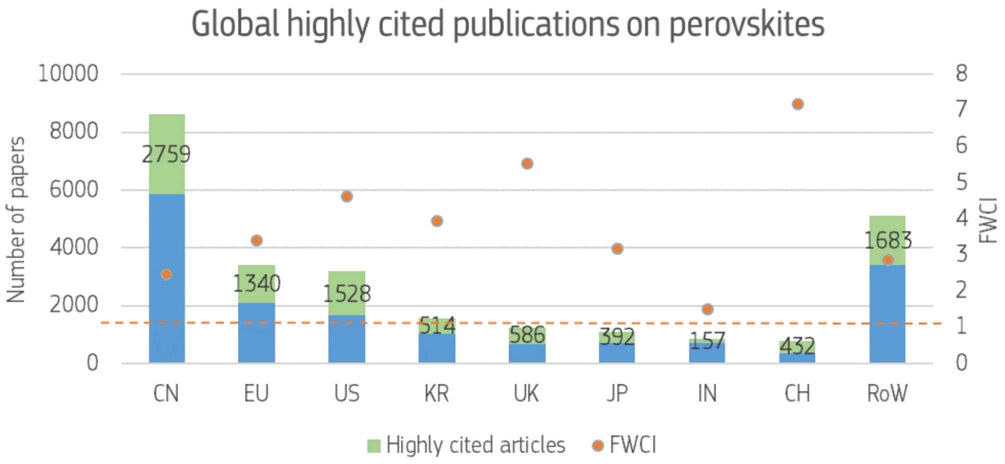
Figure 29. Global publications on perovskites for the period 2010-2021.



Source: JRC analysis

EU has the highest number of publications on PV compared to the rest of the world. This is also true for each PV technology with the exception of CdTe and perovskites. For CdTe, the country with the highest number of papers is the US, followed by China, whereas for perovskites most papers are from China and the EU follows. Publications on kesterites were similar in number for the EU and China until 2020 but in 2021 China seems to have surpassed the EU.

Figure 30. Global highly cited publications on perovskites and EU position for the period 2010-2021.



Source: JRC analysis

However, the total number of publications does not necessarily depict the quality of the work. As depicted in Figure 30, the EU has less than half of China's publications on perovskites and of these, the EU's highly cited publications are slightly more than China's highly cited publications (39 % against 32 %). In terms of Field Weighted Citation Impact (FWCI), China's FWCI is significantly lower (2.5) in comparison to the EU's (3.4), meaning a less frequent citation despite the large number of papers as a total. Almost half of the total number of publications on perovskites in the US are highly cited publications and the country's FWCI is 4.6, denoting the high quality and frequent citation of the relevant papers.

At EU level, Germany is the country with the highest number of publications and citations on all PV technologies. The other countries in the EU's top 5 are France, Italy, Spain and Sweden. In terms of collaboration networks for the publication of papers, China has strong bonds with the US while the EU is mainly collaborating with UK, Switzerland and countries other than Japan, India, US and China. At EU level, the countries with the highest number of publications (Germany, Italy, France and Spain) collaborate mainly between themselves as well as with the Netherlands and Belgium.

In the field of PV systems, the publications in the EU as depicted in Figure 28b evidence a predominance of literature on the topic of inverters. The same is true at global level as well. Globally, from 2010 until 2021, 8 034 papers on inverters were published. Papers dealing with PV tracking systems were only 454. For BoS and hardware installation, there were 116 and 59 papers respectively over the same period. Germany, Spain, Denmark and Italy account for slightly more than half of the EU's publications on inverters. Germany ranks 1st in the EU, with 17 % of the EU's papers. Spain ranks 2nd with 14 % and Denmark and Italy follow with 13 % and 11 % respectively.

In 2020, 14 % of the papers on inverters globally were published by institutions based in the EU. China also has a high number of publications in this field. India, having a tradition in power systems research, is the 3rd country in the ranking.

China has the greatest number of publications on inverters, followed by the EU and the US. Only 15 % of China's publications are highly cited, whereas EU's and US's portion of highly cited publications is 22 % and 27 % respectively. China's FWCI is 1.4 against 1.7 for the EU and 2.3 for the US. It should be noted that EU's excellence in the inverters segment of the PV value chain is not necessarily reflected in the number of publications on inverters, as these publications are usually produced by research centres rather than private companies that are also very active in this field.

At EU level, even though Germany has the highest number of publications on inverters, Denmark is the country with the highest portion of highly cited papers (7 % of the total), followed by Germany (5 % of the total) and Spain (4 % of the total). A strong collaboration between the EU and the US has been identified for the BoS-related publications. For publications on inverters, China, the EU and the US, the countries with the highest number of publications, seem to co-publish with countries labelled under 'RoW' rather than among themselves.

At EU level, the strongest collaborations clusters on inverter publications are Germany-UK-Austria, France-Italy-Sweden and Spain-Denmark.

BIPV is the PV application that attracted the highest number of publications to date, as illustrated in Figure 28c. The interest in FPV has increased over the past 4 years and so has the number of publications. AgriPV-related publications spiked in 2020 and VIPV started coming to the fore.

The EU, from 2010 until 2021, has published the highest number of papers on BIPV making up for 23 % of the total number of papers on the topic globally. China follows with 15 %. Half of the EU's publications on BIPV come from Italy (20 % of the total number), Spain (19 % of the total number) and Germany (11 % of the total number).

Even though the EU has the highest number of papers on BIPV, the highly-cited ones represent only 16 % of the total. By comparison, China's highly-cited papers on BIPV represent 22 % of the total. Both, however, have similar FWCIs (EU 1.5 and China 1.6). 27 % of UK's publications on BIPV are highly cited papers and UK's FWCI is 2.2.

At EU level, the country with the highest number of publications on BIPV, Italy, has also an impressive percentage of highly cited publications on BIPV equal to 30 %. The respective percentage for Spain and Germany is significantly lower at 9 % for each. In this field, the main collaborations identified for publications are between China and the UK and between the US and South Korea. At EU level, Spain and UK are co-publishing several papers on BIPV, just like Italy and Switzerland. In the field of VIPV, for the first time, a clear strong collaboration between the EU and China and Japan has been identified.

2.8 Impact and Trends of EU-supported Research and Innovation

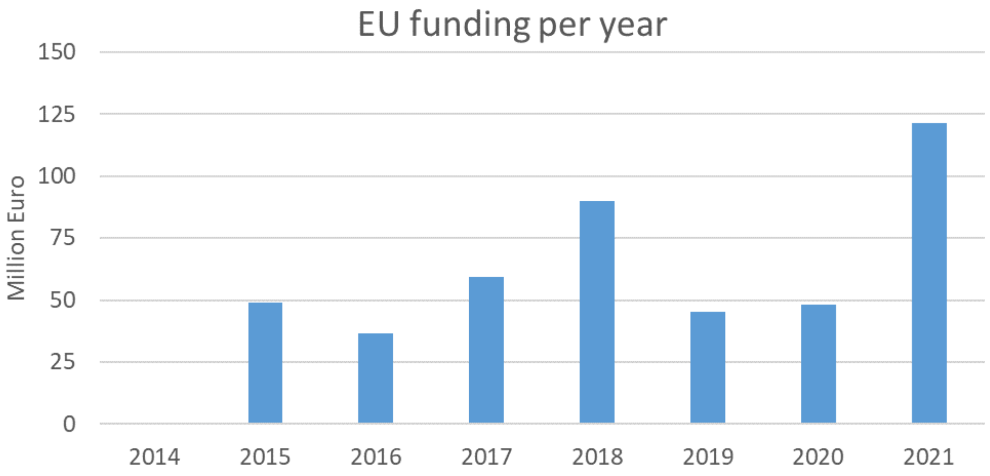
The following data was collected from different EU programmes such as the Strategic Energy Technology Plan (SET plan), Horizon 2020 (EC, 2022a) and SOLAR-ERA.NET network (SOLAR-ERA.NET, 2022). Other research and innovation programmes were also identified (European Metrology Programme for Innovation and Research (EMPIR), European Cooperation in Science and Technology (COST), EIT Innoenergy, EIB InnovFin, NER-300 and IEA Photovoltaic Power Systems Programme). For this report, the Innovation Fund projects were also taken into consideration. In the future reports, projects funded by Horizon Europe will be included. The initial results of this analysis were presented in (EC, 2021) and have now been updated and presented in this report.

From 2014, a total of approximately EUR 455 million (Table 7) has been invested in one hundred and forty PV projects. Of this amount, EUR 221 million were granted to projects that are now concluded and the rest EUR 234 million concern ongoing projects. As far as the one hundred and fifteen concluded projects are concerned, the EUR 221 million were spent mostly on innovation (42 %) and research and innovation (34 %) actions. Actions for SMEs were granted 8 % of the total and fellowships awarded by the Marie Skłodowska-Curie programme were granted 6 % of the overall investment. Coordination actions and grants to researchers provided by the European Research Council (ERC) attracted 5 % each of the overall investment.

For the twenty-five ongoing projects, the remaining amount of investment under the H2020 funding programme accounts for approximately EUR 108 million. To this is added a substantial amount of around EUR 126 million from the Innovation Fund (IF). The IF is directly financed by the EU Emission Trading System (EU ETS) and will provide around EUR 38 billion of support from 2020 to 2030 (at EUR 75 / tCO_2), depending on the carbon price, for the commercial demonstration of innovative low-carbon technologies, aiming to bring to the market industrial solutions to decarbonise Europe and support its transition to climate neutrality (EC, 2022f). Of the twenty-five ongoing projects in total, three are funded under the IF and account for 54 % of the total EU financial contribution for on-going projects, followed by innovation actions which account for another 32 %. Research and innovation actions and grants to researchers provided by the European Research Council (ERC) represent 5 % each of the overall on-going funding. Coordination actions and fellowships awarded by the Marie Skłodowska-Curie programme received 3 % and 1 % of the overall investment respectively.

Small projects receive below EUR 1 million in funding whereas large projects receive funding over EUR 1 million. There have been seventy-nine large projects identified which received approximately EUR 446 million in funding, corresponding to 98 % of the total EU financial contribution and sixty-one small projects which received around EUR 9 million, corresponding to the remaining 2 % of the total EU financial contribution to projects.

Figure 31. EU funding contribution for the period 2014-2021.



Source: JRC analysis based on various data

Funding in 2014 was only EUR 50 000 and is not visible in Figure 31. The year with the highest financial contribution under H2020 was 2018 when EUR 90 million were granted to PV-related projects. However, as seen in Figure 31 the EU financial support in 2021 was EUR 122 million, mainly due to the financing of the TANGO project with approximately EUR 118 million under the IF programme.

The Strategic Energy Technology Plan (SET plan) (Shtjefni *et al.*, 2021) aims to accelerate the development and deployment of low-carbon technologies necessary to achieve the European transition to climate neutrality by 2050. The implementation working group (IWG) on photovoltaics involves representatives of the Member States, other stakeholders and the European Commission. This group issued a detailed implementation plan (TWG, 2017) in 2017 and is now in the process of updating it[9]. The 2017 plan identifies six main areas that are presented in Box 4.

Box 4. Set-Plan TWP PV Implementation Plan priorities.

***Priority 1*:** PV for BIPV and similar applcations.

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

Priority 3: New Technologies & Materials.

Priority 4: Operation and diagnosis of photovoltaic plants.

Priority 5: Manufacturing technologies.

Priority 6: Cross-sectoral research at lower TRL.

Source: (TWG, 2017)

Since the last LCEO report (Taylor and Jaeger-Waldau, 2020), published in 2020, there were no significant changes to the allocation of funding to priorities related to (i) BIPV and similar applications, (ii) silicon cell and module technologies, (iii) plant operation and diagnosis and (iv) cross-sectoral R&D at lower TRL. However, the priority of new technologies and materials has suffered a decrease in budget (from 39 % to 24 %) while the

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[9] The upcoming report of the SET plan TWP PV Implementation Plan will be better aligned with the ETIP PV strategic research innovation agenda (SRIA).

priority regarding manufacturing technologies saw its budget increase by 17 % (from 23 % to 40 %). This is mainly due to the large-scale IF-funded project TANGO that deals with the production of bifacial HJT modules at GW scale. As seen in Table 7, silicon cell and module technologies together with cross-sectoral R&D at lower TRL receive less funding in comparison to the other priorities.

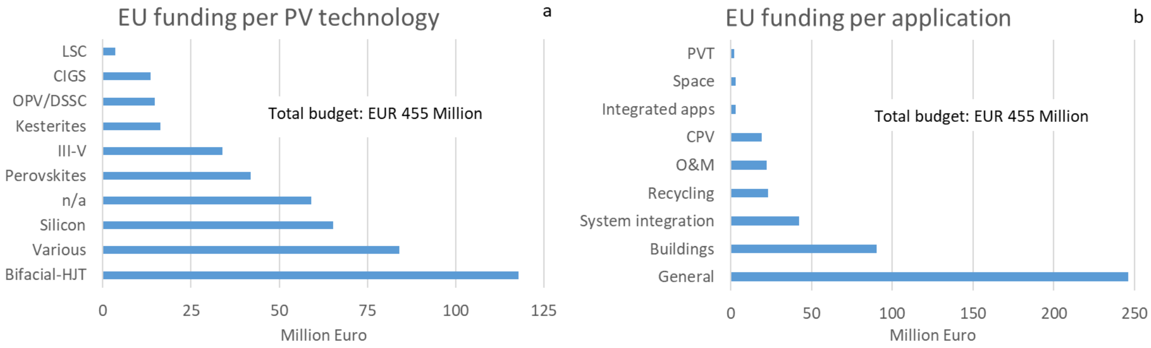
Table 7. EU contribution per SET Plan PV IWG priorities.

SET Plan PV IWG	EU Contribution [EUR Million]	Share of EU Contribution [EUR Million]
BIPV and similar applications	81,442,023	18 %
Silicon cell and module technologies	8,900,195	2 %
New technologies & materials	108,439,819	24 %
Plant operation and diagnosis	60,465,930	14 %
Manufacturing technologies	181,344,743	40 %
Cross-sectoral R&D at lower TRL	9,669,365	2 %
Total	**454,618,076**	**100 %**

Source: JRC analysis based on various data

In terms of PV technology, the bifacial HJT modules of the TANGO project receive 26 % of the total funding through the IF funding scheme. A significant increase in funding was received for perovskites, kesterites and OPV (Figure 32a), thus indicating a shift towards the development/empowerment of new technologies. According to Figure 32b, applications characterised as “general” account for most of the funding (TANGO project included in this category), followed by buildings (EUR 246 million and EUR 91 million respectively). The system integration, with EUR 43 million in total, also received an increased level of EU funding compared to the approximately EUR 10 million received in the period 2014-2019 (Taylor and Jaeger-Waldau, 2020).

Figure 32. EU contribution per (a) PV technology and (b) application.



Source: JRC analysis based on various data

The breakdown to country level finds Germany being the country participating in most H2020 projects (62) from 2014 until 2021, followed by Spain and France with 48 and 47 projects respectively. Germany, Spain and France together, by participating in 157 projects, account for approximately 35 % of the total H2020 funding for the period 2014-2021. The individual funding was EUR 56 million for Germany, EUR 47 million for Spain and EUR 46 million for France.

Italy participated in 42 projects in total between 2014 and 2021. The total funding received by Italy is EUR 153 million, mainly thanks to the TANGO project. If TANGO is excluded, Italy's funding reached EUR 53 million. The non-EU countries benefitting from EU funding are the UK and Switzerland with participations in 40 and 35 projects respectively. Together they received 11 % (EUR 50 million) of the H2020 funding. Other countries completing the top 10 list regarding H2020 funding are Belgium, the Netherlands, Austria and Sweden. The topic of new technologies and materials priority represents the highest number of projects, with Germany participating in 25 projects and receiving EUR 20 million and Spain participating in 15 projects with a total funding of EUR 15 million.

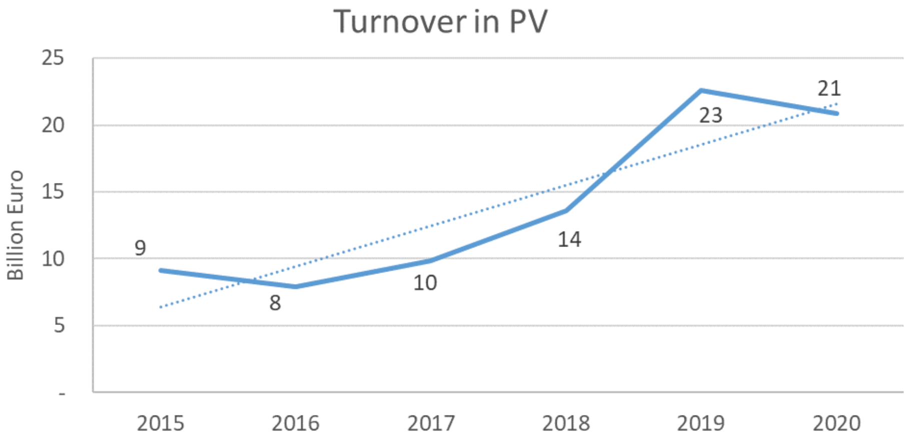
A list of the concluded, as well as the ongoing projects that have received EU financial funding, can be found in Annex 2 and Annex 3 respectively. The list includes R&I projects with a starting date from 2014 until the end of 2021 (beginning of 2022).

3 Value chain Analysis

3.1 Turnover

The PV turnover in 2020 was approximately EUR 21 billion, experiencing a slight decrease compared to the EUR 23 billion observed in 2019. This slight decrease in turnover is the result of a price effect rather than a volume effect, as the installed capacity between 2019 and 2020 actually increased. This indicated that cost reductions are translating into price reductions for consumers. The compound annual growth rate of the turnover was 18 % between 2015 and 2020 (Figure 33). Globally, the PV market reached a turnover of approximately USD 155 billion (EUR 136 billion[10]) in 2020 (Fortune Business Insights, 2022) and thus, the EU's share was 15.4 % of the total.

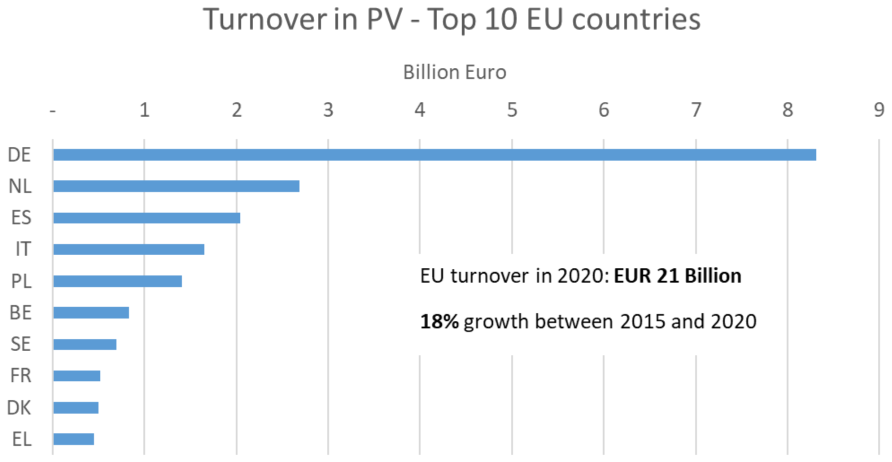
Figure 33. EU turnover in PV for the period 2015-2020.



Source: JRC analysis based on EurObserv'ER data

Germany and Netherlands accounted for almost half of the EU's turnover in 2020, whereas the aggregated turnover of the top 5 countries in Figure 34 (Germany, Netherlands, Spain, Italy and Poland) makes up for three-quarters of the EU's turnover in the same year.

Figure 34. EU turnover in PV for the top 10 countries in 2020.



Source: JRC analysis based on EurObserv'ER data

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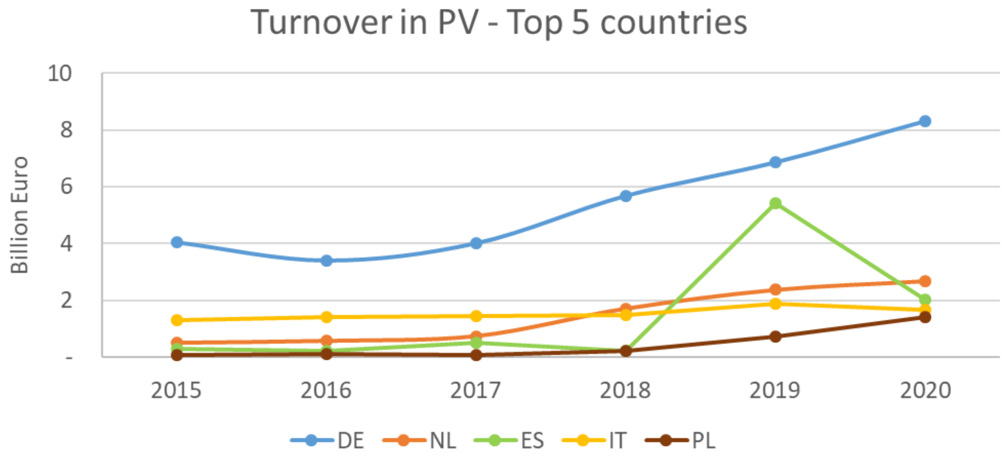
[10] Euro foreign exchange reference rates: 1 USD_{2020} = 0.8755 EUR_{2020}, https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/index.en.html

Germany and Netherlands have steadily increased their turnover from 2015 to 2020 with market compound annual growth rates of 16 % and 41 % respectively, while Italy on the other hand experienced a slower growth (5 % of market compound annual growth rate between 2015 and 2020). The case of Spain is interesting since, after a sudden increase in its turnover from EUR 0.2 billion in 2018 to EUR 5.5 billion in 2019, the market decreased in 2020 to a total of EUR 2.0 billion. Still, the country's market compound annual growth rate remains high with 48 % between 2015 and 2020. While the above-mentioned countries are traditionally in the top 5 list for all the years, Poland has an emerging market with a compound annual growth rate of 78 % between 2015 and 2020 (Figure 35).

Figure 35. EU turnover in PV - Top 5 countries.



Source: JRC analysis based on EurObserv'ER data

Sweden exhibited a remarkable market compound annual growth rate of 70 % between 2015 and 2020, while France's market was marked by an 18 % decrease in turnover for the same period. Greece, Belgium and Denmark complete the top 10 EU countries with compound growths of 35 %, 28 % and 11 % respectively.

EU's position in the upstream and downstream value chain segments (Annex 4) is distinctively different. The EU holds a considerable share in the equipment and inverter manufacturing segments of the PV value chain. However, it lags as far as large-scale production of polysilicon, wafers, cells and modules is concerned. The high labour, energy, materials and equipment costs for the large-scale production segment are the main reason why countries like China, where these costs are lower, dominate these segments of the value chain. China is the leader in the polysilicon, ingot, wafer, cell and module manufacturing segments of the value chain with a share of 63 %, 95 %, 97 % (96 % in 2021), 79 % and 71 % (78 % in 2021) of these global markets respectively (SolarPower Europe, 2021b; IRENA, 2022a). EU was a leader in equipment and inverter manufacturing as it is more knowledge-intensive and EU has a highly skilled workforce and research infrastructure (Bolscher *et al.*, 2017). In 2015, the EU's share in turnover related to equipment manufacturing was 63 % and related to inverter manufacturing it was 20 % of the global turnover. Its share in the other value chain segments was less than 10 % (Bolscher *et al.*, 2017). However, in more recent years, the situation has changed as one of the strongest EU-based inverter manufacturer, SMA (Germany), has gradually seen its market share being reduced (from 8 % in 2018 and 2019 to 7 % in 2020 and 6 % in 2021) while China-based companies increased their share in the segment. The 2nd European inverter manufacturing company in the global top 10 inverter shipments is Power Electronics (Spain) which has also seen its market share reduce from 6 % in 2018 and 2019 to 5 % in 2020 and 2021. Apart from SMA and Power Electronics, other important EU inverter manufacturers at global level are Fronius, Ingeteam and Fimer. In other BoS activities, Soltec is a strong global competitor in the field of trackers. EU companies are also strong competitors in downstream activities (EPC, O&M and recycling) (SolarPower Europe, 2021b).

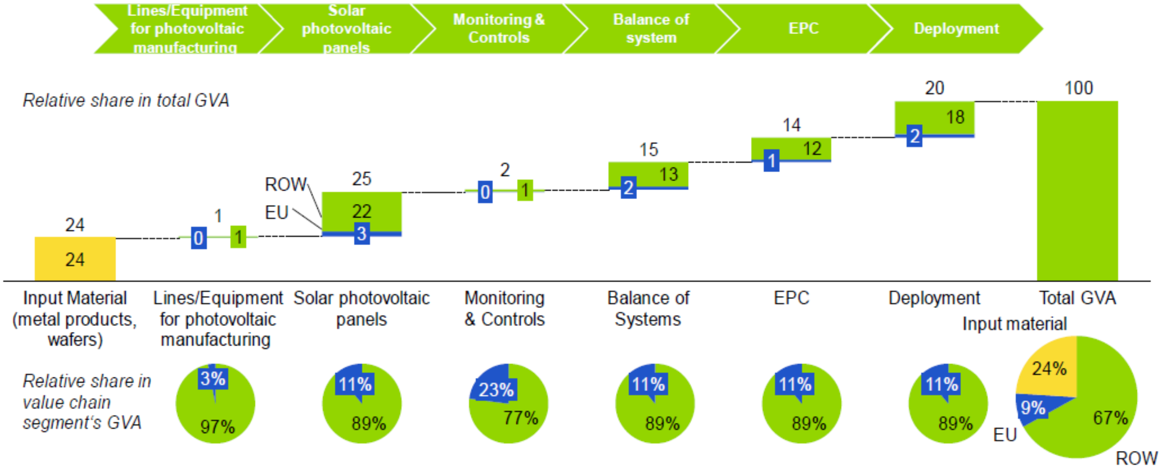
Based on PV turnover, the EU exhibits high competitiveness according to the CIndECS annual report for 2021 (Kuokkanen *et al.*, 2022).

3.2 Gross value added

The gross value added (GVA) is an economic productivity metric that measures the contribution of a corporate subsidiary, company, or municipality to an economy, producer, sector, or region.

Figure 36, as already presented in previous work (EC, 2021) shows the EU share of the global gross value added (GVA) in the different segments of the PV value chain after being disaggregated according to their market size. It must be noted that inaccuracies may be present because there may be positive (equipment for PV manufacturing) and negative (for PV panels) trade balances in the different segments of the value chain. As input materials for the GVA calculation, metal products and wafers are featured in this chart as these are mainly used for the PV cells and modules manufacturing (EC, 2021).

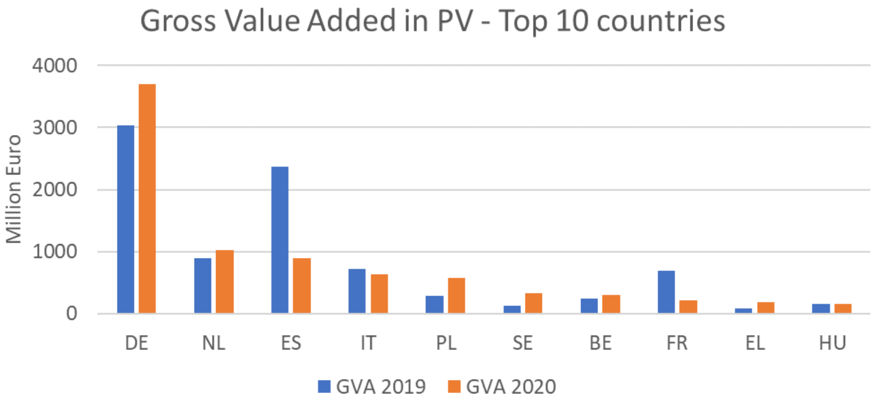
Figure 36. Breakdown of GVA throughout the solar PV value chain.



Source: Guidehouse Insights, 2020 (CPR, 2021)

Similarly to turnover, Spain had a remarkably high gross value added in 2019 that reached EUR 2.4 billion and then decrease to around EUR 900 million in 2020. Italy and France similarly decreased their gross value added in 2020 compared to 2019. Germany is again the leading EU market (Figure 37).

Figure 37. Gross Value Added in PV for the top 10 EU countries in 2019 and 2020.



Source: JRC analysis based on EurObserv'ER data

3.3 Environmental and Socio-economic Sustainability

<table>
<tr><th>*Parameter/Indicator*</th><th>*Input*</th></tr>
<tr><td>***Environmental***</td><td></td></tr>
<tr><td>*LCA standards, PEFCR or best practice, LCI databases*</td><td>

- At international level the IEA PVPS Task 12 group issued methodology guidelines on PV-specific parameters used as inputs in LCA (Frischknecht *et al.*, 2016).
- ‘Product Environmental Footprint category rules’ for PV power systems[11], developed by the European Commission in the framework of the Product Environmental Footprint initiative pilot phase. The results for all the 16 impact categories based on the Environmental Footprint method are available in the PEFCR document (EC, 2019).
- Italy's LCA legislation Promotion of the Green Economy - Legislation fully based on the Environmental Footprint methods. Voluntary "Made Green in Italy" label.
- France's public tenders for utility-scale PV plants - ADEME guidelines.
- Country-specific Product Category Rules (Italy, France, Norway, Finland, Netherlands) based on EN 15804.
- NSF/ANSI 457 Sustainability Leadership Standard for PV Modules and PV Inverters.

</td></tr>
<tr><td>*GHG emissions*</td><td>

PV systems

A recent study from IEA PVPS indicates that, through their lifetime, mono c-Si systems emit 42.5 gCO_2*/kWh, poly c-Si systems emit 42.3* gCO_2*/kWh, CIS systems emit 36.3* gCO_2*/kWh and CdTe systems emit 26.5* gCO_2*/kWh* (Frischknecht and Krebs, 2021)[12].

PV modules

In terms of technologies, thin-film modules have the lowest emissions, followed by poly c-Si and then mono c-Si. There is considerable scope to reduce these values, and projections for 2050 indicate that life cycle emissions for PV can drop to 10 gCO_2eq*/kWh and below* (Pehl *et al.*, 2017).

Carbon footprint values corresponding to the Climate Change impact category, calculated as per the PEFCR (EC, 2019)*:*

<table>
<tr><th>PV technologies</th><th>Life cycle excl. use stage Climate change (gCO_2e_q/kWh)</th><th>Use stage Climate change (gCO_2eq/kWh)</th></tr>
<tr><td>Representative (virtual) product</td><td>59.3</td><td>0.0105</td></tr>
<tr><td>CdTe</td><td>19.9</td><td>0.0107</td></tr>
<tr><td>CIGS</td><td>35.9</td><td>0.0139</td></tr>
<tr><td>Micromorphous silicon</td><td>43.0</td><td>0.0150</td></tr>
<tr><td>Polycrystalline silicon</td><td>48.8</td><td>0.0102</td></tr>
<tr><td>Monocrystalline silicon</td><td>80.4</td><td>0.0099</td></tr>
</table>

The partial adjustment of some technical parameters for PV modelling based on LCI and LCA outdated datasets leads to significant overestimation of the environmental impacts of PV technologies. For this reason a careful and in depth examination and update is crucial to obtain realistic results. The amount of silicon use in the production of c-Si modules, the wafer thickness and the kerf play a significant role. A moderate wafer thickness reduction from 180 µm

</td></tr>
</table>

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[11] https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_PV_electricity_v1.1.pdf

[12] Average residential PV system: 1 kWh AC energy, produced with a 3 kW_p roof-mounted PV system in Europe (included PV panel, cabling, mounting structure, inverter and system installation), 975 kWh/kW_p annual production, linear degradation 0.7% per year, service life: panel 30 years, inverter 15 years. Module efficiencies assumed: mono c-Si: 19.5 %, poly c-Si: 18 %, CIS: 16 % and CdTe: 18 %.

<table>
<tr><td></td><td>*in 2010 to approximately 170 µm in 2021 and a notable silicon usage reduction from 7 g/Wp in 2010 to 2.5 g/Wp in 2021, contributed to a lower carbon footprint* (Fraunhofer ISE, 2022a). *New approaches indicate that the carbon footprint of crystalline technology may be notably lower and between 13 and 30 gCO$_2$eq/kWh* (Müller *et al.*, 2021).</td></tr>
<tr><td>*Energy balance*</td><td>*The Energy Payback Time of PV systems is dependent on the geographical location: PV systems in Northern Europe need around 1.2 years to balance the input energy, while PV systems in the South equal their energy input after 1 year and less, depending on the technology installed and the grid efficiency (Fraunhofer ISE, 2022b).*
According to the IEA PVPS Task 12, the Non Renewable Energy Payback Time (NREPBT)[13] for mono c-Si, poly c-Si, CIS and CdTe technology PV system is 1.2, 1.2, 1.3 and 0.9 years respectively (Frischknecht and Krebs, 2021).
For low irradiation locations (1 000 kWh/m^2/year), mono c-Si module installations have an EPBT of 1.3 years and poly c-Si module installations of 1.5 years. For high irradiation locations, the EPBT is 0.6 years (Fthenakis and Leccisi, 2021).</td></tr>
<tr><td>*Ecosystem and biodiversity impact*</td><td>*The European Commission has published a report on the potential impacts of PV applications on the ecosystem and the biodiversity (Lammerant, Laureysens and Driesen, 2020).*
The EU biodiversity strategy specifically mentions solar-panel farms providing biodiversity-friendly soil cover as a win-win solution for energy and biodiversity. Any intervention on water bodies must respect the conditions set out in the Water Framework Directive and the Marine Strategy Framework Directive (EC, 2020).</td></tr>
<tr><td>*Water use*</td><td>*PV modules*
The available reported water consumption of PV module technologies in studies is considered outdated due to the rapid technological advancements of PV. Therefore, the reported values of water consumption must be used with caution. Results for the impact category water use are available also in the PEFCR for PV panels (EC, 2019)*:*
<table>
<tr><th>PV technologies</th><th>Life cycle excl. use stage
Water use
(l worlde$_q$/kWh)</th><th>Use stage
Water use
(l worlde$_q$/kWh)</th></tr>
<tr><td>Representative (virtual) product</td><td>22.8</td><td>0.158</td></tr>
<tr><td>CdTe</td><td>4.30</td><td>0.161</td></tr>
<tr><td>CIGS</td><td>6.27</td><td>0.209</td></tr>
<tr><td>Micromorphous silicon</td><td>11.2</td><td>0.226</td></tr>
<tr><td>Polycrystalline silicon</td><td>19.6</td><td>0.154</td></tr>
<tr><td>Monocrystalline silicon</td><td>31.7</td><td>0.150</td></tr>
</table>
A 2017 IEA PVPS report, based on LCIs from 2010 and 2013, reports that the share of consumptive water use during the life cycle of mono c-Si and CdTe rooftop systems, defined as the amount of water consumed divided by the volume of water withdrawn, is 20 % and 34 % respectively (Stolz *et al.*, 2017).
According to the most recent IEA PVPS report on water use of PV module systems over their lifetime, systems with mono c-Si modules consume 7.49 l/kWh, systems with poly c-Si modules consume 6.71 l/kWh while systems with CIS modules consume 6.27 l/kWh and systems with CdTe modules 3.08 l/kWh (Frischknecht and Krebs, 2021)[14].
PV system operation
Water consumption for the operation of PV systems has been reported to be 0.08 l/kWh for utility-scale PV installations and 3.3 l/kWh for Concentrated Solar Power (CSP) installation in the US (Solar Energy Industries Association, 2022).</td></tr>
</table>

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[13] Non renewable energy payback time (NREPBT) is defined as the period required for a renewable energy system to generate the same amount of energy (in terms of non renewable primary energy equivalent) that was used to produce the system itself.

[14] Average residential system as described above in footnote [12].

	PV systems withdraw and consume between 2 % and 15 % of the water consumed by coal or nuclear plants for 1 MWh of generated electricity (Lohrmann *et al.*, 2019).
Air quality	*In the case of thin film PV module technologies, there are some hazards that need to be taken into consideration. These hazards include the toxicity and explosiveness of specific gases. Health issues for workers (and public health in extreme cases) from accidents or elusive air emissions may arise if proper measures are not taken. However, the proper manufacturing procedures together with the use of less toxic materials ensure the avoidance of accidental releases of toxic gases and vapors that may potentially put in danger the health of humans and the air quality* (Tchognia Nkuissi *et al.*, 2019).
Land use	*1.9 hectares/MW* (IRENA, 2020c). *1-2 hectares/*MW_p (IFC, 2015).
Soil health	*Soil health may be influenced in a negative way by manual and automated cleaning that uses mostly water to remove debris that accumulates on the surface of the PV panels* (Tawalbeh *et al.*, 2021).
Hazardous materials	*There are materials used in the manufacturing procedure covered by dispositions under the REACH regulation (lead in c-Si and perovskites, cadmium in CdTe, etc.)* (Tchognia Nkuissi *et al.*, 2019; Gebhardt *et al.*, 2022). *Also, chemicals and solvents are used throughout the manufacturing processes of different PV technologies* (Tawalbeh *et al.*, 2021). *The back-sheet layer of the PV panel may contain halogenated plastic layer that can pose potential waste management problems* (Latunussa *et al.*, 2016; Ardente, Latunussa and Blengini, 2019).
Economic	
LCC standards or best practices	
Cost of energy	*See 2.3 Technology Cost – Present and Potential Future Trends*
Critical raw materials	*Some of the raw materials used to manufacture solar cells are critical, such as borates, silicon metal, germanium, indium, and gallium* (Bobba *et al.*, 2020). *These materials are characterized as CRMs for the EU* (Dodd *et al.*, 2020). *Copper, cadmium, selenium, silver and tellurium are raw materials used in the PV industry with a low supply risk (Bobba et al., 2020).* *Other studies suggest that also boron, molybdenum, phosphorus, tin and zinc are raw materials that should be closely monitored (EC, 2022c).*
Resource efficiency and recycling	*In the EU, the treatment of end-of-life PV modules must comply with the WEEE Directive since 2012. Several organisations have developed recycling processes. Several sustainability aspects are being addressed in the framework Ecodesign* (EC, 2022b). *The assessment of the resource efficiency and related environmental benefits and burdens of a pilot PV waste recycling processes showed the advantages of an innovative PV recycling process, compared to current recycling processes. The benefits are even more evident with regard to the recovery of silver and silicon (critical raw materials). Overall, recycling processes with high efficiency can recycle up to 83 % of the waste panel* (Ardente, Latunussa and Blengini, 2019). *An ongoing EU-funded project called PHOTORAMA*[15] *is currently working to improve the recycling of Photovoltaic (PV) panels and recovery of Raw Materials (RM). This project is implemented by a consortium of 13 organisations in the period 2021-2024.*
Industry viability and expansion potential	*For market data see section 4.1*
Trade impacts	*For trade data see section 4.2*
Market demand	*For market data see section 4.1*
Technology lock-in/innovation lock-out	

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[15] https://www.photorama-project.eu/

Tech-specific permitting requirements	
Sustainability certification schemes	
Social	
S-LCA standard or best practice	
Health	
Public acceptance	*Photovoltaics are generally accepted by the public as public awareness has increased the in last years (oppositions are expressed mostly for aesthetical reasons). However, there are still oppositions regarding mainly emerging applications like agri-photovoltaics (AgriPV) and floating photovoltaics (FPV) (competition to agricultural use of land and fishing, biodiversity and environmental impact concerns).*
Education opportunities and needs	
Employment and conditions	*For employment data see section 3.5*
Contribution to GDP	
Rural development impact	
Industrial transition impact	
Affordable energy access (SDG7)	
Safety and (cyber)security	
Energy security	
Food security	
Responsible material sourcing	

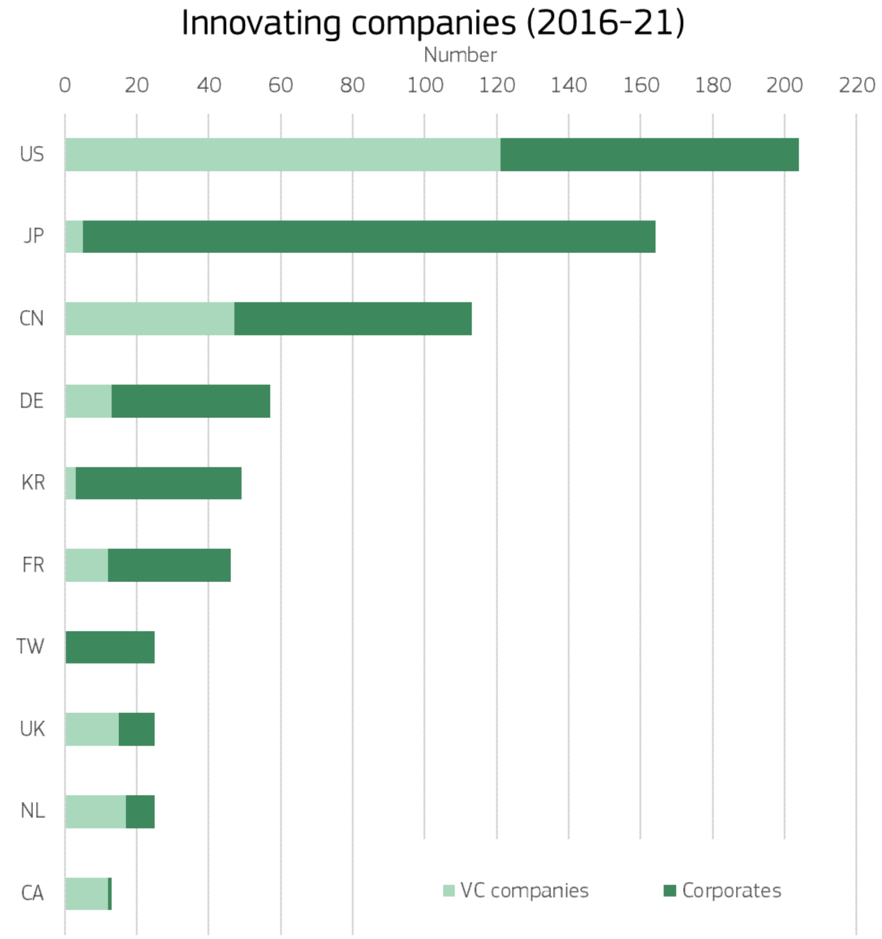
3.4 Role of EU Companies

Background information on the terminology used in this section: Private Equity refers to capital investments (ownership or interest) made into companies that are not publicly traded. Venture capital (VC) is a form of private equity and a type of financing that investors provide to start-up companies and small businesses that have long-term growth potential. The early and later stages indicators in this analysis aggregate different types of equity investments in a selection of companies and along the different stages of their growth path. For each technology, companies are selected based on their activity description (keyword selection and expert review).

Five countries host almost 70 % of identified innovators. The US (1st) and China (3rd) have a very strong base of venture capital companies while most of the innovators in Japan (2nd), Germany (4th) and South Korea (5th) are corporate innovators (Figure 38). Within the EU (hosting 23 % of identified companies), the Netherlands and Sweden report a stronger share of venture capital companies.

Global VC investments increased sharply in 2021, surpassing the highest levels seen in the early 2010s to amount to EUR 1.35 billion (Figure 39). This represents a threefold increase as compared to 2016 and puts an end to a period of lower investments started in 2014 (due to lower levels of investments in the US). The main drivers of this trend are later stages investments realised outside of the EU: the number of deals doubled in 2021 and average deal sizes grew back to early 2010s highs.

Figure 38. Global number of innovating companies for the period 2016-2021.

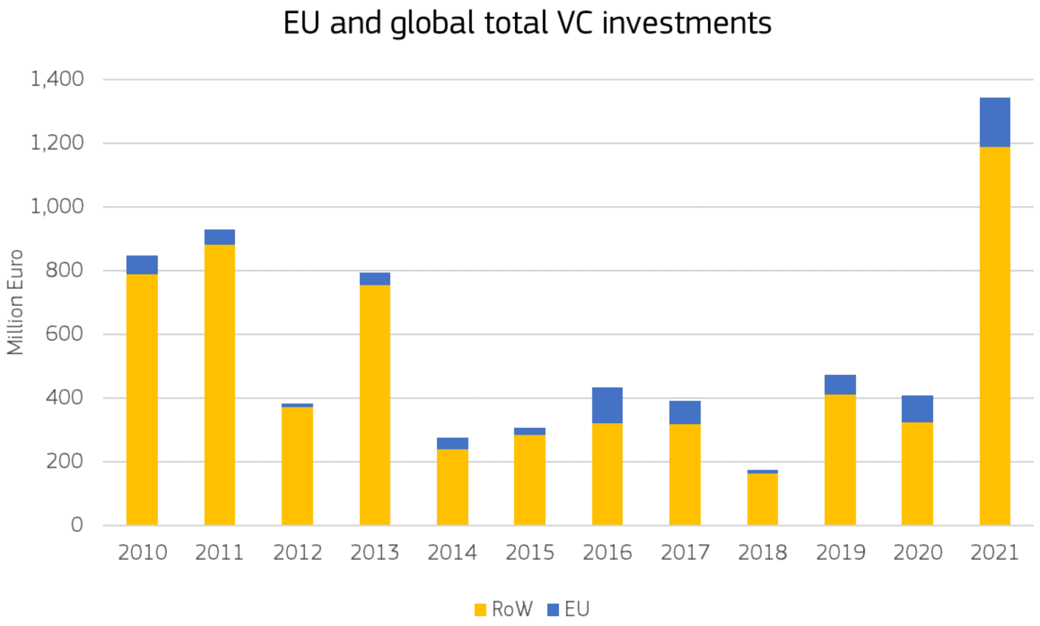


Source: JRC analysis based on various data

For early and later stages investments, only pre-venture companies (that have received Angel or Seed funding, or are less than 2 years old and have not received funding) and venture capital companies (companies that have, at some point, been part of the portfolio of a venture capital investment firm) are included.

In the period between 2010 and 2015, both at EU and global level, the breakdown of capital invested was 85 % for later stages investments and 15 % for early stages investments. The situation slightly changed in the period from 2016 until 2021 in the EU and globally. The share of later stages investments decreased by 5 %, resulting in being 80 % of the total investments, leaving 20 % to the early stages investments, thus suggesting that investment in scaling-up phases is still preferred, but to a lesser extent than before, to start-up phase investments.

Figure 39. EU and global total Venture Capital investments for the period 2010-2021.



Source: JRC analysis based on Pitchbook

The total VC investments for two distinct periods, 2010-2025 and 2016-2021 for the top 10 countries are presented in Figure 40. Overall VC investments are difficult to compare between different countries due to the different tax regimes and economic conditions. Taking this into consideration the following ranking should be taken only as a general indication and comparison between countries should be avoided. However, a comparison between the different periods analysed for the same country is a useful indication of how VC investments have evolved.

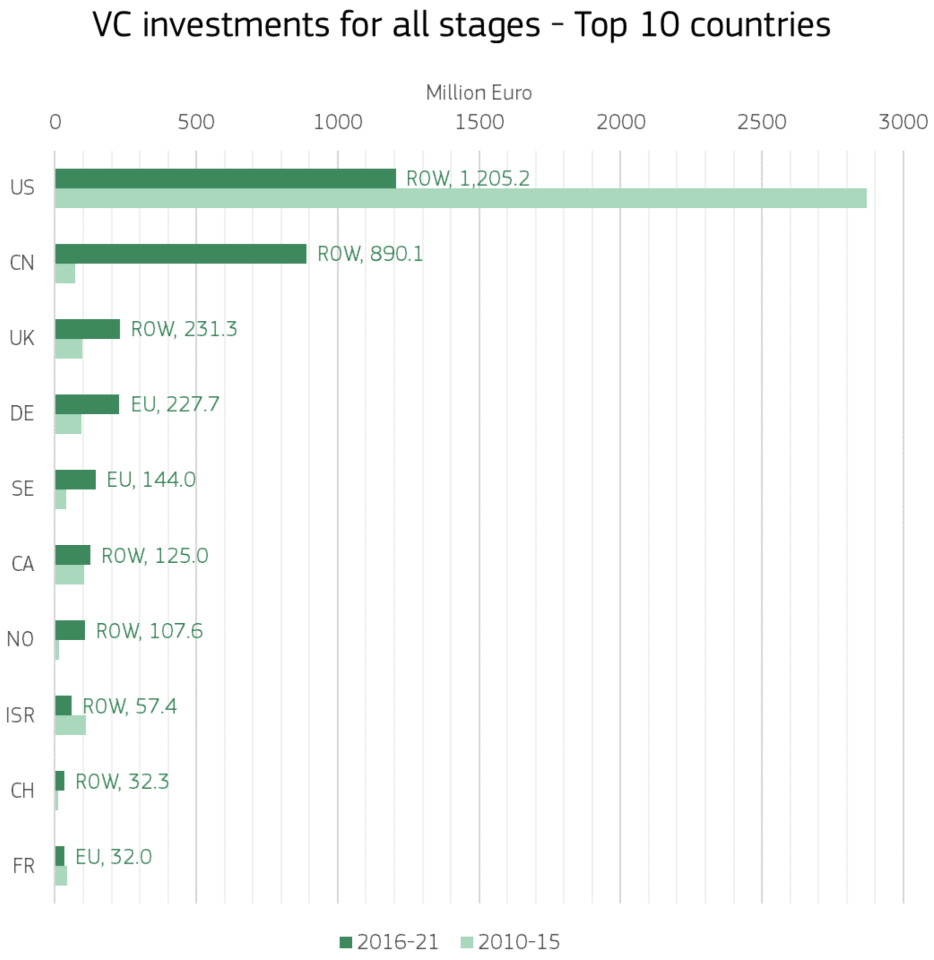
Three EU countries appear in the indicative top 10 countries, with Germany ranking in 4th position, Sweden in 5th and France in 10th position. VC investments have decreased significantly in the US and Israel (almost by half) in the period 2016-2020 in comparison to 2010-2015. At EU level, the overall amount of VC investments decreased only in France, from EUR 43.5 million to EUR 32, million overall VC investments between the two periods. Germany saw an increase in its total VC investments from EUR 94 million in 2010-2015 to EUR 228 million in 2016-2020, whereas investments in Sweden grew from EUR 40 million to EUR 144 million for the same periods. A remarkable increase in VC investments is observed in China. From EUR 72 million in 2010-2015, the Asian country increased its total investments to EUR 890 million.

When breaking down the total investments, early stages investments have doubled in 2020 (+117 %), almost tripled in 2021 (+193 %) and amounted to EUR 688 million over the 2016-2021 period (+25 % compared to 2010-2015). The EU strengthened its position and accounts for 16 % of early stages investments over the current period (compared to 6 % over 2010-2015). However, investments in the EU remain only supported by fewer deals and lower levels of grant funding than in the rest of the world. The European country which attracted the greatest amounts of investments over the current period is Germany (6.5 %), similar to Canada and the United Kingdom but far behind China (30 %) and the United States (29 %).

Despite investment values reaching an all-time high in 2021, later stages investments decreased over the 2016-21 period (-15 %) as compared to the previous period), amounting to EUR 2.5 billion. The EU accounts for 16 % of those investments and strengthens its position with higher investment levels since 2016 (EUR 396.5 million, +115 % as compared to 2010-15).

While predominant, investments outside of the EU are still insufficient to match the levels seen over the previous period (-23 % as compared to 2010-15). The United States remains the first destination of later stages investments over the current period (39.5 %) but is challenged by China (26.9 %), which attracted more investments in 2020 and 2021. The United Kingdom (7.4 %) ranks next together with Germany (7.2 %) and Sweden (5 %), which attracted most of the EU later stages investments.

Figure 40. Top 10 countries total Venture Capital investments for all stages for the periods 2010-2015 and 2016-2021.



Source: JRC analysis based on Pitchbook

According to the 2021 annual report of CIndECS, the EU's competitiveness in the early stage investments for PV is high whereas in the later stage investments is medium. With regard to the innovating companies in the field of PV, the EU's competitiveness is low (Kuokkanen *et al.*, 2022).

3.5 Employment in value chain incl. R&I employment

Employment in the PV sector is another parameter reflecting its market growth. The available data run until 2020/2021. An older report reveals the dramatic decrease that jobs in the PV sector suffered between 2008 and 2016. According to the available data, between 2008 and 2016 there has been a 15 % compound decrease in total PV jobs in the EU. This decrease reflected a decrease of 8 % for rooftop and 23 % for ground-mounted applications. This is in part due to base effects, owing to the sudden increase in the number of PV jobs in 2008 in Spain for the installation of around 3 000 MW of ground-mounted systems that were not maintained afterwards (EY, 2017). According to EurObserv'ER, the total number of (direct and indirect) PV jobs in the EU was approximately 166 000 in 2020 (EurObserv'ER, 2022a). For the same year, IRENA estimates the total number of PV jobs in the EU to be 195 000 (4.9 % of the global 3 975 000 PV jobs) while SolarPower Europe (SPE) reports a total of 357 000 of PV related jobs from which 150 000 (42 %) are direct and 207 000 (58 %)

indirect jobs[16] (SolarPower Europe, 2021a). For 2021, IRENA estimates that the EU slightly increased its share in the PV job market (from 4.9 % to 5.5 %) and from the 4 291 000 PV jobs globally, 235 000 were located in the EU (IRENA, 2022b). For the same year, according to SPE the EU reached a total of 466 000 PV jobs (a 30.5 % increase) of which 205 000 (44 %) were direct and 261 000 (56 %) indirect (SolarPower Europe, 2022a).

Employment data differ significantly based on the data source as can be seen in Box 5.

Box 5. Differences in EU PV employment data.

For 2020:	***For 2021:***
SolarPower Europe: 357 000 PV jobs	*SolarPower Europe:* 466 000 PV jobs
EurObserv'ER: 166 000 PV jobs	*EurObserv'ER:* Not available yet
IRENA: 195 000 PV jobs	*IRENA:* 235 000 PV jobs

Source: (SolarPower Europe, 2021a, 2022a; EurObserv'ER, 2022a; IRENA, 2022b)

In the following paragraphs, the analysis of the employment of the different value chain segments as well as the relatively short-term projections regarding the EU PV jobs market are based on data from SPE. EurObserv'ER data was used for the EU trend and Top 10 EU countries while data from IRENA was used for comparison with major economies.

According to (Dodd *et al.*, 2020), 25 % of EU employment supported by the PV industry was for the upstream (i.e production) and 75 % for the downstream (i.e. installation) PV sector in 2016. A 2022 report from Fraunhofer ISE (Fraunhofer ISE, 2022a) suggests that 7 500 full-time equivalents (FTEs) are needed for the production of a 10 GW production from silicon ingot via wafer and cell to module, whereas the installation of 10 GW of PV requires 46 500 FTEs, suggesting a standard ratio of 14 % for upstream versus 86 % for downstream activities (Fraunhofer ISE, 2022a).

SPE produces solar PV jobs reports regularly (SolarPower Europe, 2022a). According to Figure 41a in 2020, most PV jobs in the EU were related to deployment activities (79 %). Of those, half were identified as direct and half as indirect jobs. O&M activities, which represent 9 % of total PV jobs, have the same ratio of direct versus indirect jobs. Jobs related to manufacturing activities account for 9 % and are mostly direct jobs. Manufacturing-related PV jobs in 2021 have increased by 3 % from 2020 (SolarPower Europe, 2021a, 2022a). The manufacturing activities are further divided into the manufacturing of inverters with an increased 70 % PV jobs share in 2021 in comparison to the 46 % PV jobs share in 2020 (SolarPower Europe, 2021a, 2022a). On the contrary, according to the same studies, PV jobs in the polysilicon production and module production activities appear to have decreased between 2020 and 2021 from 29 % to 10 % for the former and from 22.5 % to 18 % for the latter (SolarPower Europe, 2021a, 2022a). PV jobs in the inverter, polysilicon and modules sectors account for 98 % of the total manufacturing jobs (Figure 41b). In the polysilicon production sector, half of the jobs are direct and half indirect, whereas, in the rest of the sectors, jobs are mostly direct.

Regarding projections, SPE employs 3 scenarios. These are the low, medium and high scenarios that are based on the non-, partial- and full-accomplishment of the targets of the European Solar Initiative (ESI)[17] respectively (European Solar Initiative, 2022). According to these scenarios, the EU PV jobs may decrease by 8 % (low scenario) or increase between 14 % (medium scenario) and 30 % (high scenario) in 2022. The predictions for 2026 are between 16 % (540 000 jobs for the low scenario) and 126 % (1 054 000 jobs for the high scenario) with a moderate increase of 64 % (764 000 jobs) for the medium scenario (SolarPower Europe, 2022a). In a previous jobs report, SPE forecasted that direct jobs are expected to grow more than indirect PV jobs (10-15 % vs. 5-9 % growth) (SolarPower Europe, 2021a). For the same scenarios, the deployment jobs in the EU may increase in 2060 by approximately 56 % according to the medium scenario while the O&M-related jobs may

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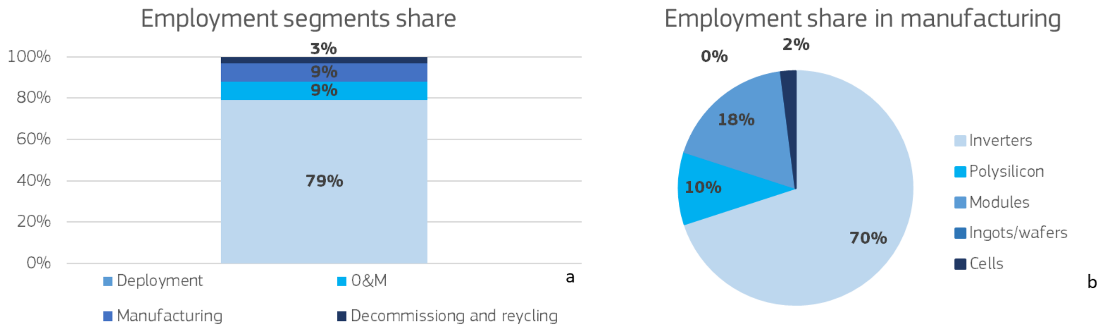
[16] Direct jobs are full-time equivalent jobs (FTEs) are referring to manufacturing, deployment, O&M and decommissioning & recycling. Indirect jobs are a result of business-to-business purchases in the supply chain that are considered intermediate transactions (SolarPower Europe, 2021a).

[17] The European Solar Initiative, an industrial alliance launched by SolarPower Europe and EIT InnoEnergy together with other partners, aims to establish 20 GW of manufacturing capacity in Europe from polysilicon to modules, up from less than 1 GW on the solar cell level today (https://europeansolarinitiative.eu/).

increase by 100 % according to the same scenario. Manufacturing-related jobs are expected to grow by 75 % and decommissioning and recycling jobs by 135 % based on the medium scenario as several PV systems are approaching their end of operating lifetime (SolarPower Europe, 2022a).

Figure 41. (a) Employment in PV value chain segments and (b) employment in manufacturing segment share in 2021.

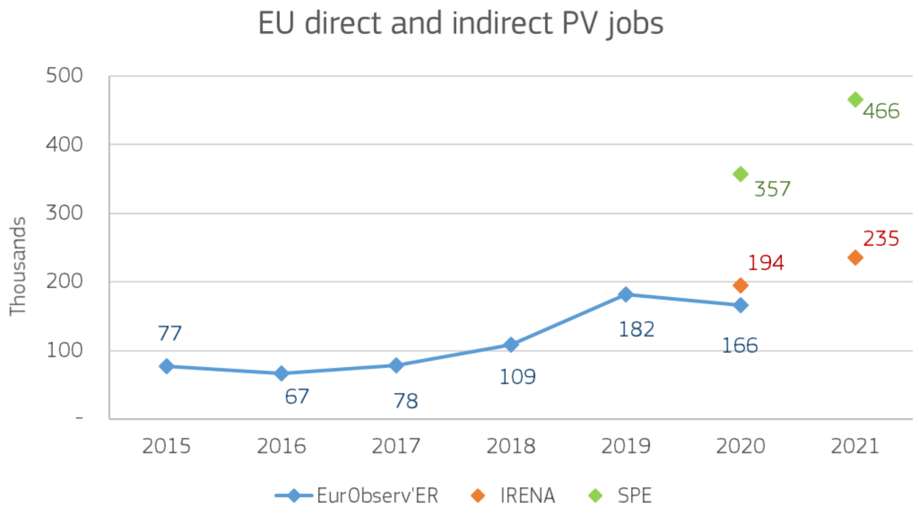


Source: JRC analysis based on (SolarPower Europe, 2022a)

As far as PV jobs with relation to applications are concerned, in 2021, 75 % of the jobs in the EU were for rooftop and 25 % for utility applications. The country with the highest proportion of jobs (72 % in 2020 and 56 % in 2021) for utility applications was Spain. For rooftop applications, the highest proportion of jobs can be found in Poland and Greece (>90 %) (SolarPower Europe, 2021a, 2022a). For 2026, SPE projects that the portion of rooftop-related jobs will decrease to 60 % and that of utility-scale related jobs will increase to 40 % (SolarPower Europe, 2022a).

Figure 42 shows the evolution of direct and indirect PV jobs in the EU according to EurObserv'ER from 2015 until 2020. The IRENA and SPE EU PV jobs, as reported in Box 5 are included in the graph for the completeness of the available data but the analysis performed is based on the EurObserv'ER dataset. The compound growth between 2015 and 2019 was 24 % and between 2015 and 2020 was 17 %.

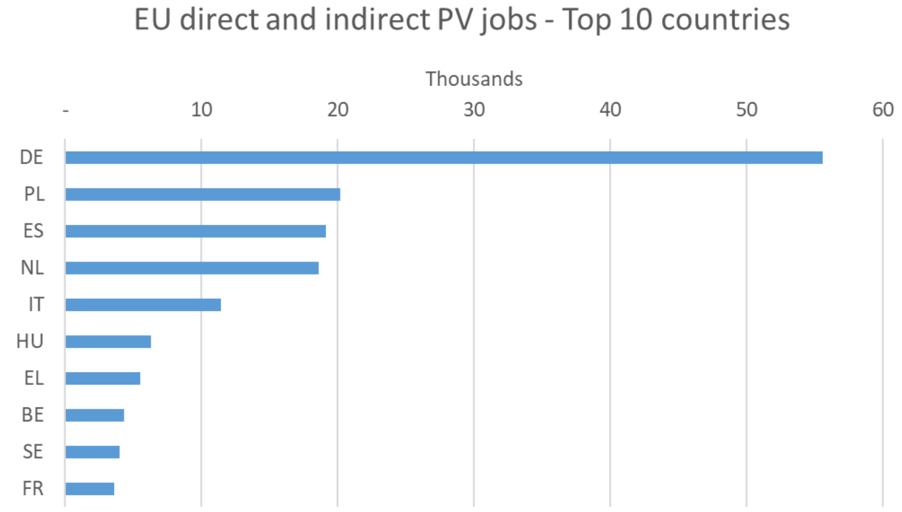
Figure 42. EU direct and indirect PV jobs for the period 2015-2021.



Source: JRC analysis based on (SolarPower Europe, 2021a, 2022a; EurObserv'ER, 2022b; IRENA, 2022b)

Most PV jobs have been created in Germany, the country with the biggest PV market and the highest number of GWs of PV installations in the EU. For 2020, in Germany, the total number of jobs, according to EurObserv'ER was just a bit over 55 000. Germany is followed by Poland, which was the 7th country in PV installed capacity in the EU in 2020 creating around 20 000 jobs. Spain and Netherlands had a bit less than 20 000 jobs in 2020 (Figure 43). The decrease in EU PV jobs between 2019 and 2020 is mainly due to the significant respective decreases taking place in Spain and France. The 2017 auction in Spain required that all installations be realised before the next one in 2019. For this reason, the number of PV-related jobs increased notably until 2019 but decreased again afterwards as the annual installed power decreased from about 5 GW_p in 2019 to 3 GW_p in 2020.

Figure 43. EU direct and indirect PV jobs for the top 10 countries for 2020..

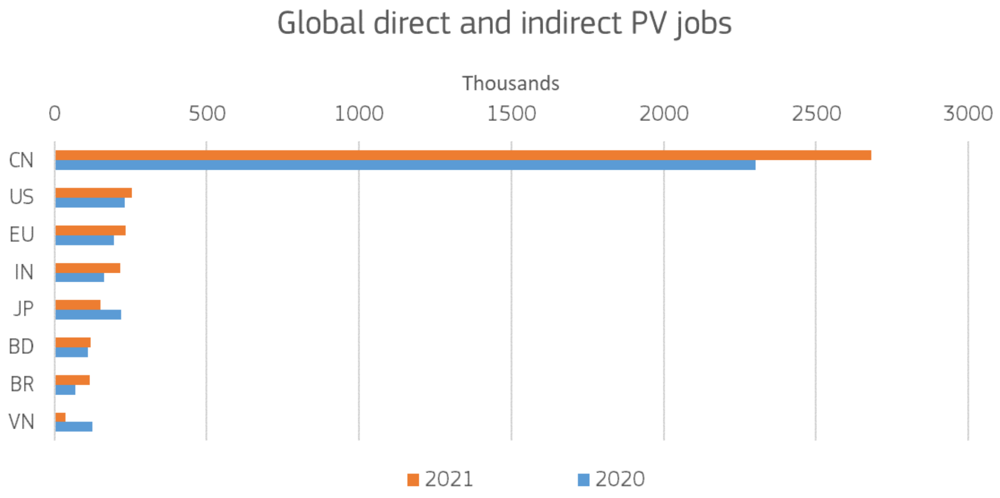


Source: JRC analysis based on (EurObserv'ER, 2022a)

For the period between 2015 and 2020, Germany's PV employment sector was on an upward trend with a compound increase of 12 %, whereas in Spain after a sudden increase in 2019 (from 2 200 jobs in 2018 to 52 200 jobs in 2019), the number of PV jobs decreased again in 2020 (19 100 jobs) down to amounts similar to those of Poland and the Netherlands (also on a steadily upward trend). Spain's compound increase in jobs between 2015 and 2020 was 45 %. Poland's and the Netherlands' were 76 % and 35 % respectively. Italy by contrast appears to be on a much flatter trajectory. In 2020 PV jobs in the country are almost the same as in 2015. The compound increase was only 3 %. For 2021, both SPE and IRENA data suggest that Poland grew its PV jobs market so much that it surpassed Germany, thus becoming the country with the highest number of PV jobs in the EU. Spain and Netherlands maintain their 3rd and 4th position while in the 5th position enters France according to IRENA and Greece according to SPE.

EU's position in the world for the number of total PV jobs in 2020 and 2021 is depicted in Figure 44. In its latest annual report, IRENA estimates that the PV-related jobs in 2021 have increased to 4.3 million from 4 million in 2020. China, that has also the largest PV market in the world, accounted for 58 % of the world PV jobs in 2020 (2.3 million jobs) and increased its share in the PV employment market by 5 %, reaching 63 % (2.7 million jobs) in 2021 (IRENA, 2022a). In 2020, the EU was in the 4th place globally, just after Japan and before India. However, in 2021, the EU conquered the 3rd position as Japan fell to the 5th position following India. It has to be noted that most of the countries in the graph are countries with low labour costs (like India, Bangladesh and Vietnam).

Figure 44. Global direct and indirect PV jobs for the top 8 countries for 2020 and 2021.



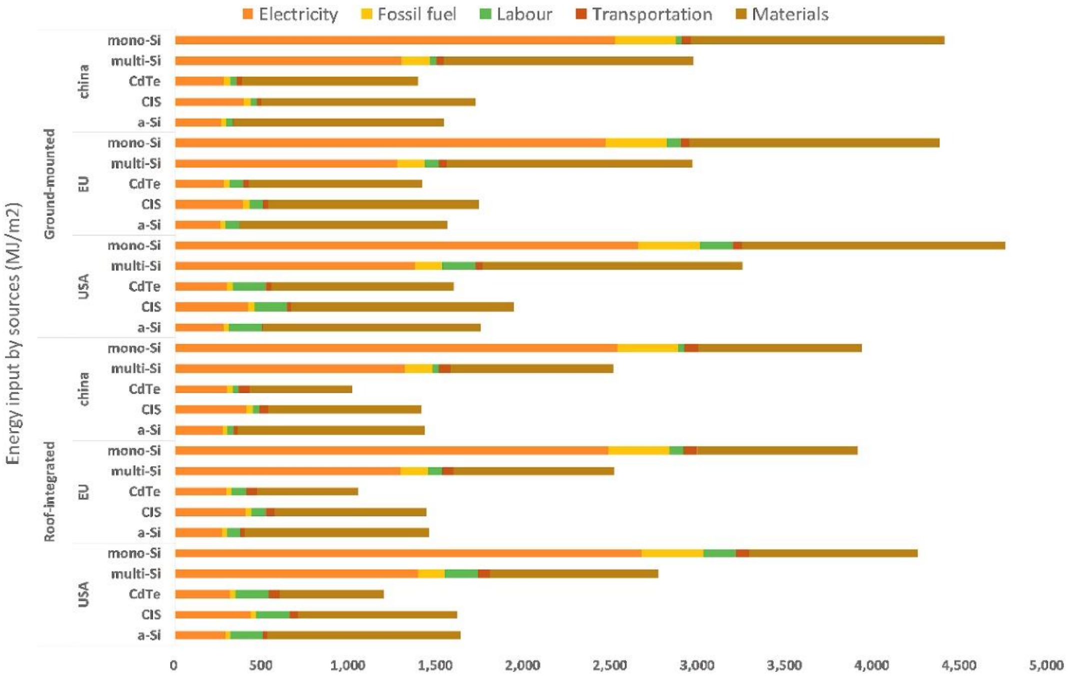
Source: JRC analysis based on (IRENA, 2022b)

The CIndECS annual report for 2021 has identified that the EU is a strong global competitor in the field of PV employment (Kuokkanen *et al.*, 2022).

3.6 Energy intensity / labour productivity

Energy intensity is the amount of energy used to produce a given level of output or activity. Figure 45 presents the energy needed for the production of different PV technologies and for different applications (Liu and van den Bergh, 2020). A distinction can be drawn between direct (electricity, fossil fuels and energy for transportation) and indirect (labour and material) energy inputs.

Figure 45. Direct and indirect energy investment of PV technologies in China, EU and USA.

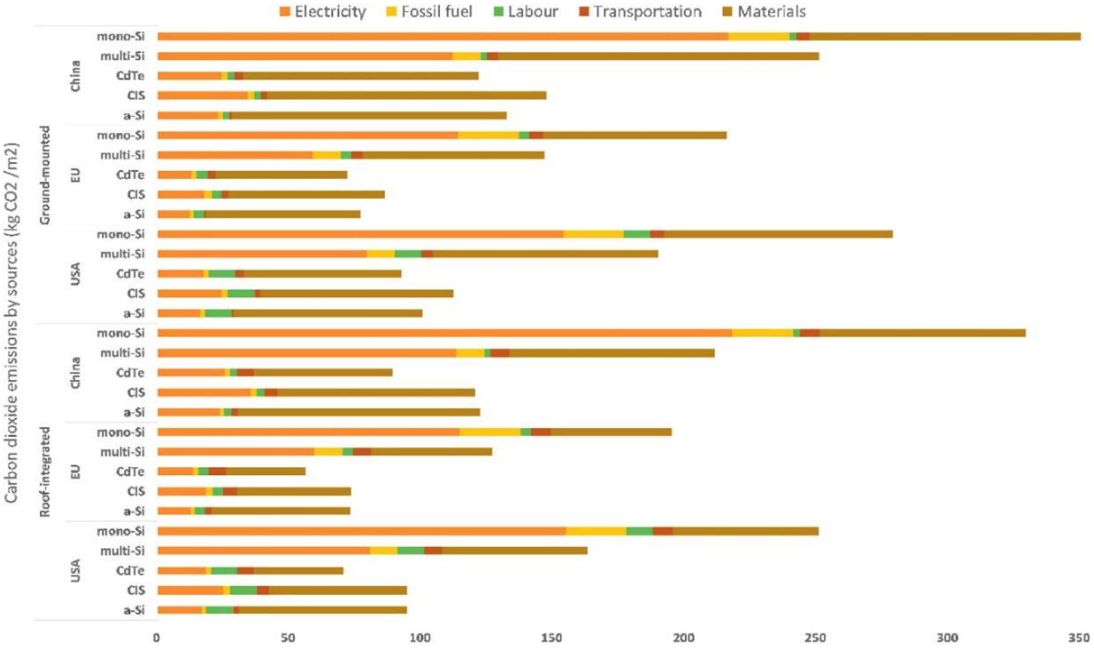


Source: (Liu and van den Bergh, 2020)

Thin-film PV technologies require less energy for their production (CdTe, CIS and a-Si) than poly c-Si technology. The most energy-intensive PV technology to manufacture is the mono c-Si and yet in the past 16 years, the use of materials has dropped from approximately 16 g/W_p to around 3 g/W_p due to increased efficiencies, thinner wafers, diamond wire sawing and larger ingots (Fraunhofer ISE, 2022b). PV technologies for rooftop applications generally need more energy input than ground-mounted applications. EU has the best energy return on energy invested (EROI), while the US has the worst mainly due to the high energy intensity of their electricity and labour. China is performing better than the US and worse than the EU. The Energy Payback Time (EPBT) of a PV wafer-based silicon modules PV system in South Italy (Sicily) is estimated to be around one year. Taking into consideration a 20 years system lifetime, this system can produce twenty times the energy needed to produce it (Fraunhofer ISE, 2022b). More in particular, the EPBT was calculated between 0.6 and 1.3 years (depending on the irradiation levels) for mono c-Si PV systems and between 0.6 and 1.5 years (depending on irradiation levels) for poly c-Si PV systems. In 2015 the respective ranges for mono c-Si PV systems were 1.1-2.6 years and for poly c-Si PV systems were 0.8-1.9 years (Fthenakis and Leccisi, 2021).

Figure 46 depicts the direct and indirect CO_2 emissions for different PV technologies that contribute to the energy return on carbon invested (EROC). The main parameter impacting EROC is the electricity used and therefore EROC for poly c-Si is worse than mono c-Si technologies. As far as the comparison between the three regions is concerned, the best-performing region is the EU and the worst is China. US's EROC is between that of the EU's and China's.

Figure 46. Direct and indirect CO_2 emissions for PV technologies in China, EU and USA.

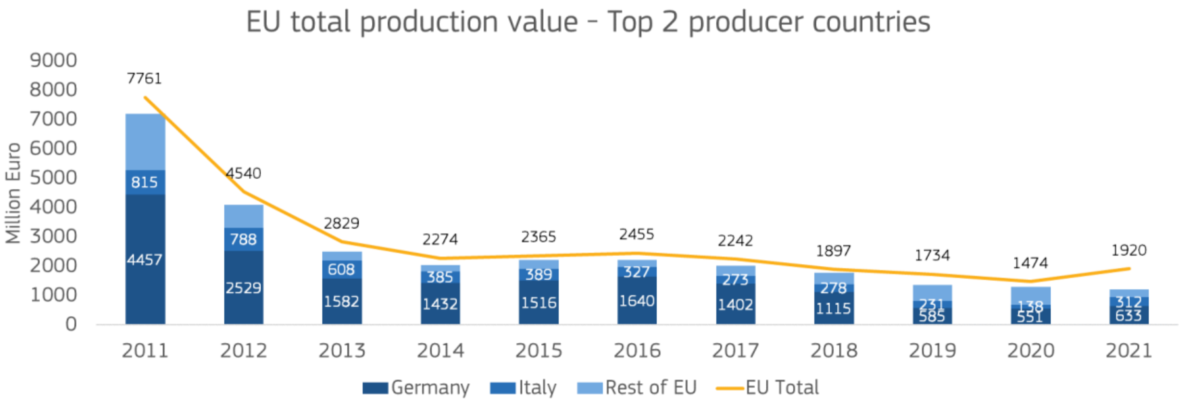


Source: (Liu and van den Bergh, 2020)

3.7 EU production Data

Prodcom "PRODuction COMmunautaire" (Community Production) provides statistics on the production of manufactured goods carried out by enterprises on the national territory of the reporting countries (EC, 2022e). Only modules are considered since other components/goods' (e.g. inverters) production codes are not explicitly associated with photovoltaics and data would not be representative.

Figure 47. EU total production and top producers for the period 2011-2020.



Source: JRC analysis based on PRODCOM

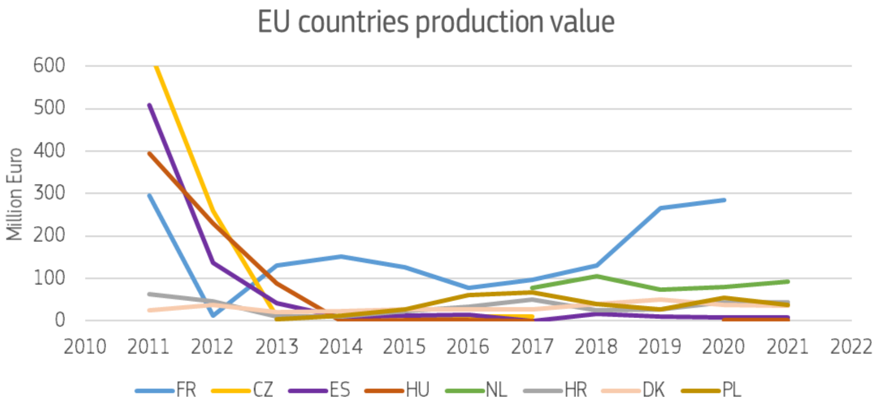
The collection of data for the EU production was based on the 26112240 and 26114070 codes which correspond to vague product groups that include solar cells and semiconductor devices and photovoltaic cells. For some trading goods, not all EU MS disclose their production data. "EU Total" includes estimates of the confidential information. The distance between the line ("EU Total") and the boxes ("Grand Total") indicates the amount of information that has been kept confidential.

Figure 47 shows the total production value in the EU and the two top production countries Germany and Italy. There is a significant overall reduction in production over the past years. The EU production has decreased by EUR 6 287 million from 2011 to 2020 with a sharp decline occurring between 2011 and 2013. However, in 2021, EU production seems to have slightly recovered with an increase of approximately EUR 450 million in comparison to 2020.

The growth of Asian production is overwhelming and has contributed to the EU decline over the years. In 2010, about 82 % of PV modules have been produced in Asia and in 2020 this portion increased to 92 %. China alone contributed with 67 % in 2020 (Fraunhofer ISE, 2022b).

Excluding the two major producers (Germany and Italy), the rest of the top 10 EU countries have suffered a notable decline. However, France is recording a slight increase after 2017, while other countries, like Croatia, Denmark and Poland, seem to maintain a stable production value after 2017 (Figure 48).

Figure 48. EU countries production for the period 2011-2021.



Source: JRC analysis based on PRODCOM

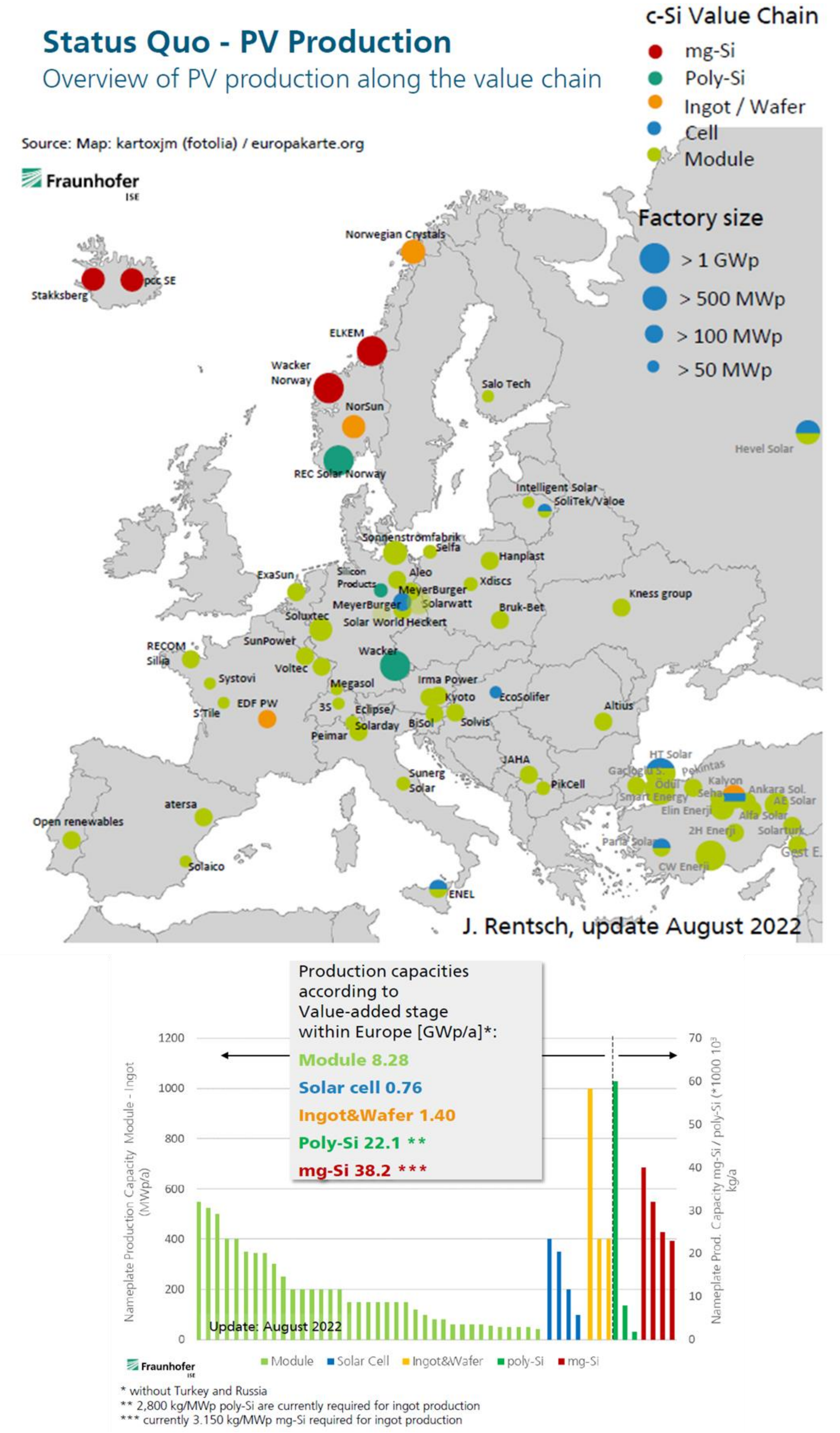
At the end of 2020, within the EU, the production capacity across the PV value chain was 30.2 GW_p/year for metallurgical grade silicon (mg-Si) mainly in Iceland and Norway, 22.1 GW_p/year for poly-Si mainly in Norway and Germany, 1.25 GW_p/year for ingot and wafer mainly in Norway and France, 0.65 GW_p/year for solar cells mainly in Hungary and Lithuania and 6.75 GW_p/year for modules in several European countries (Fraunhofer ISE, 2022b).

China accounted for 73 % of the global PV cell production in 2020 and increased its market share by 29 %, reaching approximately 150 GW production in 2021 while the global production for the same year was 190 GW (Jäger-Waldau, 2022).

The c-Si manufacturing capacities in Europe are presented in Figure 49. The figure presents the existing manufacturing facilities and their capacities as well as a few in the planning phase that are included in Table 9 in the following section.

According to the CIndECS annual report for 2021, the EU has a low competitiveness score as far as PV production is concerned (Kuokkanen *et al.*, 2022).

Figure 49. Current European c-Si PV manufacturing landscape in August 2022.



Source: Fraunhofer ISE

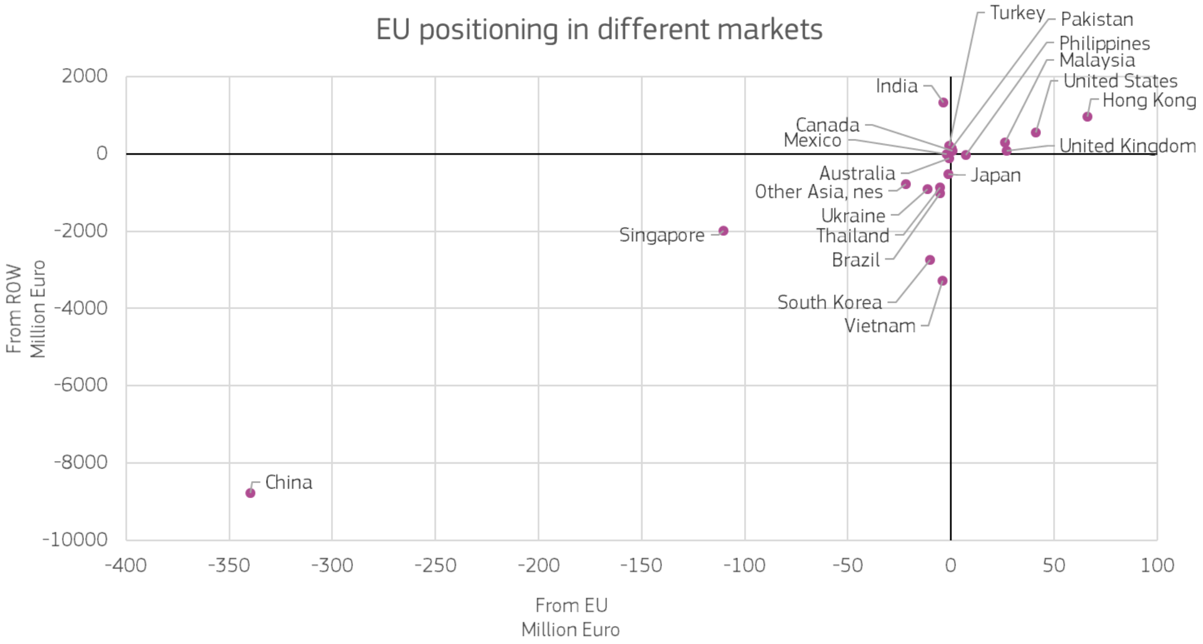
4 EU position and Global competitiveness

4.1 Global & EU market leaders (Market share)

Figure 50 demonstrates EU's position in different markets for the period 2019-2021. China is differentiated from the rest of the markets as it has a minimal dependence on the EU as far as its imports are concerned whereas countries like the United Kingdom and the United States are importing from the EU. Above the horizontal axis, countries like India and Turkey are characterised as growing markets, with a tendency towards increasing their imports. Potential markets for EU export activities are India, Australia, Mexico and Canada as they are in the phase of increasing their imports due to their growing PV markets.

China's market is experiencing rapid growth as it is the most cost-competitive location for the manufacturing of all PV components throughout the entire supply chain (IEA, 2022b). It is reported that costs in China are lower by 10 % compared to India, by 20 % compared to the US and by 35 % compared to Europe. This is due to lower energy, labour and investment costs existing in China (IEA, 2022b).

Figure 50. EU positioning in different markets with 2-year average of change in import from the EU and ROW for the period 2019-2021.



Source: JRC analysis based on UN Comtrade data

In 2010 PV modules manufactured in China accounted for around 40 % of the global shipments in the same year. China's share in global shipments of PV modules increased to 62 % in 2019 (IEA, 2020).

The industry leaders at global level are presented in Table 8 (IEA-PVPS, 2021). These top 5 leading companies are all based in China apart from Canadian Solar which is based in Canada. Other major companies in the sector are Hanwha Q CELLS (South Korea), First Solar (US), BrightSource Energy, Inc. (U.S.), SunPower Corporation (U.S.)[18], Yingli Solar (China), Wuxi Suntech Power Co. Ltd. (China), Waaree Group (India), AccionaEnergia S.A. (Spain), Nextera Energy Sources LLC (U.S.), Vivaan Solar (India), eSolar Inc. (U.S.), Tata PowerSolar Systems Ltd. (India) and Abengoa (Spain) (Fortune Business Insights, 2022).

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[18] Purchased by Total Energies in 2011 but listed as a US company.

Table 8. Global top 5 manufacturers for cells, modules and shipment in 2020.

Rank	Solar cell production (GW)	PV module production (GW)	PV module shipment (GW)
1	Tongwei Solar (21.4)	LONGI Green Energy Technology (26.6)	LONGI Green Energy Technology (24.5)
2	LONGI Green Energy Technology (17.6)	Jinko Solar (17.6)	Jinko Solar (18.8)
3	Shanghai Aiko Solar Energy JA (13.3)	Trina Solar (16.4)	Trina Solar (15.9)
4	Solar Technology (11.3)	JA Solar Technology (14)	JA Solar Technology (15.9)
5	Jinko Solar (10)	Canadian Solar (11.4)	Canadian Solar (11.3)

Source: IEA-PVPS, TRENDS IN PHOTOVOLTAIC APPLICATIONS 2021

EU's landscape in large-scale production is starting to change after several European manufacturers announced their intention to increase their production capacities. ENEL's TANGO project which has obtained EUR 118 million of funding through the Innovation Fund, will increase its current 200 MW production of heterojunction modules to 3 GW. The first phase includes an increase of production capacity to 400 MW by September 2023 and the second phase of 3 GW production is expected in July 2024. Another project expected to boost the EU's manufacturing sector is that of Meyer Burger in Freiberg and Thalheim, with an expected capacity of 1.4 GW of heterojunction cells and 1 GW of heterojunction modules respectively by the end of 2022. The construction of a 5 GW production of monocrystalline silicon wafers for PERC cells in Seville was also announced by Greenland (a Spanish start-up) in collaboration with Fraunhofer Institute (ISE) and Bosch. The 2 GW (first phase) and 4 GW (second phase) heterojunction modules production facility planned by REC Solar is at the moment on hold as the manufacturer was taken over by Reliance Industries (India) and no decision on whether the facility will ultimately be realised has been taken yet. Figure 49 presents the facilities planned in the near future that will boost the EU's production sector (EurObserv'ER, 2022b). The details of the already-announced production facilities are presented in Table 9.

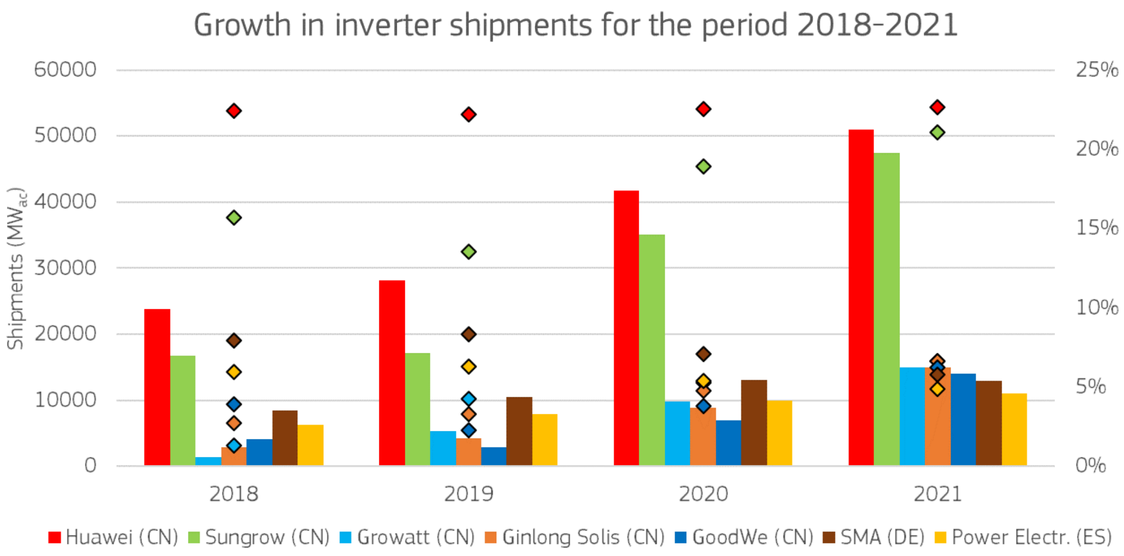
Table 9. Production facilities announced.

Company	Plant location	Actual plant capacity	Manufacturing plans	Technology
Meyer Burger	Freiberg (DE) Thalheim (DE)	400MW	1400 MW (cell) (2022) 1000 MW (module) (2022) 5000 MW (long-term objective)	HJT Heterojunction
Greenland Giga Factory	Sevilla (ES)	-	5000 MW (module) (2023)	PERC
Enel Green Power	Catane (IT)	200 MW	3000 MW (cell & module) (2024)	HJT Heterojunction
REC Solar	Hambach (FR)	-	2000 MW (module) (first stage) 4000 MW (module) (2025)	HJT Heterojunction
Solarge B.V.	Eindhoven (NL)	-	300 MW (module) (2022)	PERC
Kioto Energy	St. Veit/Glan (AT)	150 MW	450 MW (module) (2022) 750 MW (module) (2023)	Mono c-Si Mono c-Si bifacial
Saule technologies	Wroclaw (PL)	Pilot production line	100 MW (module) (-)	Perovskites
Oxford PV	Brandenburg an der Havel (DE)	Pilot production line	200 MW (cells and modules) (-)	Perovkite-c-Si

Source: (PHOTOVOLTAIC BAROMETER – EUROBSERV'ER – APRIL 2022)

The inverter market has also seen a tremendous market expansion as a result of the extended PV deployment activities and revenues for the manufacturing companies have increased over the years. Global inverter shipments grew from 98.5 GW_{ac} in 2017 to 225.3 GW_{ac} in 2021, a compound growth of 23 % (PV Magazine, 2018, 2019, 2020, 2022c; CDS Solar, 2022). Huawei is the leading inverter supplier for the past seventeen years. After a consecutive three-year period (2018-2020) of ranking in the 3rd and 4th position, the two European suppliers SMA (Germany) and Power Electronics (Spain) have been surpassed by three Chinese companies (Growatt, Ginlong Solis and GoodWe) and are placed in the 6th and 7th position respectively based on their growth in shipments in 2021 (Figure 51) (CDS Solar, 2022; PV Magazine, 2022c).

Figure 51. Global inverter shipments for the period 2018-2021.



Source: JRC analysis based on (CDS Solar, 2022; PV Magazine, 2022c)

Between 2019 and 2021 the inverter shipments exhibited a 33 % increase in compound growth from approximately 127 GW_{ac} (2019) to 225.3 GW_{ac} (2021). In the same period, the compound growths of the two major inverter manufacturers Huawei and Sungrow were 35 % and 66 % respectively. Growatt, Ginlong Solis and GoodWe have increased their shipments by 67 %, 89 % and 121 % (compound growth) and completed the top 5 inverter manufacturers list. SMA and Power Electronics have exhibited an 11 % and 18 % compound growth and hence have been shifted outside the top 5 global leading manufacturers for 2021.

In 2021, half of the global inverter shipments were destined for the Asia-Pacific market (the largest market), while the US and Europe had a 23 % and 14 % share (PV Magazine, 2022c).

4.2 Trade (Import/export) and trade balance

For the trade, import and export analysis the Comext (Eurostat's reference database for detailed statistics on international trade in goods) (EC, 2022d) and the UN Comtrade (repository of official international trade statistics and relevant analytical tables) (UN, 2022) databases were used.

The available data for imports, exports and trade are available until 2021 and their collection was based on the 854140, 854190, 26112240 and 26114070 codes, which correspond to vague product groups that include solar cells and semiconductor devices and photovoltaic cells. Only modules are considered since other components/goods (e.g. inverters) production codes are not explicitly associated with photovoltaics and data would not be representative.

Netherlands and Germany are the top two importers and exporters in the EU (Table 10). Netherlands' extra-EU imports account for 85 % of its total imports (intra-EU imports are 15 %), whereas its extra-EU exports account for only 5 % (95 % are intra-EU exports). The situation of the 2nd major EU importer-exporter, Germany, with relation to extra-EU trade is better but still reflects high extra-EU import activities (65 %) and low extra-EU export (35 %). On the other hand, France appears as the 4th largest EU importer and 3rd largest EU exporter and exhibits a more positive trade balance than Netherlands and Germany. In fact, France imports only 50 % of its total imports from extra-EU countries and exports 70 % of its total exports to extra-EU countries.

Table 10. Top 5 EU importers and exporters for the period 2019-2021.

Top EU Importers			**Top EU Exporters**		
	Extra-EU [EUR Million]	**Intra-EU [EUR Million]**		**Extra-EU [EUR Million]**	**Intra-EU [EUR Million]**
Netherlands	11345	2025	Netherlands	585	9133
Germany	5788	3185	Germany	2442	4726
Spain	2871	1084	France	1332	568
France	1528	1112	Italy	784	301
Poland	799	1431	Portugal	7	711

Source: JRC analysis based on COMEXT

The extra-EU trade for the EU as a total shows a rather stable export activity for the period while imports have increased significantly due to the constant increase in demand for the realisation of PV projects and the lack of in-house production (Figure 52).

The relative trade balance[19] is essentially the exports minus the imports for a given period. Between 2019 and 2021 the relative trade balance is negative for all the EU countries. Luxembourg has the least negative relative trade balance value (-0.02) and is one of the two EU countries that slightly improved their position compared to the 2016-2018 period when it had a relative trade balance of -0.06. The other country that improved its trade balance, thus still a negative one, is Croatia (from -0.14 in the 2016-2018 period to -0.08 in 2019-2021). Germany is the only country not experiencing any change between the two periods. Its relative trade balance remained stable at -0.11. Portugal, with a positive 0.46 trade balance for 2016-2018, has seen its imports rise compared to its exports between 2019 and 2021, resulting in a trade balance of - 0.28. Cyprus is the country that has suffered the highest change in trade (from -0.05 in the 2016-2018 period to -0.99 in the 2019-2021 period).

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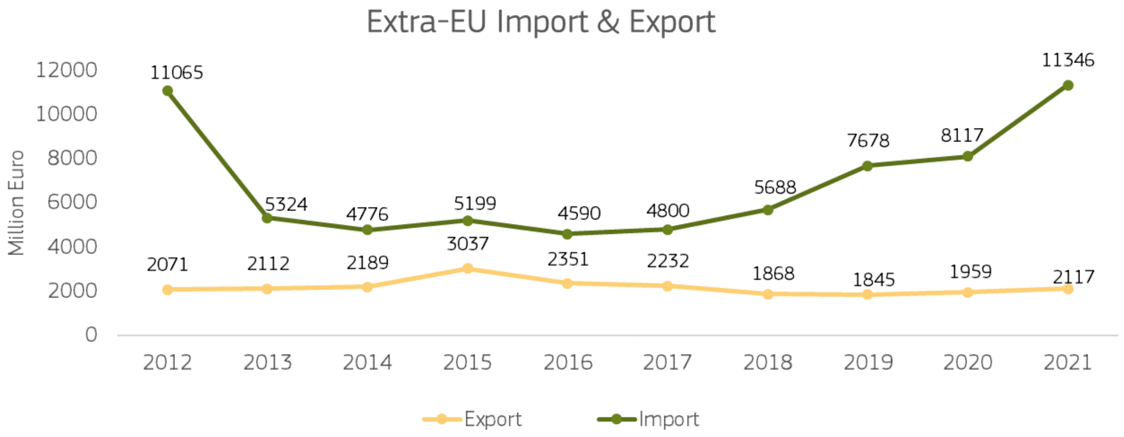
[19] The relative trade balance is calculated as (Export - Import)/ (Export + Import) and shows which trade flow is higher (export if >0, import if <0) compared to the total trade flows.

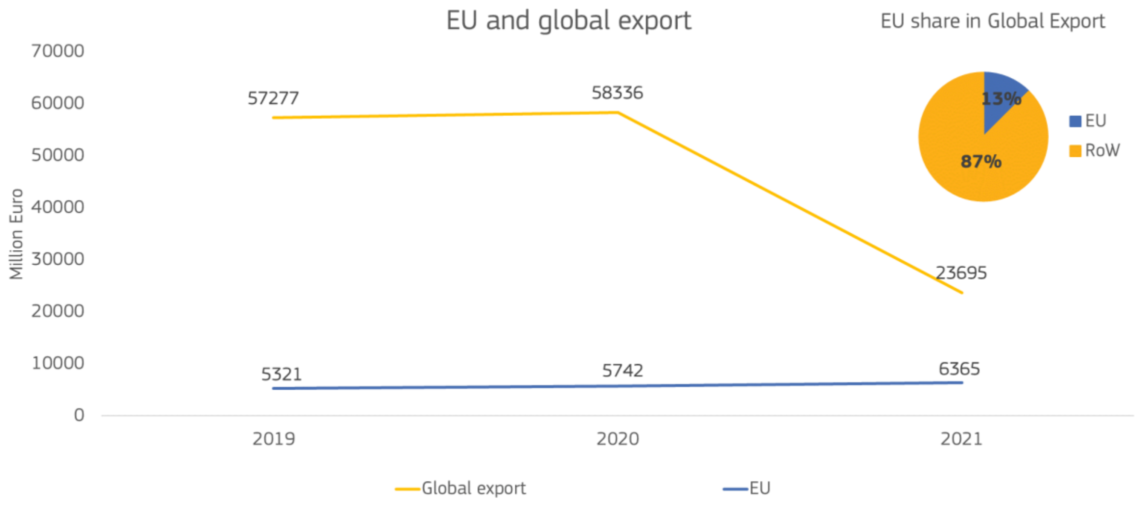
Figure 52. Extra-EU import and export for the period 2012-2021.



Source: JRC analysis based on COMEXT

For the period 2019-2021, the EU export activities have been stable, while the global export activities demonstrated a stable trend for 2019 and 2020 and declined by more than half for 2021. This decline is partly due to Covid-19 disruptions and partly because China and other Asian manufacturers have withheld their PV modules for domestic installation (as these have significantly increased) rather than exporting them. This decline in global exports in 2021 has resulted in an EU share of 9 %, 10 % and 27 % of global export in 2019, 2020 and 2021 respectively and 13 % for the period 2019-2021 (Figure 53).

Figure 53. EU and global export and EU share in global exports for the period 2019-2021.



Source: JRC analysis based on UN Comtrade data

The EU as a whole is mainly exporting to the United States, Singapore, the UK, China and Switzerland. The EU is importing mainly from China (Table 11). EU's share in US's total imports is 4 %. The respective percentages for Singapore, the UK and China are 12 %, 36 % and 7 %. Since the UK is not an EU member since 1 February 2020, it is treated as a third-party country, however for the period analysed it was partially still in the EU, hence its high share of imports from the EU.

Table 11. Global Top 5 importers from the EU and exporters to the EU for the period 2019-2021.

Top global Importers from the EU		Top global Exporters to the EU	
	[EUR Million]		**[EUR Million]**
United States	1083	China	20389
Singapore	724	Malaysia	1773
United Kingdom	622	Japan	1130
China	594	South Korea	827
Switzerland	403	Taiwan	680

Source: JRC analysis based on COMEXT

The ranking of the largest importers from the EU and exporters to the EU at global level finds Germany and Netherlands in the first 10 positions of both lists. However, their imports are more than their exports. The same applies also to the US, Hong Kong and Vietnam. By contrast, China, Malaysia, Japan and South Korea, demonstrate more exports compared to imports (Table 12).

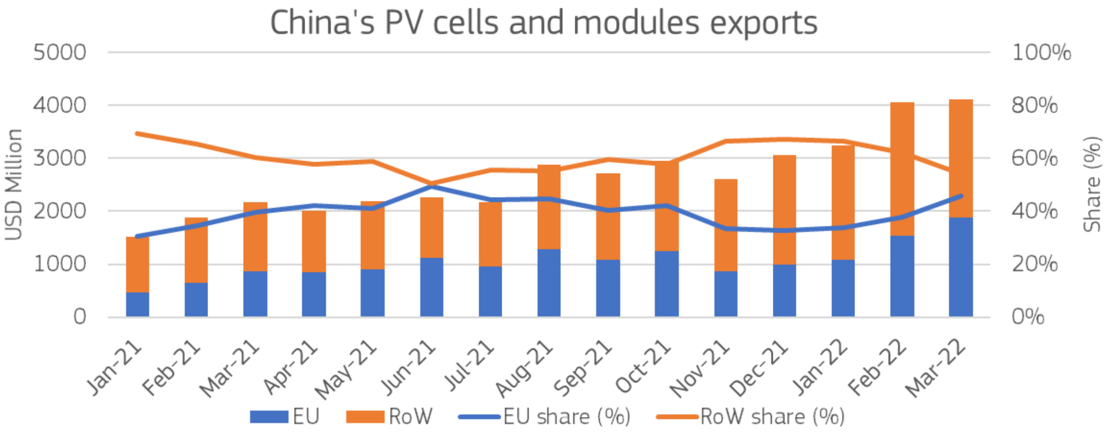
Table 12. Top 10 global importers and exporters for the period 2019-2021.

Top EU Importers from the EU		Top EU Exporters to the EU	
	[EUR Million]		**[EUR Million]**
United States	25645	China	44097
China	18662	Malaysia	15197
Hong Kong	14049	Hong Kong	12625
Germany	**8951**	Japan	11311
Japan	8877	**Germany**	**7173**
Vietnam	7954	Vietnam	7163
Netherlands	**7271**	Singapore	6915
India	7107	United States	6846
South Korea	5489	South Korea	6098
Malaysia	4999	**Netherlands**	**4542**

Source: JRC analysis based on UN Comtrade data

China, the largest exporter of solar cells and modules has seen a record of USD 4.1 billion in its exporting activities in March 2022 with exports to the EU reaching USD 1.9 billion (an increase of USD 0.8 billion since January 2022) (Figure 54). This is mainly due to the increase in demand for PV cells and modules for the realisation of solar projects and the acceleration of the EU's plans for a larger-scale deployment of PV due to the current geopolitical risks and the need for energy security and independence.

Figure 54. China's solar exports in 2021 and 1Q 2022.



Source: JRC analysis based on (BloombergNEF, 2022a)

According to the CIndECS annual report for 2021, the EU has a low competitiveness score both in trade balance as well as imports and exports (Kuokkanen *et al.*, 2022).

4.3 Resources efficiency and dependence in relation to EU competitiveness

The consumption of raw materials for PV panel manufacturing is expected to increase drastically in the next years due to the massive deployment of the photovoltaic technology. However, projections regarding the raw materials demand in 2030 and 2050 are difficult to perform and they are strongly dependent on the generation capacity and lifetime of the deployed infrastructure, the market share of each sub-technology and the material usage intensity.

A review regarding the critical materials used in the PV value chain has concluded that the EU's dependency on China, which is a leading producer and user of many critical minerals (including rare earths), must be taken seriously into consideration (Bobba *et al.*, 2020). The materials that have a high supply risk and are defined as CRMs for the EU are silicon metal, indium, gallium, germanium and borates while copper, cadmium, selenium, silver and tellurium are considered materials with a low supply risk (Bobba *et al.*, 2020). In the same report, the authors identify the supply risk for the processed materials as medium, whereas the components segment is characterised by the highest supply risk and in fact, the EU is importing over 90 % of the main components of solar modules, mainly wafers and solar cells (PVEurope, 2022).

Other primary raw materials reported as potentially critical for the EU's dependency due to the imports are boron, molybdenum, phosphorus, tin and zinc (EC, 2022c).

As far as the future consumption of raw primary materials is concerned, the projections for 2050 show a variation between the different materials depending on the scenarios (low, medium and high demand) and the market share of each technology. In general, no significant supply issues are identified but there is a concern regarding the pressure expected on the supply of a few like germanium, tellurium, indium, selenium and silicon (Carrara *et al.*, 2020).

However, the above-mentioned analysis that identifies a high-risk supply of primary raw materials does not directly influence the EU since it is importing the final product (e.g. cadmium telluride) rather than the primary raw materials (e.g. tellurium).

The use of silver for connections has been identified as a potential concern. The expected large-scale manufacturing activity in the next few years may render this concern more concrete and therefore there is continuous R&D for the minimisation of silver use as well as material substitution like copper. In addition, even though crystalline silicon will remain a key component of solar technology in the coming years, the possibility to resort to alternative technologies to achieve higher efficiencies and/or substitute currently critical materials should be assessed with perspicacity in order to avoid favouring one material over the other and creating other material dependencies (for example the current supply availability of tellurium, indium and germanium may get into distress in the future if we deliberately choose to favour thin-film technologies over silicon-based technologies for material dependency reasons (EC, 2022g)).

As far as the materials used for structural and electric components (such as concrete, steel, plastic, aluminium and copper) are concerned, the large-scale deployment foreseen in the future will increase their demand between 2 to 21 times (EC, 2022c) but no supply problems are expected since they are already abundantly available. Caution is however advised as steel and concrete sectors are producing many GHG emissions which is at odds with the objectives of favouring the large-scale deployment of PV as a means of EU's decarbonisation path (EC, 2022g).

Particular attention is needed regarding PV glass that is lacking in the EU and has to be imported in massive volumes. A major exporter of PV glass to the EU is China and the cost is high due to the custom duties. According to Sunman, PV glass output is expected to be 20 %-30 % less than its global demand in 2021 (PV Magazine, 2022b). The shortage was created due to restrictions imposed on glass manufacturing facilities in an attempt to reduce the country's environmental pollution. This shortage coincides with and can be amplified by the growing market share of bifacial modules (PV Magazine, 2022b).

5 Conclusions

Photovoltaics (PV) has been the fastest-growing technology for electricity generation from renewable energies in the past decade. It is an already mature technology, indispensable in achieving the targets set by the European Green Deal (EGD) to tackle climate change and, at the same time, accomplish the EU's energy transition.

The global cumulative PV installed capacity exceeded 1 TW in March 2022. The EU alone reached a cumulative installed PV capacity of 170 GW at the end of 2021 and a cumulative electricity generation of 158 TWh from PV. Only between May and August 2022, the EU generated 99.4 TWh of solar electricity in comparison to the 77.7 TWh generated in the same period in 2021, corresponding to a 28 % increase. According to projections, the EU capacity will increase to 328 GW in 2025, between 500 GW and 1 TW in 2030 and between 7 GW and 8.8 GW in 2050, whereas the projected global installed capacity will increase between 22 TW and 60 TW.

The average PV module efficiency has increased from 9.0 % in 1980 to 14.7 % in 2010 and 20.9 % in 2021. In the next few years, silicon-based PV technology will remain the predominant technology with module efficiencies reaching 24.0 % and over. As a possible future alternative to silicon, perovskite technology has developed rapidly and has the potential to achieve comparable costs (current module efficiency is 17.9 % while the record cell efficiency is 25.7 %). Two of the most promising and efficient technologies are silicon-based tandems with III-V top material (currently at 32.7 % module efficiency) and perovskite-silicon tandem devices (currently at 31.3 % module efficiency). The market's tendency towards the replacement of Passivated Emitter and Rear Contact (PERC) architecture (currently at ~21.0 % module efficiency with projections reaching ~22.5 % in 2032) by the n-type Tunnel Oxide Passivated Contact (TOPCon) (currently at ~21.3 % module efficiency with projections reaching ~24.0 % in 2032) is bringing further efficiency increases towards 25.0 % in 2032. Continuous research and improvement are required to achieve such higher efficiencies, combined with lower material consumption and lower costs.

The Energy Payback Time (EPBT) of a PV system in Southern Europe is one year, whereas in Northern Europe less than a year and a half. Nonetheless, it is also of paramount importance that the PV sector further reduces its environmental footprint and becomes more sustainable and circular along the entire PV value chain.

The Levelised Cost of Electricity (LCoE) from photovoltaics and electricity storage has decreased significantly in the past years. The global weighted-average LCoE for utility-scale projects fell by 88 % between 2010 and 2021 from USD 0.417/kWh to USD 0.045/kWh. Projections for the EU indicate that it will further decrease from the 2020 values of EUR 0.050/kWh (Northern Europe) and EUR 0.020/kWh (Southern Europe) to EUR 0.020/kWh (Northern Europe) and EUR 0.010/kWh (Southern Europe) in 2050, rendering PV technology as a competitive renewable energy technology.

EU PV companies are facing considerable competition, especially from China, which has a leading market in PV and exhibits minimal dependence on the EU. Most of the leading solar cell and module production companies are Chinese and they dominate the PV module shipments. In 2020, Chinese companies have produced 67 % of the total c-Si PV modules and in 2019 accounted for 62 % of the global shipments of PV modules. As far as cell production is concerned the five leading companies are all Chinese. In module production as well as module shipments, four of the top 5 companies are based in China. Regarding the PV module shipments, the first four Chinese companies account for 87 % of the top 5 companies' total shipments volume. Additionally, according to the IEA, the costs for PV manufacturing in China are considerably lower than in Europe. Costs in China are 10 % lower than in India, 20 % lower than in the United States, and 35 % lower than in Europe. EU's recent competitiveness regarding the inverter market has suffered a considerable hit in 2021 as more Chinese companies have entered the market and surpassed the European companies in market share. The European companies reduced their market share from 14 % in 2018 to 11 % in 2021. There are two important enablers for this development in China: First, better access to the capital needed for capacity expansions and second, faster permitting for new factories as well as faster construction and ramp-up times.

The EU hosts almost one-fourth of the innovators in the field of PV and is leading in high-value patents and produces highly cited publications. EU funding on PV in H2020 is estimated to have been around EUR 329 million. The efforts to boost the EU's innovation and demonstration activities in PV need to continue in Horizon Europe if the EU's leading role is to be maintained. The new Innovation Fund (IF) is already making an impact, and the TANGO project alone has received approximately EUR 108 million for a 3 GW manufacturing plant that will contribute to the EU's PV market development building on EU research.

The current trend of the EU market shows that it will be capable to respond to the requirements for the new PV system capacity installations between 2021 and 2030 as described in the recent European Solar Strategy communication. However, important aspects to consider are the material efficiency and the avoidance of disruption of the international value chain. The EU value chain needs to supply at least 25-35 % of the EU market. At the moment, this is possible for polysilicon manufacturing, backsheets, contact materials, inverters and balance of system components. New capacities for wafers, cells and solar glass production are needed.

The current geo-political situation leading to the acceleration of EU's energy independence and climate neutrality together with the promising advancements will give to the EU PV market the opportunity to re-emerge more competitive in the next years and possibly play a leading role in the international PV market.

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List of abbreviations and definitions

General

AgriPV	Agri-Photovoltaics
BIPV	Building Integrated Photovoltaics
BoS	Balance of System
CAPEX	Capital Expenditure
CCS	Carbon Capture and Sequestration
CIndECS	European Climate Neutral Industry Competitiveness Scoreboard
Comext	Statistical database on trade of goods managed by Eurostat
CPC	Cooperative Patent Classification
CRM	Critical Raw Material
CSP	Concentrated Solar Power
EC	European Commission
EGD	European Green Deal
EMPIR	European Metrology Programme for Innovation and Research
EPC	Engineering, Procurement and Construction
EPBT	Energy Payback Time
ERC	European Research Council
EROC	Energy Return On Carbon invested
EROI	Energy Return On energy Invested
ESI	European Solar Initiative
ETIP-PV	European Technology and Innovation Platform for Photovoltaics
EU	European Union
EU ETS	European Union Emission Trading System
Extra-EU	Transactions with all countries outside of the European Union
FPV	Floating Photovoltaics
FTE	Full-Time Equivalent
FWCI	Field Weighted Citation Impact
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GVA	Gross Value Added
H2020	Horizon 2020 funding programme
IF	Innovation Fund
ITRPV	International Technology Roadmap for Photovoltaic
Intra-EU	Transactions within the European Union
IRENA	International Renewable Energy Agency
IWG	Implementation Working Group
JRC	Joint Research Centre
LCA	Life-Cycle Analysis

LCEO	Low Carbon Energy Observatory
LCoE	Levelised Cost of Electricity
MS	Member State
NREPBT	Non Renewable Energy Payback Time
O&M	Operation and Maintenance
OPEX	Operational Expenditure
Prodcom	Production Communautaire (Community Production)
PV	Photovoltaics
R&D	Research and Development
R&I	Research and Innovation
SET-Plan	Strategic Energy Technology Plan
SME	Small and medium-sized enterprise
SPE	SolarPower Europe
SRIA	Strategic Research and Innovation Agenda
TIM	Tools for Information Monitoring
TRL	Technology Readiness Level
TWG	Temporary Working Group
UN Comtrade	United Nations International Trade Statistics Database
VC	Venture Capital
VIPV	Vehicle Integrated Photovoltaics
WACC	Weighted Average Costs of Capital

Technical

AC	Alternating current
a-Si	Amorphous silicon
CdTe	Cadmium Telluride
CI(G)S	Copper Indium (Gallium) Selenide
CO_2eq	Carbon dioxide equivalent
DC	Direct current
gCO_{2eq}	Grams of CO_2 equivalent
GW_{ac}	Giga Watt alternating current
GW_p	Giga Watt peak
GWh	Giga Watt hour
HJT	Heterojunction technology
mono c-Si	Mono crystalline silicon
OPV	Organic Photovoltaics
PERC	Passivated Emitter and Rear Contact
PERT	Passivated Emitter Rear Totally diffused

Pks	Perovskites
poly c-Si	Poly-crystalline Silicon
TOPCon	Tunnel Oxide Passivated Contact
TW_p	Terra Watt peak
TWh	Terra Watt hour
W	Watt
W_p	Watt peak
Wh	Watt hour

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Annex 1 European Union Member State coding.

Code	**Country**
AT	Austria
BE	Belgium
BG	Bulgaria
HR	Croatia
CY	Cyprus
CZ	Czech Republic
DK	Denmark
EE	Estonia
FI	Finland
FR	France
DE	Germany
EL	Greece
HU	Hungary
IE	Ireland
IT	Italy
LV	Latvia
LT	Lithuania
LU	Luxembourg
MT	Malta
NL	Netherlands
PL	Poland
PT	Portugal
RO	Romania
SK	Slovakia
SI	Slovenia
ES	Spain
SE	Sweden

Annex 2 Concluded EU Supported R&D Projects for PV.

Id	Acronym	Title	PV Technology	Application	Project Type	EU Contribution	Start	End
666507	ADVANCED -buildings	New Generation of buildings glass with advanced integation properties	various	buildings	SME-2	1,887,121	01/04/2015	31/03/2017
774686	AlbaSolar	Developing perovskite-based solar panels	perovskites	general	SME-1	50,000	01/05/2017	30/09/2017
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
763989	APOLO	SmArt Designed Full Printed Flexible RObust Efficient Organic HaLide PerOvskite solar cells	perovskites	general	RIA	4,997,191	01/04/2018	31/07/2022
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	30/11/2020
818009	Be-Smart	BE-Smart: Innovative Building Envelope for Sustainable, Modular, Aesthetic, Reliable and efficient construction	N/A	buildings	IA	8,155,173	01/10/2018	30/09/2022
641972	CABRISS	Implementation of a CircularAr 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
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
653296	CHEOPS	Production technology to achieve low Cost and Highly Efficient phOtovoltaic Perovskite Solar cells	perovskites	general	RIA	3,299,095	01/02/2016	31/01/2019
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
699935	Crystal Tandem Solar	Single-Crystal Perovskite Tandem Solar Cells For High Efficiency and Low Cost	perovskites	general	MSCA-IF-GF	269,858	01/01/2017	31/12/2019
887915	cs-BIPV-FS	Next-generation transparent PV for Building Integrated Photovoltaics	Silicon	buildings	SME-1	50,000	01/11/2019	31/01/2020
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
727529	DISC	Double side contacted cells with innovative carrier-selective contacts	Silicon	general	RIA	4,743,519	01/10/2016	30/09/2019
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
767180	Envision	ENergy harVesting by Invisible Solar IntegratiON in building skins	various	buildings	IA	4,900,313	01/10/2017	31/03/2022
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
878182	ESMOS	Efficient, Safe and Multi-Functional Operation of Solar-Roads	Silicon	integrated apps	SME-1	50,000	01/08/2019	31/01/2020
764047	ESPResSo	Efficient Structures and Processes for Reliable Perovskite Solar Modules	perovskites	general	RIA	5,412,658	01/04/2018	30/09/2021
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
825669	ETIP PV - SEC II	Support to all stakeholders from the Photovoltaic sector and related sectors to contribute to the SET-Plan	N/A	general	LC-SC3-CC-4-2018	922,875	01/10/2018	30/06/2022
764805	EU HEROES	EU routes for High pEnetration of solaR PV into lOcal nEtworkS	N/A	system integration	CSA	1,230,558	01/09/2017	31/08/2020
797546	FASTEST	Fully Air-Processable and Air-Stable Perovskite Solar Cells Based on Inorganic Metal Halide Perovskite Nanocrystals	perovskites	general	MSCA-IF-EF-ST	180,277	01/09/2018	31/08/2020
966334	FREENERGY	Lead-free halide perovskites for the highest efficient solar energy conversion	perovskites	general	ERC-POC	150,000	01/02/2021	31/07/2022
792059	GOPV	Global Optimization of integrated PhotoVoltaics system for low electricity cost	N/A	system integration	IA	9,403,873	01/04/2018	30/09/2022
687008	GOTSolar	New technological advances for the third generation of Solar cells	perovskites	general	RIA	2,993,404	01/01/2016	31/12/2018
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

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
839136	HES-PSC-FCTL	High efficiency and stability perovskite solar cells based on the functionalized charge transport layers	perovskites	general	MSCA-IF-EF-ST	224,934	01/08/2019	31/07/2021
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
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
850275	HORIZON	Redefining solar technology with retractable soalr 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
795716	HYBRICYL	Organic-Inorganic Hybrid Heterojunctions in Extremely Thin Absorber Solar Cells Based on Arrays of Parallel Cylindrical Nanochannels	perovskites	general	MSCA-IF-EF-ST	159,461	01/07/2018	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
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
717956	HyTile	Sensitive integrated Solar Hybrid Roofing for historical buildings.	Silicon	buildings	SME-1	50,000	01/03/2016	30/06/2016
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
826013	IMPRESSIVE	ground-breakIng tandeM of transPaRent dyE SenSitIsed and peroVskite solar cElls	perovskites	general	RIA	2,929,050	01/01/2019	30/06/2022
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
841265	LOVETandemSolar	Local Optoelectronic Visualisation for Enhancing Tandem Perovskite/Silicon Solar Cells	perovskites	general	MSCA-IF-EF-ST	212,934	01/10/2019	30/05/2022
856071	LUMIDUCT	Transparent PV that regulates indoor climate	III-V	buildings	SME-1	50,000	01/02/2019	31/05/2019
764787	MAESTRO	MAking pErovskiteS TRuly explOitable	perovskites	general	MSCA-ITN-ETN	3,829,217	01/11/2017	30/04/2022
707168	MatchForSolar	Mechanochemical Approach to Inorganic-Organic Hybrid Materials for Perovskite Solar Cells	perovskites	general	MSCA-IF-EF-ST	131,565	01/09/2016	28/02/2018
795206	MolDesign	Molecule design for next generation solar cells using machine learning approaches trained on large scale screening databases	various	general	MSCA-IF-GF	208,964	01/04/2018	01/01/2022
653184	MPerS	Sustainable Mixed-ion Layered Perovskite Solar Cells	perovskites	general	MSCA-IF-EF-ST	195,455	01/04/2015	31/03/2017
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
696519	NanoSol	Accelerating Commercialization of Nanowire Solar Cell Technologies	III-V	general	SME-2	1,740,375	01/02/2016	30/04/2019
655039	NANOSOLAR	HYBRID QUANTUM-DOT/TWO-DIMENSIONAL MATERIALS PHOTOVOLTAIC CELLS	various	general	MSCA-IF-EF-ST	158,122	02/06/2015	01/06/2017
641023	Nano-Tandem	Nanowire based Tandem Solar Cells	III-V	general	RIA	3,561,842	01/05/2015	30/04/2019
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
656208	NEXTNANOCELLS	Next generation nanowire solar cells	III-V	general	MSCA-IF-EF-ST	173,857	01/08/2015	25/04/2018
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	31/03/2022
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
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

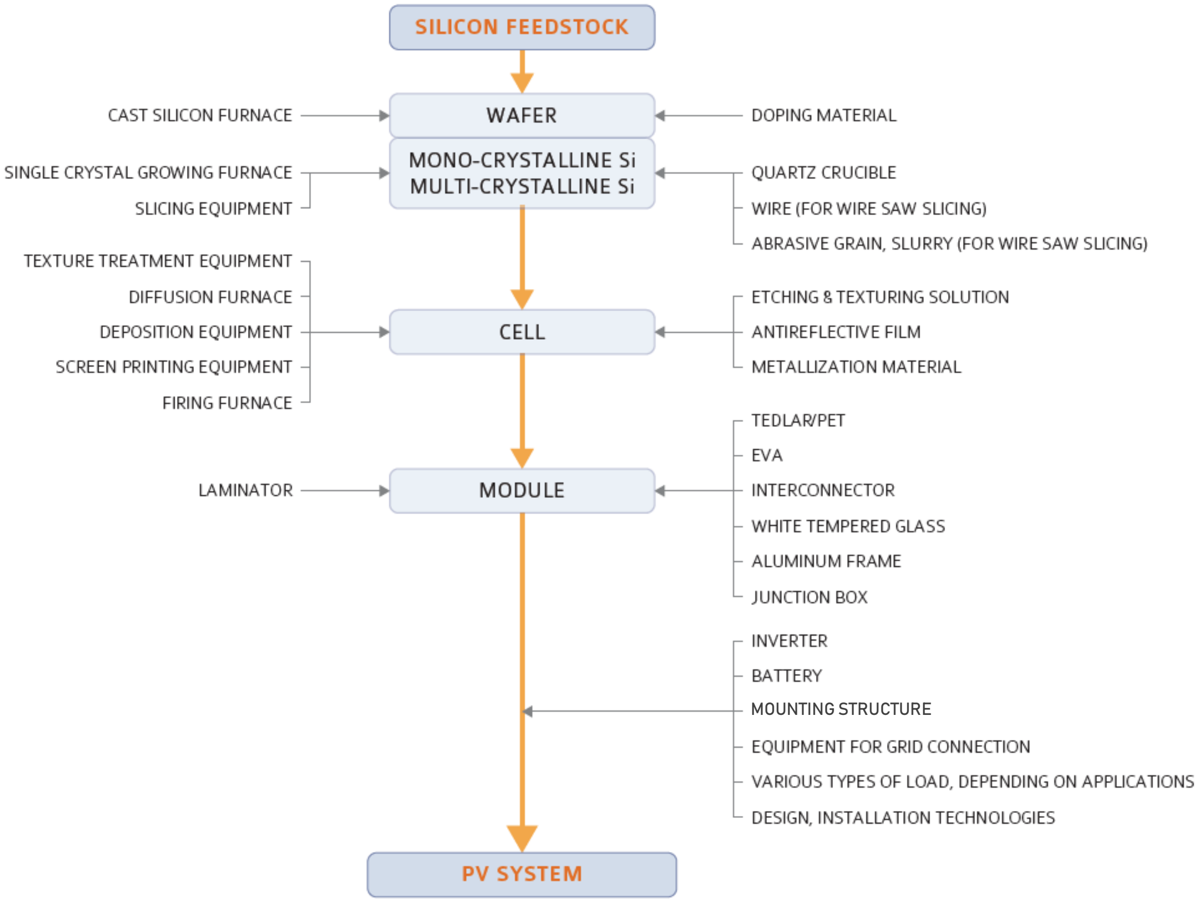
804554	PanePowerSW	Transparent Solar Panel Technology for Energy Autonomous Greenhouses and Glass Buildings	OPV/DSSC	buildings	SME-2	1,491,783	01/03/2018	28/02/2021
639760	PEDAL	Plasmonic Enhancement and Directionality of Emission for Advanced Luminescent Solar Devices	LSC	buildings	ERC-STG	1,447,410	01/04/2015	30/09/2021
659237	PerovskiteHTM	New Hole-Transport Materials to Enhance Perovskite Solar Cells	perovskites	general	MSCA-IF-EF-ST	195,455	01/02/2016	31/01/2018
841005	PerSiSTanCe	Low-cost and Large-Area Perovskite-Silicon Solar Tandem Cells	perovskites	general	MSCA-IF-EF-ST	203,149	01/05/2019	30/04/2021
763977	PERTPV	Perovskite Thin-film Photovoltaics (PERTPV)	Perovskites	general	RIA	4,996,041	01/04/2018	30/09/2021
745776	PHOTOPEROVSKITES	Photoexcitation Dynamics and Direct Monitoring of Photovoltaic Processes of Solid-State Hybrid Organic-Inorganic Perovskite Solar Cells	perovskites	general	MSCA-IF-EF-ST	195,455	01/09/2017	29/02/2020
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
737447	PHYSIC	Photovoltaic with superior crack resistance	Silicon	O&M	ERC-POC	149,500	01/01/2017	30/06/2018
889405	PIPER	Printing of Ultra-Thin, Flexible Perovskite Solar Cells and its Commercial Application	perovskites	buildings	SME-1	50,000	01/12/2019	31/05/2020
661480	PlasmaPerovSol	A full plasma and vacuum integrated process for the synthesis of high efficiency planar and 1D conformal perovskite solar cells	perovskites	general	MSCA-IF-EF-ST	158,122	01/01/2016	31/12/2017
762726	PLATIO	Innovative outdoor solar and kinetic energy harvesting pavement system	silicon	integrated apps	SME-1	50,000	01/01/2017	30/04/2017
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
747221	POSITS	High Performance Wide Bandgap and Stable Perovskite-on-Silicon Tandem Solar Cells	perovskites	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	perovskites	general	ERC-POC	150,000	01/09/2016	28/02/2018
646554	PV FINANCING	PV FINANCING	N/A	system integration	CSA	2,050,939	01/01/2015	30/06/2017
842547	PV Impact	Actual execution of the Implementation Plan for Photovoltaics and monitoring the Implementation Plan's delivery	N/A	general	LC-SC3-JA-2-2018-2019	1,094,565	01/04/2019	31/03/2022
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
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
684528	PVFINAL	Photo Voltaic Fully Integrated and Automated Line	Silicon	general	SME-1	50,000	01/07/2015	31/12/2015
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
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
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
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
776362	RadHard	Ultra High Efficiency Radiation Hard Space Solar Cells on Large Area Substrates	III-V	space	RIA	3,072,973	01/01/2018	31/01/2022
674628	RAYGEN	A unique innovative utility scale solar energy technology that utilises a field of low cost heliostat collectors to concentrate sunlight onto an ultra-efficient multi-junction photovoltaic cell array	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
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
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
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	31/01/2021

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	01/08/2022
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	31/10/2021
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
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
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
649997	Solar Bankability	Improving the Financeability and Attractiveness of Sustainable Energy Investments in Photovoltaics: 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
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
791411	SolarGaps	SolarGaps - Energy generating solar smart window blinds	N/A	buildings	SME-1	50,000	01/11/2017	28/02/2018
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
870004	Solar-Win	Next generation transparent solar windows based on customised integrated photovoltaics	CIGS	buildings	IA	2,419,594	01/10/2019	31/12/2021
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
647311	Sol-Pro	Solution Processed Next Generation Photovoltaics	Various	general	ERC-COG	1,840,940	01/07/2015	30/06/2020
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
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
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
720907	STARCELL	Advanced strategies for substitution of critical raw materials in photovoltaics	Kesterites	general	RIA	4,832,185	01/01/2017	31/12/2019
843453	STARS	STable perovskite solar cells via interfacial engineering of 2D/3D mixed-dimensional Absorbers and Robust dopant-free hole transporting materialS	perovskites	general	MSCA-IF-EF-ST	191,149	01/09/2019	31/08/2021
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
738842	SUNINBOX	Portable SolUtioN for dIstributed geNeration in a BOX	N/A	system integration	SME-2	1,407,543	01/02/2017	31/07/2019
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
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
828485	THE SOLAR URBAN HUB	A SOLAR URBAN HUB with integrated lighting and information system for optimal Smart Cities efficiency	N/A	integrated apps	SME-1	50,000	01/09/2018	31/01/2019
751375	TinPSC	Towards Stable and Highly Efficient Tin-based Perovskite Solar Cells	perovskites	general	MSCA-IF-EF-ST	185,857	01/08/2018	31/07/2020
706094	TONSOPS	Titanium Oxide Nanocomposites for Scalable Optimized Perovskite Solar cells	perovskites	general	MSCA-IF-EF-ST	170,122	16/03/2016	15/03/2018
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
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	31/08/2022
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
825142	ZeroR	Resistance-free charge spreading for LEDs and solar cells	various	general	ERC-POC	150,000	01/01/2019	31/10/2020

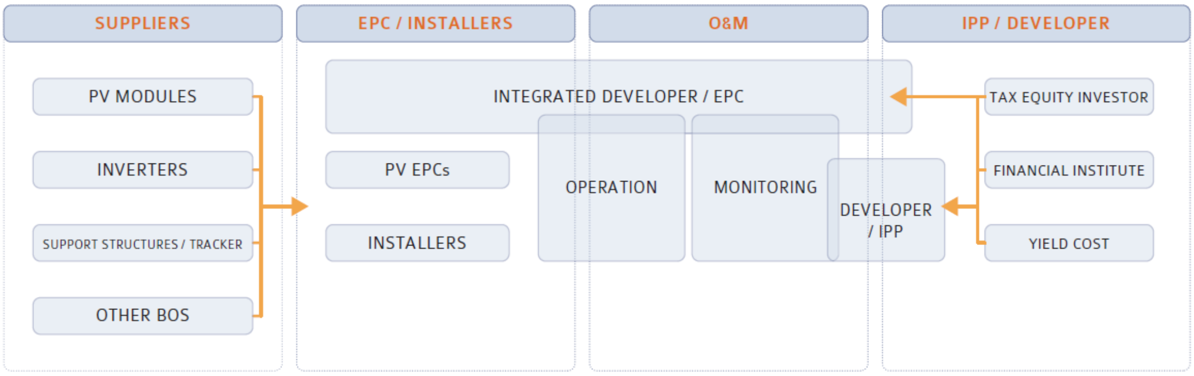
Annex 3 Ongoing EU Supported R&D Projects for PV.

Id	Acronym	Title	PV Technology	Application	Project Type	EU Contribution	Start	End
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	31/05/2023
952911	BOOSTER	Boost Of Organic Solar Technology for European Radiance	OPV/DSSC	buildings	IA	6,106,624	01/09/2020	31/08/2024
776680	CIRCUSOL	Circular business models for the solar power industry	various	recycling	IA	7,014,893	01/06/2018	30/11/2022
101007084	CITYSOLAR	ENERGY HARVESTING IN CITIES WITH TRANSPARENT AND HIGHLY EFFICIENT WINDOW-INTEGRATED MULTI-JUNCTION SOLAR CELLS	Various	buildings	RIA	3,779,242	01/12/2020	30/11/2023
952982	CUSTOM-ART	DISRUPTIVE KESTERITES-BASED THIN FILM TECHNOLOGIES CUSTOMISED FOR CHALLENGING ARCHITECTURAL AND ACTIVE URBAN FURNITURE APPLICATIONS	Kesterites	buildings	IA	6,999,745	01/09/2020	29/02/2024
804519	FREENERGY	Lead-free halide perovskites for the highest efficient solar energy conversion	perovskites	general	ERC-STG	1,500,000	01/02/2019	31/01/2024
857775	HIPERION	Hydrid photovoltaics for efficiecny record using optical technology	III-V	CPV	IA	10,590,511	01/09/2019	31/08/2023
756962	HYPERION	HYbrid PERovskites for Next GeneratION Solar Cells and Lighting	perovskites	general	ERC-STG	1,759,733	01/11/2017	31/10/2022
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	31/10/2022
726360	MOLEMAT	Molecularly Engineered Materials and process for Perovskite solar cell technology	perovskites	general	ERC-COG	1,878,085	01/11/2017	31/10/2023
850937	PERCISTAND	Development of all thin-film PERovskite on CIS TANDem photovoltaics	perovskites	general	RIA	4,997,437	01/01/2020	30/06/2023
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
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
862474	RoLA-FLEX	Roll-2-Roll and Photolithography post-processed with LAser digital technology for FLEXible photovoltaics and wearable displays	OPV/DSSC	general	IA	4,705,038	01/05/2020	30/04/2023
953016	SERENDI-PV	Smooth, REliable aNd Dispatchable Integration of PV in EU Grids	N/A	system integration	IA	9,779,146	01/10/2020	30/09/2024
952879	SolAqua	Accessible, reliable and affordable solar irrigation for Europe and beyond	N/A	system integration	CSA	1,757,211	01/10/2020	30/09/2023
786483	Solar Cofund 2	SOLAR-ERA.NET Cofund 2	N/A	general	ERA-NET-Cofund	6,333,425	01/06/2018	31/05/2023
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
792245	SUPER PV	CoSt redUction and enhanced PERformance of PV systems	various	O&M	IA	9,907,793	01/05/2018	31/10/2022
826002	Tech4Win	Disruptive sustainable TECHnologies FOR next generation pvWINdows	various	buildings	RIA	2,877,045	01/01/2019	31/12/2022
952957	TRUST-PV	Increase Friendly Integration of Reliable PV plants considering different market segments	N/A	system integration	IA	9,969,044	01/09/2020	31/08/2024
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
101051356	TANGO	ITaliAN PV Giga factOry	Bifacial HJT	general	IF	117,675,100	01/01/2021	31/08/2033
101038919	HELEXIO line	Demonstrating manufacturing for innovative BIPV roof components	Silicon	buildings	IF	3,733,140	01/10/2021	30/04/2027
101038836	CO2-FrAMed	CO2-Free Agriculture for the Mediterranean region.	N/A	system integration	IF	4,356,000	01/01/2022	30/06/2027

Annex 4 Upstream c-Si technology sector and downstream utility-scale installation sector



Source: IEA-PVPS, TRENDS IN PHOTOVOLTAIC APPLICATIONS 2021



Source: IEA-PVPS, TRENDS IN PHOTOVOLTAIC APPLICATIONS 2021

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