ISSN 1831-9424

European Commission

CLEAN ENERGY
TECHNOLOGY
OBSERVATORY

Photovoltaics in the European Union

STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS & MARKETS

2024

EUR 40073

Joint
Research
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Contact information
Name: Anatoli Chatzipanagi
Address: European Commission, Joint Research Centre, Ispra, Italy
Email: anatoli.chatzipanagi@ec.europa.eu

EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC139297

EUR 40073

PDF ISBN 978-92-68-20993-6 ISSN 1831-9424 doi:10.2760/1812909 KJ-01-24-077-EN-N

Luxembourg: Publications Office of the European Union, 2024

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How to cite this report: European Commission, Joint Research Centre, Chatzipanagi, A., Jaeger-Waldau, A., Letout, S., Mountraki, A., Gea Bermudez, J., Georgakaki, A., Ince, E. and Schmitz, A., *Clean Energy Technology Observatory: Photovoltaics in the European Union - 2024 Status Report on Technology Development, Trends, Value Chains and Markets*, Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/1812909, JRC139297.

Contents

Abstract

As part of the Clean Energy Technology Observatory (CETO), this report on Photovoltaics (PV) 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. PV is the fastest-growing source of electricity production from renewable energies and a pillar for EU's energy transition. According to projections, an even broader deployment of photovoltaic systems is required in order to achieve the goals set in the European Green Deal (EGD). The current trend of the EU market shows that it is growing faster than what is required to reach the new PV system capacity installations by 2030 as described in the EU Solar Strategy communication. As the overall global demand for PV components is growing even faster than in the EU and trade frictions can occur, precaution is required to avoid a fallout of international supply chain disruptions on the deployment of PV in the EU. To hedge such a risk, the EU value chain should be able to supply at least 25-35 % of the EU market. At the moment, this is possible for the production of polysilicon, backsheets, contact materials, inverters and balance of system components. Additional new capacities for wafers, cells and solar glass production are needed.

Foreword on the Clean Energy Technology Observatory

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-faced character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognising the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), who run the observatory, and Directorate Generals Research and Innovation (R&I) and Energy (ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal
- assess the competitiveness of the EU clean energy sector and its positioning in the global energy market
- build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020)
- publish reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform.

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and inventive technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation of and development of EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore).
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy system, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport.
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis
- Clean Energy Outlooks: Analysis and Critical Review
- System Modelling for Clean Energy Technology Scenarios
- Overall Strategic Analysis of Clean Energy Technology Sector

More details are available on the CETO web pages

Acknowledgements

The authors would like to thank

- Teodor Kuzov (JRC.C.7) and Leonidas Mantzos (JRC.C) for their reviews and comments.
- Nigel Taylor (CETO project leader) for his support, review and comments.

The authors would like to thank the following colleagues for their valuable contribution to this report:

- Marcelina Grabowska and Olivier Eulaerts (JRC.I.3 TIM team) for the bibliometrics and R&I projects data.
- Lucia Mancini, Cynthia Latunussa, Umberto Eynard and David Pennington (JRC.D.3) for their contribution regarding the environmental sustainability of PV.
- Ugo Simeoni, Maider Machado, Daniel Maraver (CINEA) and Maria Getsiou (DG RTD) for the Innovation Fund and Horizon Europe data.
- Moritz Wegener, Marc Jaxa-Rozen, Raffaele Salvucci, Frederik Neuwahl, Przemyslaw Sikora, and Máté Rózsai for the POTEnCIA energy sytem modelling.
- Burkhard Schade, Kimon Keramidas, Florian Fosse, Paul Dowling, Peter Russ for the POLES-JRC energy system modelling.

The authors would like to acknowledge the valuable input received by the following experts:

- Johan Lindahl (European Solar Manufacturing Council - ESMC).
- Gaëtan Masson and Melodie de l’Epine (Becquerel Institute, IEA-PVPS Task 1).

Authors

Anatoli Chatzipanagi, Arnulf Jäger-Waldau, Simon Letout, Aikaterini Mountraki, Juan Gea Bermudez, Aliki Georgakaki, Ela Ince and Andreas Schmitz.

Executive Summary

Following the EU's commitment towards climate neutrality by 2050, the publication of the 6th Intergovernmental Panel on Climate Change (IPCC) Assessment Report in April 2022 combined with the geopolitical developments in 2022 and the COP28 agreement that fossil fuels are responsible for the climate change accentuated the urgent need of the clean energy transition. To this end, in 2022, the European Commission presented the REPowerEU and the EU Solar Energy Strategy with the aim of reducing net emissions by at least 55 % by 2030 and more than 500 GW_p additional increase of the photovoltaic capacity by 2030. Furthermore, it raised the share of renewable energy in the EU's overall energy consumption to 42.5 % by 2030 (with an additional 2.5 % indicative top up to allow the target of 45 % to be achieved) in order to reduce net emissions by at least 55 % by 2030 through the "Fit for 55" package. In addition, the recently proposed Net-Zero Industry Act aims to set the required environment to scale up manufacturing of net-zero industry in the EU and face up to the future demand. The target set is for 30 GW_p of European manufacturing along the entire value chain by 2025 and 40 % of installed solar PV being manufactured within the continent by 2030, with an additional specific target for an increased 15 % EU share of global production by 2040.

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 1.6 TW_p in 2023 and estimates for 2024 vary from a shrinking market to a significant increase to over 550 GW_p, which would bring the total cumulative installed PV capacity to over 2 TW_p. The EU alone reached a cumulative installed PV capacity 271 GW_p at the end of 2023 and a cumulative electricity generation of approx. 230 TWh from PV systems. The average PV module efficiency has increased from 9 % in 1980 to 14.7 % in 2010 and 21.8 % in 2023. Silicon-based photovoltaic technology remains the predominant technology (efficiency of 25 %) but research regarding performance, integration and sustainability is still essential. As far as thin-film technologies are concerned, they account for only 3 % of global production and 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 (module efficiency 19.2 %, record cell efficiency 25.2 %) manufacturing could quickly achieve comparable costs compared to current technologies. Multi-junction technology, silicon-based tandems with III-V top material (32.65 % module efficiency) together with perovskite-silicon tandem devices (25.8 % 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 % in 2034) by n-type Tunnel Oxide Passivated Contact (TOPCon) (23 % module efficiency with projections reaching 24 % in 2034) that will further increase efficiency. Bifacial modules are emerging in the market (increase of their 50 % market share in 2023 to 73 % in 2034). 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 agrivoltaics.

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 decreases are foreseen in the next years. The global weighted-average LCoE for utility-scale projects fell by 90 % between 2010 and 2023 from USD 417/MWh to USD 41/MWh. 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 Research & Innovation (R&I) funding in solar was approx. 30 % of the global public R&I funding solar in 2010 and grew to 56 % in 2022. The compound growth of public R&I funding on PV between 2012 and 2022 in the EU increased by 1 % whereas at a global level it decreased by 4 %. The EU's share in the global private Research & Development (R&D) funding in PV increased from 15 % in 2010 to 16 % in 2020. Both EU's and global private R&D funding in PV experienced a 23 % compound increase in the period 2010-2020. 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 United States (2nd) and the rest of the world (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 slightly more highly-cited (as are also publications from Switzerland and the United States).

From 2014, a total of approximately EUR 1.4 billion has been invested in three hundred and forty four PV projects through EU funding programmes. Half of the total budget was dedicated for projects on performance enhancement and cost reduction, whereas one fifth on projects related to diversified applications and integrations. In terms of technology, one fourth of the total budget was given to silicon heterojunction projects (of these EUR 344 million, 90 % was awarded to the Innovation Fund TANGO and HOPE projects) and 10 % to projects related to perovskite technology.

The Energy Payback Time (EPBT) of PV systems has experienced a 12.8 % decrease over the past 24 years. The 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 circular along the entire PV value chain.

EU's PV estimated turnover increased from EUR 9 billion in 2015 to EUR 41 billion in 2022. The compound growth between 2015 and 2022 is estimated to be 24 % with the top five Member States (Germany, the Netherlands, Spain, Italy and Poland) accounting for 70 % of the EU's turnover in 2022. Germany together with the US, Japan, China and South Korea host almost 70 % of identified innovators. The EU as a total hosts 19 % of innovators in the field of PV in 2022 (against 22 % in 2021). In particular, Germany holds the 4th position behind the US, China and Japan 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 have been 32 % in the period between 2020 and 2023. According to a medium scenario, jobs in 2028 are expected to more than double in the manufacturing sector compared to current levels. Jobs in the deployment and Operation & Maintenance (O&M) sectors are projected to increase by 20 % and 87 % respectively by 2028. Decommissioning and recycling-related jobs could increase by 89 % according to the same medium scenario. Finding the needed workforce will be challenging and the appropriate actions must be taken at an early phase (skilling, re-skilling, up-skilling, etc.). 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 2012 and 2023, the compound decrease in production value in the EU was 7 %, slightly recovering from the EUR 1 474 million of production in 2020 to reach EUR 2 143 million in 2023. China has a leading market in PV and exhibits small dependence on the EU as far as imports are concerned. Almost all leading solar cell and module production companies are Chinese and they dominate the PV module shipments. In 2023, China accounted for 87 % (from 65 % in 2015) of the global cell production and 82 % (from 69 % in 2015) of the global module production. The respective share for the EU was 0.3 % for cells and 0.9 % for modules. In addition to the above mentioned shares, it is essential to consider that manufacturing utilisation rates have decreased considerably in 2023. The most pronounced decreased occurred in the polysilicon segment (61 % in 2023 against 86 % in 2022 globally). More in particular, China changed its polysilicon utilisation rate from 91 % in 2022 to 61 % in 2023, while the EU decreased from 81 % in 2022 to 63 % in 2023. The global utilisation rate for cell manufacturing remained rather stable, around 60 %. The global module manufacturing utilisation rate in 2023 was 53 %, whereas the EU was 33 %. These utilisation rate decreases are the result of demand overestimation resulting into overproduction, mainly in China.

For 2023, the top five module manufacturing companies, include four Chinese and one Canadian company and they accounted for 50 % of the global module production. With regard to manufacturing capacities under construction, the EU is investing mostly in module capacities, accounting for 7 % of the global module capacities under construction and remains behind in the other segments. China's under construction capacities range between 60-96 % (depending on the segments) of the global total. China is expected to maintain its dominance in market share of global supply chains (80-95 % depending on the segment). Additionally, the costs for PV manufacturing in China are considerably lower than in other regions. According to a 2022 IEA report, costs in China are 10 % lower than in India, 30 % lower than in the United States, and 60 % lower than in Europe. The Agency draws attention to the possibility that these cost differences will increase to 70 % for India, 100 % for the United States and 140 % for the EU by 2028, despite the adopted policies aiming to strengthen their domestic manufacturing market. In the inverter market, in the recent years, SMA (Germany) and Power Electronics (Spain) have grown less than other companies from China and therefore did not maintain the considerable market share they enjoyed until 2020. Together, the above-mentioned European companies accounted for 14 % in 2018 to 7 % in 2022. SMA has decreased its 6 % share in global inverter manufacturing in 2021 to 3 % thereafter. In 2023, the top two companies, Huawei and Sungrow, with annual inverter productions of 160 GW_{AC} and 150 GW_{AC} respectively, accounted for half of the PV inverter production, whereas, the top ten for 82 %. The EU saw its market share in inverter manufacturing decrease from 23 % in 2019 to 6 % in 2023.

The EU as a total but also each member state (MS) individually exhibit a growing negative relative trade balance already since 2013. The EU's extra-EU imports have increased by 18 % between 2015 and 2023, while for the same period, its exports decreased by 14 %. In 2021-2023, China remained the main importing partner holding 94 % of total extra-EU imports in value, while the EU exported mainly to the United Kingdom, Switzerland and the United States.

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. However, taking into consideration the planned large-scale EU domestic PV manufacturing and the commitment to render EU competitive, raw materials supply may become crucially relevant in the short-term. 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.

Therefore, the increasing deployment of photovoltaic systems is crucial for the next years, both to reach the EGD targets and to allow the reduction of electricity generation costs.

Table 1. CETO SWOT analysis for the competitiveness of photovoltaics.

Strengths	**Weaknesses**
– The EU is a technology leader in polysilicon as well as certain manufacturing equipment. – The EU has advanced and highly automated manufacturing techniques. – Strong EU support (under REPowerEU policy) and global markets. – Strong R&I activities regarding new materials (e.g. perovskites) and applications. – Low carbon footprint for EU sourced and produced PV modules.	– Energy and labour costs in the EU are significantly higher than for trading partners. – Planning procedures and permitting is too long, which increases costs. – Financing is a major issue to build PV production plants along the value chain. – Limited acceptance of low profit margins in value chain parts of PV manufacturing. – Shortage of skilled workers in case of strong growth of manufacturing and deployment in the EU. – Negative trade balance for the EU, particularly with China. – The limited support schemes for manufacturing do not follow the global market growth. – The EU has decreased its share in global inventions.
Opportunities	**Threats**
– The EU has several world-leading R&D clusters for silicon PV and thin film technologies. – PV manufacturing in the EU could be competitive under the condition that: i) it is done in large gigawatt-scale factories (economy of scale) and ii) these factories are fully integrated across all stages of the value chain (ingot, wafer, cell and module) and highly automated. – Creation of green jobs in both the manufacturing and the deployment sectors. – High automation in manufacturing will decrease labour costs.	– The economic availability of critical raw materials used in current module designs may be a limitation. – The concentration of large share parts of the supply chain in one country poses a risk for the security of supply and resilience of the industry. – More direct and targeted support schemes for manufacturing are being applied in the US (IRA) and India (PLI).

Source: JRC 2024

1 Introduction

1.1 Scope and context

This report on photovoltaic (PV) energy is part of the annual series reports from the Clean Energy Technology Observatory (CETO) (European Commission, 2023a). It address technology maturity status, development and trends; value chain analysis and global market and European Union (EU) positioning, and builds on previous European Commission studies in this field (Chatzipanagi, Jaeger-Waldau, *et al.*, 2022; Chatzipanagi, Jaeger-Waldau, Cleret De Langavant, *et al.*, 2023).

Over the past decade, photovoltaics has become a mature technology and the fastest-growing source of electricity production from renewable energies. It 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 publication of the 6th Intergovernmental Panel on Climate Change (IPCC) Assessment Report in April 2022 (IPCC, 2022) and the geopolitical developments in 2022 have highlighted the urgency of the clean energy transition. At the end of 2023, the Conference of the Parties (COP28) acknowledged officially for the first time that fossil fuels are responsible for climate change and over 100 countries agreed to triple renewable energy capacity and double the global rate of energy efficiency by 2030 (World Economic Forum, 2023). The geopolitical developments in 2022 forced the European Commission to react with the REPowerEU Communication (European Commission, 2022b) and the EU Solar Strategy Communication (European Commission, 2022a) in March and May 2022 respectively. REPowerEU aims to reduce net emissions by at least 55 % by 2030 and the EU Solar Strategy called for an additional photovoltaic capacity of over 500 GW_p between 2021 and 2030, which would mean a roughly fourfold increase of the nominal capacity to over 720 GW_p by 2030. As an intermediate step towards climate neutrality (European Green Deal) by 2050, in December 2020, the European leaders endorsed the Commission's proposed target to reduce net emissions by at least 55 % by 2030. Within the framework of the "Fit for 55" package (European Commission, 2022e) of EU legislative measures, in October 2023 the Council adopted the new Renewables Energy Directive (RED) to raise the share of renewable energy in the EU's overall energy consumption to 42.5 % by 2030 with an additional 2.5 % indicative top up to allow the target of 45 % to be achieved (European Council, 2023).

Furthermore, the recently proposed Net-Zero Industry Act aims to set the required environment to scale up manufacturing of net-zero industry in the EU. One of the identified strategic net-zero technologies is PV. A simplification of the regulatory framework (permitting) for the PV manufacturing and a skills development support are among the actions included in the Act that will help increase the EU PV competitiveness. The target is set so that by 2030, manufacturing capacity of the strategic net-zero technologies (as defined in the NZIA) in the EU approaches or reaches a benchmark of at least 40 % of the EU's annual deployment needs for the corresponding technologies necessary to achieve the EU's 2030 climate and energy targets and holds a 15 % EU share of global production by 2040 (European Commission, 2023b)(Council of the EU, 2024). In addition, the European Commission endorsed the creation of the European Solar PV Industry Alliance (ESIA) (European Commission, 2023d) that will support the above-mentioned objectives and policies that will result in scaling-up and speeding-up the production of renewable energy in Europe with the aim of regaining its independence from Russian fossil fuels, and making its energy system more resilient. The ESIA aims to expand EU's manufacturing to at least 30 GW_p across the full supply chain by 2030 (European Commission, 2023b, 2023d). Furthermore, in an attempt to support the EU photovoltaic sector, the European Solar Charter was signed in April 2024. The European Solar Charter sets out immediate actions to be taken by the Commission, EU Member States and the representatives of the solar PV value chain, in particular wholesale, distribution and manufacturing parts, to be implemented ensuring full compliance with EU competition law and state aid rules (European Commission, 2024b).

Despite the moderate increase of 13 % in PV investments compared to 2022, the new installed capacity increased by more than two thirds to 422 GW_p and exceeded 1.6 TW_p (mainly from utility scale plants). This is almost towards the upper side between the conservative (360 GW_p) and optimistic forecasts (448 GW_p) (Jäger-

Waldau, 2024). Market forecasts for 2024 vary from a shrinking market to a significant increase to over 550 GW_p, which would bring the total cumulative installed PV capacity to over 2 TW_p (Jäger-Waldau, 2024).

The EU photovoltaic market grew again by over a third to more than 56 GW_p in 2023 and could reach 100 GW_p per annum in 2030 if the current market trend continues. With this trend, EU Solar Energy Strategy's target of achieving a nominal capacity of over 720 GW_p (600 GW_{AC}) by 2030 will be exceeded (Jäger-Waldau, 2024).

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 and Annex 1 provides a summary of the indicators for each aspect, together with the main data sources.

2 Technology status and development trends

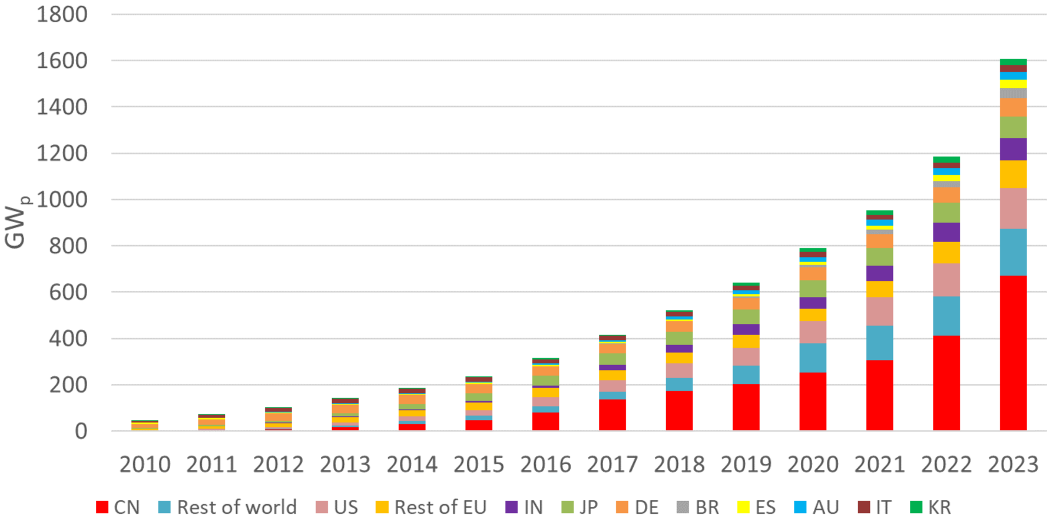
2.1 Technology readiness level

The global compound annual growth rate (CAGR) of PV installations was 28 % in the period 2013 to 2023. In 2023, overall investments in renewable energy have increased by 8 % to USD 623 billion (Bloomberg New Energy Finance, 2024c). In the same year, investments in photovoltaics reached USD 385.5 billion (increase of 13 % compared to 2022) or 62 % of the renewable energy investments.

New PV capacity increased by 36 % to over 422 GW_p in 2022, which is at the upper side between the conservative (360 GW_p) and optimistic forecasts (448 GW_p) (WoodMackenzie, 2023; Bloomberg New Energy Finance, 2024a). For 2024, market forecasts vary considerably from a shrinking market to a significant increase that may enable a cumulative installed capacity of over 2 TW_p (Jäger-Waldau, 2024). SolarPower Europe projects between 3 % (461 GW_p) and 45 % (647 GW_p) annual growth for 2024 (SolarPower Europe, 2024b).

In 2023, China had a cumulative installed capacity of more than 670 GW_p, representing 42 % of the total global 1 607 GW_p installed PV capacity. The European Union follows with about 18 % or 271 GW_p and the United States with 175 GW_p (12 %) (Figure 1). At the end of 2022, 29 countries globally and 14 in the EU installed more than 1 GW_p (IEA PVPS, 2024a).

Figure 1. Global cumulative photovoltaic installations for the period 2010-2023.



Source: (Jäger-Waldau, 2024)

The EU is a leading installer of PV per capita with 601 W_p/capita on average (from 475 W_p/capita in 2022), having seven EU Member States in the first 10 countries in this ranking (SolarPower Europe, 2023d, 2023a; Jäger-Waldau, 2024). In 2023, Australia was surpassed by Netherlands that had the highest capacity per capita (1 371W_p/capita). Australia and Denmark followed with 1 343 W_p/capita and 979 W_p/capita respectively, leaving Germany in the fourth position with 967 W_p/capita (Jäger-Waldau, 2024). The world average in 2023 was 201 W_p/capita (from 148 W_p/capita in 2022).

This growth is due to the decreasing cost of the PV modules and systems (EUR/W_p), 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 24.4 % for each doubling of cumulative global module production in the last 43 years (Fraunhofer ISE, 2024). In Germany, at the end of 2023 the price for a typical 10 to 100kW_p PV rooftop system is only 10 % of the price in 1990 (Fraunhofer ISE, 2024).

2.1.1 Photovoltaic (PV) module technologies

According to the International Technology Roadmap for Photovoltaic (ITRPV) 15th edition (VDMA, 2024), the yearly learning for module efficiency for the past 12 years is presented in Table 2.

Table 2. Yearly average module efficiencies for the period 2013-2023.

Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Aver. module efficiency [%]	16.0	16.3	17.0	17.5	17.7	18.4	19.2	20.0	20.9	21.2	21.8

Source: (VDMA, 2024)

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, 2024).

Crystalline silicon

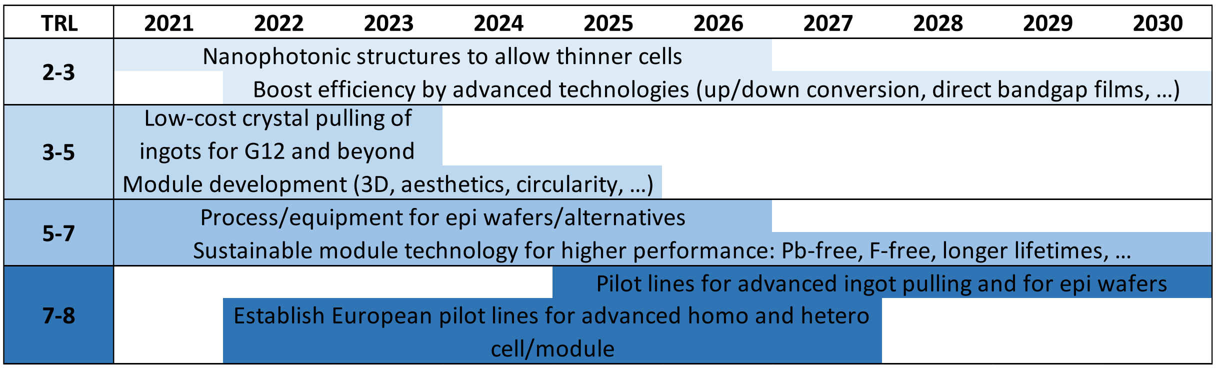
The crystalline silicon technology accounts for 97 % of global PV module production (Fraunhofer ISE, 2024; Jäger-Waldau, 2024). Of these, monocrystalline (mono c-Si) modules almost monopolise the crystalline market as polycrystalline (poly c-Si) modules have reduced their market share considerably, practically almost disappearing from the market (VDMA, 2024). The record efficiency of c-Si cells is 26.1 % (ISFH, p-type TBC) (Green *et al.*, 2024), whereas the efficiency of the modules is 24.9 % (Maxeon (112 cells)) (Green *et al.*, 2024). The efficiency of average commercial wafer-based silicon modules increased from 16 % to over 22 % over the last 10 years (Fraunhofer ISE, 2024). The silicon heterojunction (HJT) technology (crystalline silicon/amorphous silicon) has demonstrated a record cell efficiency of 26.8 % (LONGI, n-type HJT) (Green *et al.*, 2024).

The European Strategic Research and Innovation Agenda for PV (SRIA) (SNETP, 2022) identifies that further R&D support in the EU in the field of silicon PV technology is needed and it should aim at the ultimate objective of 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[1]).

The technology targets and research priorities for silicon PV modules as they were identified in SRIA (SNETP, 2022) are presented in Figure 2.

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



TRL	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
2-3	Nanophotonic structures to allow thinner cells									
		Boost efficiency by advanced technologies (up/down conversion, direct bandgap films, …)								
3-5	Low-cost crystal pulling of ingots for G12 and beyond									
	Module development (3D, aesthetics, circularity, …)									
5-7	Process/equipment for epi wafers/alternatives									
	Sustainable module technology for higher performance: Pb-free, F-free, longer lifetimes, …									
7-8					Pilot lines for advanced ingot pulling and for epi wafers					
		Establish European pilot lines for advanced homo and hetero cell/module								

Source: (SNETP, 2022)

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

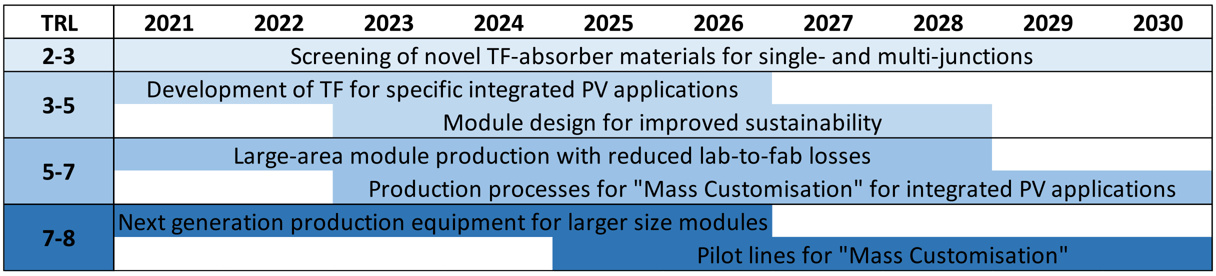
Thin-film

The thin-film share of global production is only 3 % corresponding to approx. 15 GW_p of the total PV module global production. The vast majority of these are CdTe and only a minor part CIGS and amorphous silicon (Fraunhofer ISE, 2024). The record cell efficiencies of CdTe and CIGS are 22.6 % (First Solar) and 23.6 % (Evolar/Uppsala) respectively and for the modules, CdTe modules exhibit an efficiency of 19.9 % (First Solar) and CIGS 19.2 % (Solar Frontier (70 cells)) (Green *et al.*, 2024). The CdTe module efficiency has increased from 9 % to 20 % in the last 10 years (Fraunhofer ISE, 2024).

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 United States. 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, 2022) are presented in Figure 3.

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



TRL	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
2-3	Screening of novel TF-absorber materials for single- and multi-junctions									
3-5	Development of TF for specific integrated PV applications									
			Module design for improved sustainability							
5-7	Large-area module production with reduced lab-to-fab losses									
			Production processes for "Mass Customisation" for integrated PV applications							
7-8	Next generation production equipment for larger size modules									
					Pilot lines for "Mass Customisation"					

Source: (SNETP, 2022)

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 25.2 ± 0.8 % (NUS/SERIS) in 2024 whereas the perovskite module record efficiency is 19.2 % (SolaEon) (Green *et al.*, 2024). It is expected that module efficiencies will be comparable to current existing PV technologies within the next 5 years.

The EU has strong expertise in perovskite PV modules. At the moment, several companies are starting pilot lines of production with plans to proceed to production at large scale. In the EU, the announcements towards the production of perovskites at commercial scale include Evolar[2] (Sweden) which plans to scale its processes in its prototype line in Sweden and bring its technology to the market in the short-term. Holosolis (France) plans to build a state-of-the-art module gigafactory in France and production is expected to start in 2025. Saule Technologies (Poland) is also working on a large-scale, prototype production line while Voltec Solar (France) plans to have a first 200 MW production in 2025, increasing to 1 GW in 2027 and 5 GW by 2030 (Perovskite-info, 2023c).

Other European players in the field of perovskites are Aerosolar (United Kingdom), Enel Green Power (Italy), Power Roll (United Kingdom), Solertix (Italy) and Solliance (Netherlands). Oxford PV (United Kingdom) has a research and development site as well as a pilot and production line in Germany and aims to accelerate its technology into industrial-scale perovskite-on-silicon tandem solar cell manufacturing. Perovskia (Switzerland) wants to also commercialise perovskite solar cell technology. In January 2024, Perovskia announced its intention to set up a factory for solar cell manufacturing (Perovskite-info, 2023c).

As far as the global competitors in perovskite technology are concerned, in China there have been several announcements of companies planning to commercialise perovskite technology in the next few years. Some of these companies are: Hiking PV, Huasun Energy, Mellow Energy / Vein Energy, Microquanta Semiconductor, Wuxi Utmost Light Technology (UtmoLight), Xi'an Tianjiao New Energy, Phenosolar and RenShine Solar. In the United

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[2] Acquired by First Solar (United States) in May 2023.

States, Caelux, Energy America and Halldata Solar are proceeding to commercialisation of perovskites (Perovskite-info, 2023c).

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, 2022) are presented in Figure 4.

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

<table>
<tr><th>TRL</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th><th>2030</th></tr>
<tr><td rowspan="2">2-3</td><td colspan="5">Pb-free TF PV absorbers</td><td colspan="5">Recycling strategies for Pk</td></tr>
<tr><td colspan="6">Low-cost highly performant transparent electrodes</td><td colspan="4"></td></tr>
<tr><td>3-5</td><td colspan="6">Module manufacturing</td><td colspan="4"></td></tr>
<tr><td>5-7</td><td colspan="10">Demonstrate at pilot level Pk modules on glass and on foils for various applications</td></tr>
<tr><td>7-8</td><td colspan="2"></td><td colspan="7">Establish EU pilot lines for Pk modules on glass and on foils</td><td></td></tr>
</table>

Source: (SNETP, 2022)

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 38.8 % for a 5 junction cell (NREL, Spectrolab, 2-terminal, (2.17/1.68/1.40/1.06/.73 eV)) and 32.65 ± 0.7 % for a module (Sharp, 40 cells; 8 series, InGaP/GaAs/InGaAs) (Green *et al.*, 2024).

In particular, perovskite-silicon tandem devices reach high efficiencies and benefit from lower manufacturing costs as well. The perovskite/silicon tandem cell design has a record efficiency of 34.6 % (LONGI, 2-terminal) (PV Magazine, 2024a), while the record efficiency for modules is 25.8 % (LONGI, 4-terminal) (Green *et al.*, 2024).

According to SRIA, Si based tandem technologies should reach a market share of approx. 5 % in 2028 while successfully transitioning from niche to mass market applications by 2034 (VDMA, 2024). The technology targets and research priorities for multi-junction PV modules as they were identified in SRIA (SNETP, 2022) are presented in Figure 5.

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

<table>
<tr><th>TRL</th><th>2021</th><th>2022</th><th>2023</th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th><th>2030</th></tr>
<tr><td>2-3</td><td colspan="10"></td></tr>
<tr><td rowspan="2">3-5</td><td colspan="4">Stable high-quality recombination layers and charge-selective layers</td><td colspan="6"></td></tr>
<tr><td></td><td colspan="5">Improved module concepts for 3T and 4T</td><td colspan="4"></td></tr>
<tr><td rowspan="2">5-7</td><td colspan="6">High-throughput processing up to module level</td><td colspan="4"></td></tr>
<tr><td></td><td colspan="7">Bifacial multijunction devices</td><td colspan="2"></td></tr>
<tr><td>7-8</td><td colspan="2"></td><td colspan="8">Establish European pilot lines for various tandem technologies and applications</td></tr>
</table>

Source: (SNETP, 2022)

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. Silicon heterojunctions (HJT) and Tunnel Oxide Passivated Contact (TOPCon) modules can reach considerably higher bifaciality[4] than p-type Passivated Emitter and Rear Contact (PERC). Bifacial technology is expected to increase its market share from 63 % today to over 70 % in the next ten years (VDMA, 2024). Rear contact of modules represent another major advance (Wilson *et al.*, 2020). With PERC modules being near their upper-efficiency limit (currently 21.6 % efficiency with projections reaching 22 % in 2034), the industry is investing in n-type technology with major

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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.

manufacturers switching to TOPCon (currently 22.8 % efficiency with projections reaching 24 % in 2034) and HJT technologies (currently 23 % efficiency with projections reaching 24.3 % in 2034) (VDMA, 2024). Silicon based tandem cells and modules (with efficiencies over 27 %) will start mass production after 2027 and their expected efficiency will reach 30 % in 2034 (VDMA, 2024). The n-type TOPCon manufacturing capacity increased considerably in past few years, becoming already dominant in 2024 with projections suggesting a market share of 45-55 % by 2034 (VDMA, 2024). HJT technology (current market share of 7 %) will increase its market share to 20 % in 2034. Silicon based tandem will uptake between 10 % and 20 % of market share by 2034 and back contact (p and n-type) will represent 15-20 % of the market (VDMA, 2024). PERC technology with a market share of 65-70 % in 2023, will lose its dominance already in 2024 and is expected to eventually disappear from the market between 2023 and 2032 (VDMA, 2024).

Lifetime and reliability of PV modules needs to be guaranteed. These aspects are especially crucial for highly promising new technologies like perovskites-based PV that offer great opportunities. In order to understand the performance and reliability of these new materials, testing procedures and standards have to be adjusted to new module technologies or reflect new degradation modes (SNETP, 2022).

2.1.2 Established and emerging innovative PV deployment applications

In March and May 2022, the European Commission published the REPowerEU Communication and the EU Solar Strategy Communication respectively (European Commission, 2022b, 2022a). As part of the REPowerEU package (aiming for a reduction of net emissions by at least 55 % by 2030), the EU Solar Strategy called for an additional photovoltaic capacity of over 500 GW_p between 2021 and 2030, which would mean a roughly fourfold increase of the nominal capacity to over 720 GW_p by 2030. To achieve the above-mentioned target, extended deployment will be needed and the European Commission has identified innovative forms of PV deployment that can contribute to the mitigation of land constraints linked to competition for space. These are agrivoltaics, floating photovoltaics, infrastructure integrated photovoltaics and vehicle integrated photovoltaics. The European Commission has also committed to provide guidelines to the Member States regarding these innovative forms of PV deployment. The innovative forms mentioned above, together with the well-known application of building integrated photovoltaics are alternative solutions for PV deployment that minimise land competition.

In 2023, building integrated photovoltaics, floating photovoltaics and agrivoltaics accounted for only 5 % globally. The 2024 International Technology Roadmap for Photovoltaic projects a notable increase of market share to 20 % for these applications in 2034. More in particular, building integrated photovoltaics and floating photovoltaics will reach a 5 % applications market share each and agrivoltaics a 10 % market share (VDMA, 2024).

Agrivoltaics

Agrivoltaics consists in the simultaneous use of areas of land for both solar photovoltaic power generation and agriculture. Agrivoltaics interacts with a range of policies related to clean energy, energy transition, sustainable agriculture, food security, biodiversity, rural development and research & innovation, all of which underpin the goals of the European Green Deal (EGD) (Chatzipanagi, Taylor, *et al.*, 2022).

The potential of agrivoltaics in the EU is significant. A coverage of only 1 % of Utilised Agricultural Area (UAA) with agrivoltaic systems translates into roughly 944 GW_p (assuming an installed capacity per land area of 0.6 MW_p/ha), which is half of the amount that can be achieved by traditional ground-mounted PV systems (around 1 809 GW_p). The potential 944 GW_p of agrivoltaic systems are approximately 5 times more than the EU installed capacity in 2022 and the electricity generated would cover roughly 40 % of the EU's total electricity consumption in 2022.

One of the main challenges for agrivoltaics is related to the absence of a clear and EU-harmonised definition, which could lead to land characterisation changes when agrivoltaics systems are installed on agricultural land. This change could have an impact on the eligibility to agricultural subsidies. In fact, in several cases, the land is excluded from the Common Agricultural Policy subsidies. Many Member States are general in their plans regarding the support for investments in renewable energy. Support for agrivoltaics is not directly mentioned in most of the Member States' CAP Strategic Plans and only a few have included it explicitly in their plans (without defining specific targets and/or providing dedicated financial support). Technical challenges as well as challenges regarding the permitting and grid connection procedures have also been identified. In addition, there has been an increase in land prices impacting the welfare and security of the farmers. Finally, regardless of the technological advancements, there are still technical challenges that need to be addressed in order to maximise the electricity production while taking into consideration the biodiversity and without compromising significantly the crop yield. The economic benefit and the security of property as well as investments for the farmer must be at the centre of the efforts to promote agrivoltaics and public awareness and acceptance (Chatzipanagi, Taylor and Jaeger-Waldau, 2023).

Agrivoltaic applications stand between TRL 3 and 8, depending on the agricultural context. Further studies regarding the crop suitability identification and implementation of water management optimisation will substantially contribute to the application's development (SNETP, 2022).

Building integrated photovoltaics

Building integrated photovoltaics is a known and well established PV application for many years now. It consists in the replacement of conventional building materials with materials incorporating PV technologies so as to have a double function, acting like an energy producing building component. The generated electricity is consumed close to where it is produced, thus excluding potential grid investments.

According to a recent study, when considering a building skin to building net surface area ratio of 0.78 and a building skin glazing ratio of 30 %, buildings could cover their electricity consumption using building integrated photovoltaics systems by 2030 in the EU (Gholami, Nils Røstvik and Steemers, 2021). There are 4 key initiatives to tackle barriers for building integrated photovoltaics. These are through the review of the Renewable Energy Directive II (RED II) (European Commission, 2018a) and the Energy Performance of Buildings Directive (EPBD) (European Commission, 2018b), the launch of the New European Bauhaus initiative (European Commission, 2020b) and last but not least, the revision of the Construction Products Regulation (European Commission, 2022g).

Building integrated photovoltaics applications are characterised by high TRLs. The challenge for the building integrated photovoltaics sector lays in the lack of solutions of scale, the research regarding the technological aspects for the multi-functionality of building integrated photovoltaics products and the absence of regulation harmonisation between PV and building regulations. The full upscaling of the building integrated photovoltaics market requires actions related to PV module and Balance of System (BoS) technology development, business models, design and energy integration (TRL 4-8) as well as clarity regarding PV in building regulations at regional, national and EU level in order to avoid fragmentation (TRL 8-9) (SNETP, 2022). As far as building integrated photovoltaics product manufacturing is concerned, flexibility and automation will contribute to more cost competitive applications with significantly reduced Pay Back Times (PBT).

Floating photovoltaics

Floating photovoltaics consists in the deployment of PV modules on water surfaces. The most common surfaces envisaged for this application are man-made water surfaces such as irrigation dams, industrial basins, water treatment plants or hydropower reservoirs. Floating photovoltaics has also been deployed on natural waters like lakes and offshore sea locations (mostly at low wave categories). This PV application takes advantage of the cooling effect coming from the water beneath the PV modules and the easy installation while contributing to water evaporation and algae growth reduction. The current installed capacity in Europe is close to 0.5 GW_p, while global installations have reached 2 GW_p.

When coupled with hydropower (or installed on dam surfaces) or wind energy, floating photovoltaics can exploit the already established grid connection in addition to the multiple benefits mentioned before. The coverage of only 10 % of the EU's reservoir (*i.e.* man-made) area can generate close 140 TWh per year, which corresponds to approx. 7 % of the EU's total electricity consumption in 2022 (Kakoulaki, Gonzalez Sanchez, *et al.*, 2023).

The challenges floating photovoltaics are facing are mostly technological and related to the optimisation of the system design for low wave categories (TRL 6-8 for wave categories 1-2), the feasibility of floating photovoltaics systems for high wave categories (TRL 3-4 for wave category 3-4) and lifetime and reliability aspects (SNETP, 2022). As for agrivoltaics, taking into consideration the environment, biodiversity and water preservation policies is of major importance.

Infrastructure integrated photovoltaics

Infrastructure integrated photovoltaics is the integration of PV in elements of infrastructure like noise or crash barriers in roads and highways, road pavements, dikes, landfills, flyovers, road roofing and parking lots. The infrastructure element in these applications, in addition to its main functionality (like noise or crash protection), incorporates PV modules for the simultaneous generation of electricity. The most common infrastructure applications are on noise barriers and landfills.

Research on PV on transport infrastructure (roads and railways) has shown that the potential installed capacity in the EU is 401 GW_p, translated into 280 TWh – 391 TWh per year depending on the PV technology employed (monofacial vs. bifacial PV modules). The above-mentioned electricity generations cover between 11 % and 16 % of the EU's total electricity consumption in 2022 (Kakoulaki, Fahl, *et al.*, 2023). As far as closed landfills are concerned, the potential for EU can reach 13 GW_p (Szabó *et al.*, 2017). In Netherlands, the potential installation capacity on dikes has been identified to be 11 GW_p (TNO, 2023).

Depending on the specific application, TRLs vary between 6-7 for landfills, road roofing and noise barriers to 4-5 for crash barriers and dikes. Infrastructure integrated photovoltaics is set to ramp-up when the designed integrated solutions become more mature in terms of performance and safety, as well as cost effective (SNETP, 2022).

Vehicle integrated photovoltaics

The reduction of PV costs and higher penetration of EV are the main driving forces behind vehicle integrated photovoltaics developments. However, this application can have several variations depending on the (i) type of vehicles (light-duty, heavy-duty, camper, etc.), (ii) use of energy (for extended range, refrigeration, etc.), (iii) PV technology (Si, III-V, organic, etc.).

Apart from the above-mentioned parameters, also the climatic conditions play a significant role in vehicle integrated photovoltaics. A recent publication performed on a commuter car and a light delivery van, even though it does not take into account shading, suggests that the average annual solar range (mileage) of a photovoltaic electric vehicle with 454 W_p vehicle integrated photovoltaics can amount between 12 % (worst climatic conditions for PV) and 35 % (best climatic conditions for PV). The respective range for a delivery van with 649 W_p vehicle integrated photovoltaics, is between 9 % and 23 % (considering a 51 % higher annual mileage versus the car driving pattern) (Thiel *et al.*, 2022).

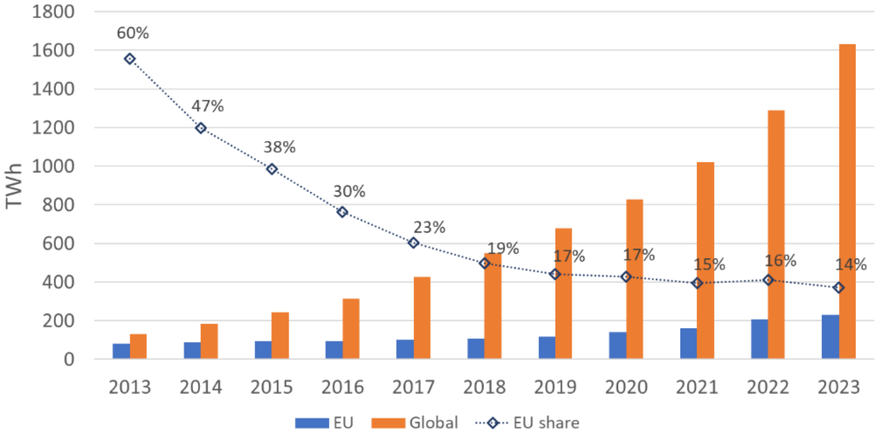
Some of the challenges that vehicle integrated photovoltaics is facing are related to technological parameters like shading of the PV modules while the vehicle is moving, safety requirements, electro-magnetic compatibility and recyclability but also to manufacturing and demonstration of the application's cost competitiveness and sustainability (SNETP, 2022). The Strategic Research and Innovation Agenda on Photovoltaics reports expected TRL between 6 and 8 by 2025.

2.2 Installed Capacity and Production

Proper and straightforward comparisons are not possible as there are several factors (IEA PVPS, 2024a; Jäger-Waldau, 2024) impacting these statistics (Box 1).

As depicted in Figure 6, the global cumulative solar electricity production (mainly from PV) increased from 132 TWh in 2013 to 1 630 TWh in 2023 (Wiatros-Motyka *et al.*, 2024), presenting a compound annual growth rate (CAGR) of 29 %. The EU generated approximately 79 TWh from PV in 2013, corresponding to a share of 60 % of the global PV electricity production.

Figure 6. Global and EU cumulative PV electricity production with EU share for the period 2013-2023.



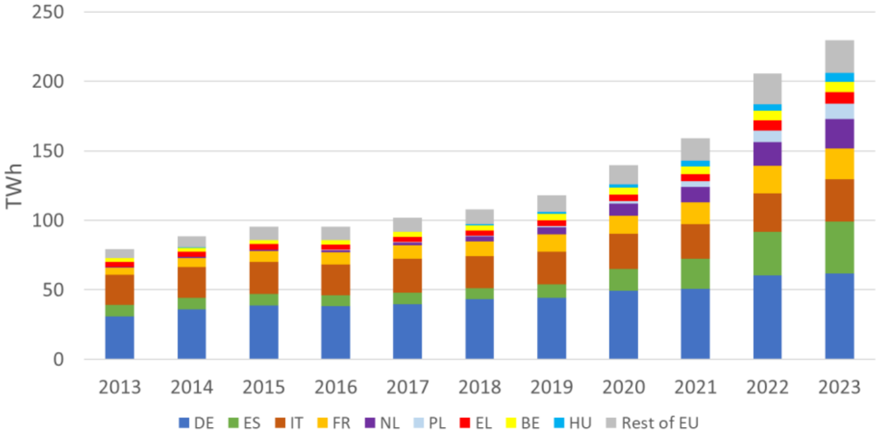
Source: JRC analysis based on Eurostat, IRENA and Ember

From 2013 to 2023, the EU's share decreased gradually to 14 % of the global cumulative PV electricity production, with a cumulative EU PV electricity production of 229 TWh in 2023 (provisional data). China, on the other hand, increased its share in global PV electricity production from 6 % in 2013 (8.4 TWh) to 36 % (584 TWh) in 2023.

Three-quarters of the EU's cumulative PV electricity in 2023 was produced in only five of the twenty-seven countries. These are Germany, Spain, Italy, France and the Netherlands (Figure 7). The same countries, in 2013 produced 84 % of the EU's cumulative PV electricity. The countries with the highest CAGR between 2013 and 2023 are Poland and Hungary. The Member State (MS) and world countries coding can be found in Annex 2.

The share of solar electricity generation in the EU's electricity mix increased from 2.9 % in 2013 to 9.2 % in 2023. The respective percentage for the world increased from 0.6 % to 5.4 % (EMBER, 2024b). The EU country with the highest share of solar electricity generation is Luxembourg (24.5 % in 2023), whereas the countries with the highest increase of solar electricity generation between 2020 and 2023 are Ireland, Poland and Lithuania.

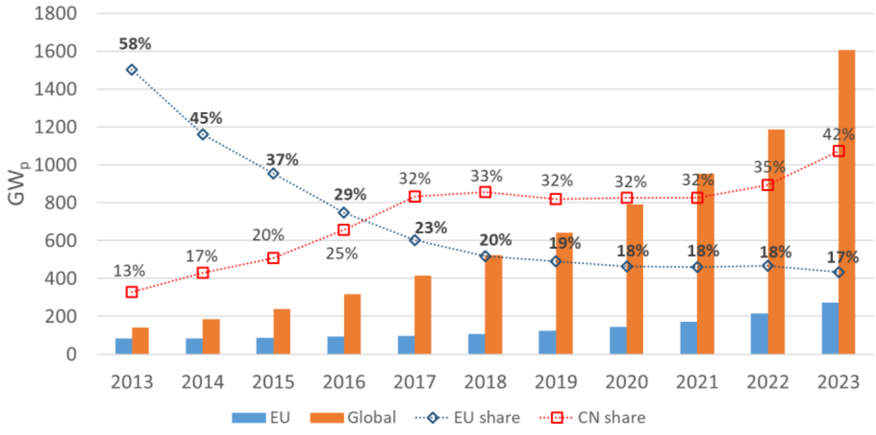
Figure 7. EU PV cumulative electricity generation per country for the period 2013-2023.



Source: JRC analysis based on Eurostat

Regarding the cumulative PV installed capacity[5], the EU had installed 82 $\mathrm{GW_p}$ in 2013, which grew to 271 $\mathrm{GW_p}$ in 2023, while globally 141 $\mathrm{GW_p}$ and 1 607 $\mathrm{GW_p}$ had been installed in these respective years (IEA PVPS, 2024b). The vast majority of the installed PV capacity (99.6 %) is connected to the grid (Fraunhofer ISE, 2024). The EU's share in global PV installed capacity decreased from 58 % in 2013 to 17 % in 2023 (Figure 8). China increased its share from only 13 % in 2013 to 42 % in 2023. EU's and China's CAGR between 2013 and 2023 are 12 % and 28 % respectively. In 2023, approx. 45 % of new capacity installation globally was on rooftops (IEA PVPS, 2024a). The estimated PV installed capacity in 2023 is 1 600 $\mathrm{GW_p}$ (Jäger-Waldau, 2024).

Figure 8. Cumulative global and EU PV installed capacity with EU and China shares for the period 2013-2023.



Source: JRC analysis based on (IEA PVPS, 2024a, 2024b; Jäger-Waldau, 2024)

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[5] Refers to the current actual operational installed capacity, without considering decommissioning. In the future, as decommissioning of PV plants will grow, a distinction will be necessary when referring to cumulative capacity.

Box 1. Uncertainty in reported capacity numbers.

- Not all countries report standard nominal power capacity for solar PV systems (DC or W_p under standard test conditions), but rather report the inverter or electrical connection capacity, which is in AC. Over the last decade the so called “overpowering”, i.e. when the DC capacity is larger than the AC capacity, has increased from 1.1 to almost 2. In 2022 constructed larger PV plants have a DC/AC ratio of 1.1 to 1.6, which means that the nominal capacity can be 10 to 60 % higher than the reported AC capacity. Overpowering of PV systems leads to a longer utilisation of the full connection capacity and can be cheaper than the installation of electricity stabilisers to maintain steady supply at the required power.

  Looking at energy scenarios, energy modellers are only interested in AC capacity, since the electricity network is AC. Therefore, significant differences can exist in the actual needed nominal power of PV systems, which determines the number of modules needed, and the modelled network capacity.

  The reported capacity numbers of PV installations in this chapter are given in nominal DC power or W_p. Where national statistics report capacities in AC, a conversion factor based on industry information and project descriptions is used.

  In 2022, China changed its national reporting system from nominal capacity to AC capacity. This created some difficulties to convert the reported capacity of 51 GW_{AC} residential/commercial systems and 36.1 GW_{AC} large scale systems to GW_p. Under the assumption that residential and commercial systems have no overpowered capacity, this would give a value of 51 GW_p for the residential/commercial systems. Under the assumption of an average overpowering ratio of 1.3 (an average between lower and higher overpowering) results in 47 GW_p for large scale systems. The total then is 98 GW_p.

- 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_p 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.

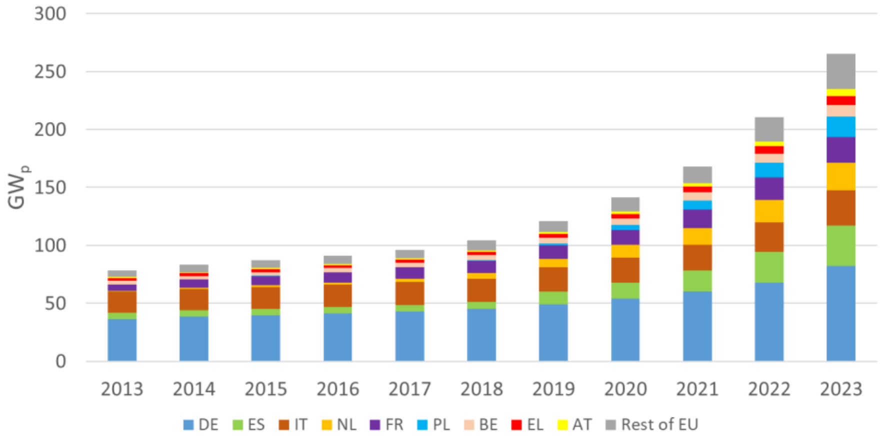
Figure 9 shows the evolution of the EU’s cumulative PV installed capacity from 2013 until 2023 per country. The countries contributing less to the EU installed capacity are shown as rest of EU. Germany, Spain, Italy, the Netherlands and France installed 71 % of the total EU installed capacity in 2023 from 84 % in 2013. Germany was the country with the highest installation in 2013, accounting for almost half of the EU’s PV installation. In 2023, Germany accounted for 30 %. Also Italy’s share decrease from 23 % in 2013 to 11 % in 2023 as more EU countries have entered the PV installations market in the recent years.

In 2023, rooftop PV installations accounted for two-thirds of the EU’s total systems, leaving the remaining 35 % for utility-scale PV (IEA PVPS, 2024b). According to SolarPower Europe (SPE), in 2027 rooftop applications will decrease to 56 % and utility-scale will increase to 44 % (SolarPower Europe, 2023a). At global level, in 2023 rooftop accounted for 41-45 % of the installed capacity whereas utility-scale PV for the remaining 55-59 % depending on the source of information (IEA PVPS, 2024b; SolarPower Europe, 2024b). For 2028, it is projected that rooftop and utility system shares will be 41 % and 59 % respectively (SolarPower Europe, 2024b).

According to SPE’s low and high scenarios, the cumulative PV installed capacity in the EU in 2027 will be between 471 GW_p and 702 GW_p , with a medium projection of 576 GW_p (SolarPower Europe, 2023a). In 2030 according to the medium scenario (which is also the most probable to occur), the PV capacity could reach

890 GW_p, well over the target set in REPowerEU (SolarPower Europe, 2024b). BloombergNEF in its short-term solar forecast projects around 380 GW_p by 2025 and between 650 and 765 GW_p by 2030 (Bloomberg New Energy Finance, 2024d). Others project an installed capacity of 625 GW_{AC} by 2030 (EurObserv'ER, 2024b). More ambitious projections for 2050 report 7-8.8 TW_p of PV installed capacity and 10-12 TWh of PV electricity production (Manish *et al.*, 2020).

Figure 9. EU PV cumulative installed capacity per country for the period 2013-2023.



Source: JRC analysis based on (IEA PVPS, 2024a, 2024b)

Projections until 2030

For the global PV installed capacity, the IEA foresees 2.4 TW_p for 2025 for the main case scenario and 2.5 TW_p for the accelerated scenario (IEA, 2024b). SPE projects 2.8 TW_p to be installed globally in 2025 (SolarPower Europe, 2024b). For 2028, the IEA projects between 3.8 TW_p and 4.3 TW_p (main case and accelerated scenario) (IEA, 2024b), while SPE is more optimistic with 5.1 TW_p and almost 6 TW_p (SolarPower Europe, 2024b). BloombergNEF's projections for global PV installations suggest a more rapid growth of 2.9 TW_p already in 2025, arriving to 6.8 TW_p in 2030 (Bloomberg New Energy Finance, 2024d).

Projections until 2050

The long-term projections for global installed PV capacity by 2050 differ substantially. Projections of installed PV capacity by 2050 can reach 9 TW_p, 20 TW_p and 62 TW_p, for a slow, base and fast growth scenario, respectively (Vartiainen *et al.*, 2020).

Discrepancies within long-term projections are not surprisingly as differences in scenario setting may have large impacts. Differences in scenario settings may refer to scenario objectives (e.g. global temperature increase, climate neutrality until a certain year), techno-economic assumptions (e.g. costs, learning rates), exogenous drivers (e.g. expected economic growth) and modelling methodologies.

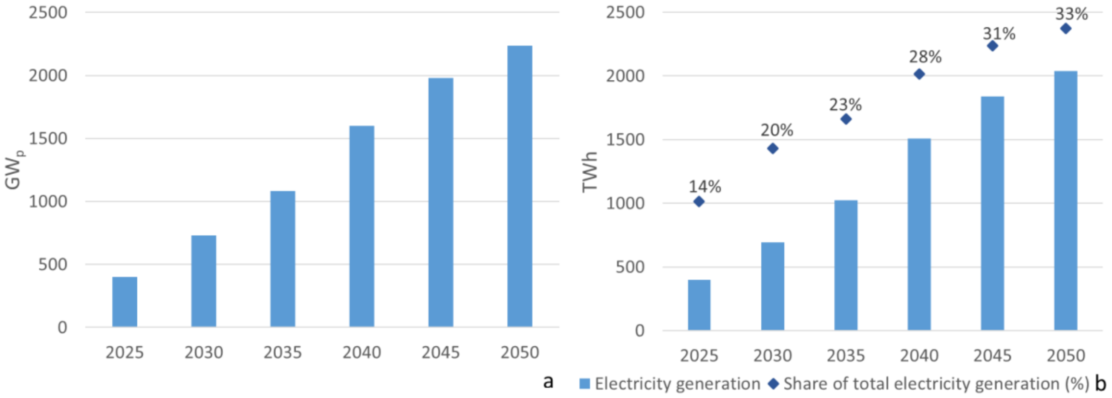
JRC projections

The here presented JRC projections for EU and global PV installed capacity and electricity generation are based on scenarios specifically modelled for CETO 2024 using the models POTEnCIA (for the EU) and POLES-JRC (for the world). Annex 3 includes more information on the energy system models and their respective CETO 2024 scenarios.

As far as the EU is concerned (Figure 10), the POTEnCIA model is in accordance with BloombergNEF and SPE for the 2025 and 2030 projections with 400 GW_p and 765 GW_p of installed PV capacity respectively. For the long-term projections, the model projects a capacity of 2.2 TW_p, where it would represent over 55% of total installed gross electric power capacity. In parallel, PV electricity production increases to 700 TWh by 2030, and to over 2000 TWh by 2050, equivalent to 33% of the total electricity generation. Thus, the projections further underline the growing importance of PV power for the near- to long-term EU electricity market.

Global projections until 2050 are shown in Figure 11 and Figure 12 based on the *Global CETO 2°C scenario 2024* calculated with the POLES-JRC model. Figure 11 presents global PV capacities of the power system along with average investment costs for both small/residential and utility-scale installations projects, and PV modules. Figure 12 illustrates global electricity generation with PV until 2050 in absolute terms and as share of total electricity generation.

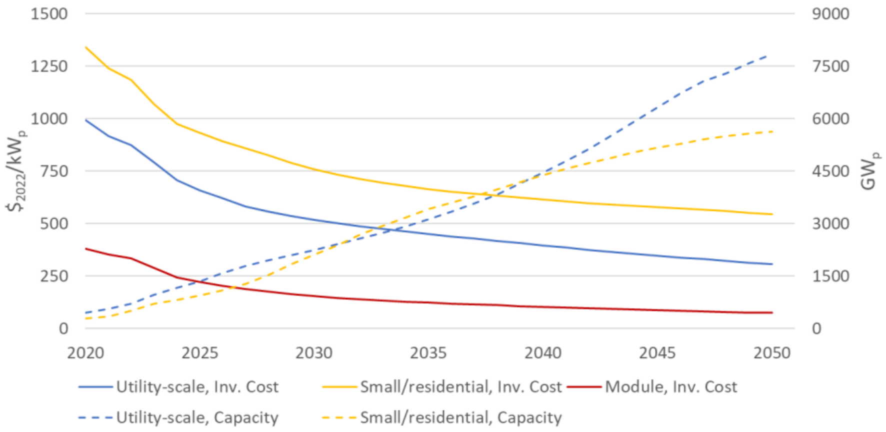
Figure 10. Projections of gross installed capacity and electricity generation in the EU.



Source: *POTEnCIA CETO 2024 Scenario*

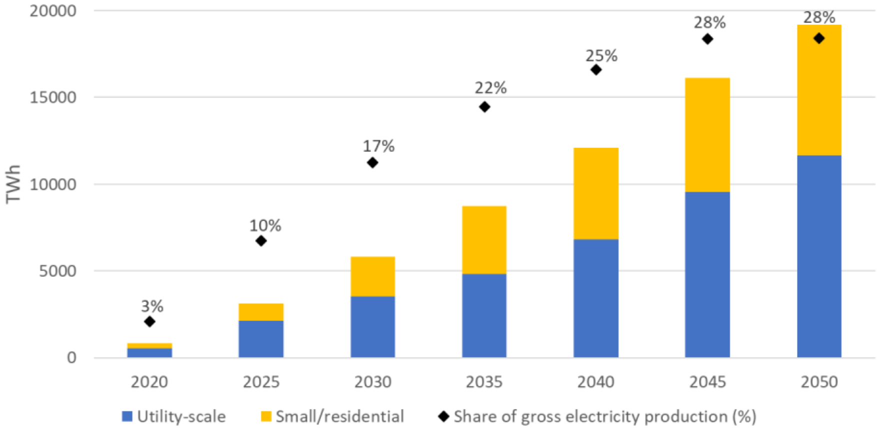
The projected global installed PV capacity of the power system, as outlined in the *Global CETO 2°C scenario 2024*, is 2.3 TW$_p$. This is consistent with projections of SPE, IEA and BloombergNEF for 2025, ranging between 2.4 TW$_p$ (IEA) and 2.9 TW$_p$ (BloombergNEF). However, the *Global CETO 2°C scenario 2024* projects less dynamic growth for the near future compared to other studies. For instance, the *Global CETO 2°C scenario 2024* projects for 2028 global PV capacities of 3.5 TW$_p$ which is at the lower end of the projections of IEA and SPE (3.8-6 TW$_p$).

Figure 11. Global average overnight investment cost and installed PV capacity of the power system for small/residential and utility-scale.



Source: *JRC POLES-JRC model*

Figure 12. Gross electricity production for small/residential and utility-scale and share of gross electricity production.



Source: *JRC POLES-JRC model*

By 2050, the *Global CETO 2°C scenario 2024* projects a global PV capacity of in total 15.2 TW_p which is composed of 13.5 TW_p PV capacity of the power system (shown in Figure 11) and 1.7 TW_p of PV capacity dedicated to the production of hydrogen and direct air capture (not shown in Figure 11) Notably, this long-term projection is at the lower end of the previously mentioned studies (Vartiainen *et al.*, 2020).

However, the dynamics of the PV sector are not entirely captured by the above projections. According to Bloomberg, this year, the installation at global level will grow and the projected installed capacity in 2030 will exceed 6.5 TW_p.

2.3 Technology Costs

Over the years, the reduction of solar PV systems cost has been remarkable. Between 2013 and 2023, the cost of residential, commercial rooftop and utility-scale PV systems decreased by 50 %, 66 % and 70 % respectively (Bloomberg New Energy Finance, 2024b). 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. These developments were fostered 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.).

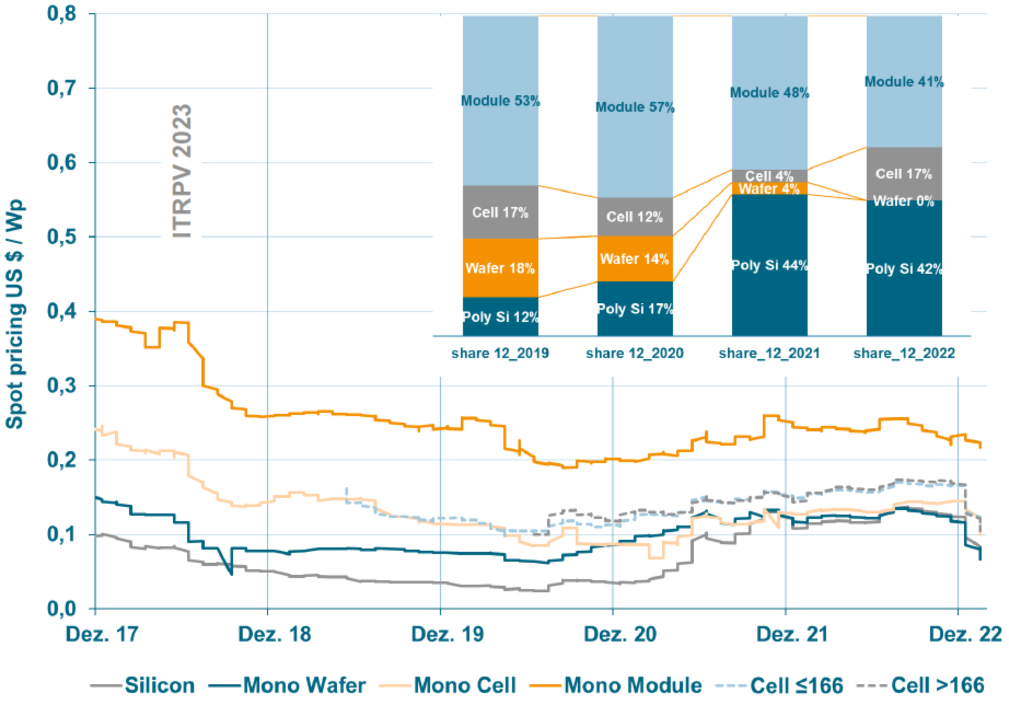
In 2022, the PV modules and the mounting /structural BoS (including labour and equipment) made up for 65 % of the total cost while the soft costs account for the remaining 36 %. (VDMA, 2023). Between 2022 and 2024, the benchmark global capital investment for utility-scale PV decreased by 20 %, mainly due to the lower module prices and lower raw material prices for aluminium and steel (IEA, 2024d).

The reduction in PV module prices has been remarkable. In the past 43 years, there is a 24.4 % decrease in module prices following each doubling of cumulative PV module production (Fraunhofer ISE, 2024). In December 2023, the average cost of c-Si modules sold in Europe was 93 % lower compared to 2009 (IRENA, 2024), while the global cumulative installed capacity grew 35-fold between 2010 and 2023, reaching 1.6 TW_p. Figure 13 presents the different cost attributions to the overall module price over the period 2018-2022. The bottom line of the figure represents the absolute spot price, while the stacked representation at the upper right corner presents the share of each attribution.

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. The land area requirement has decreased as well from 2.7 hectares/megawatt (MW_{AC}) in 2010 to 1.9 ha/MW_{AC} in 2020 (IRENA, 2020b). Further land requirement reductions may be achieved with the application of bifacial modules that exploit both sides for the conversion of light into electricity in applications like agrivoltaics, floating photovoltaics, infrastructure integrated photovoltaics and building integrated photovoltaics. These applications enable the production of electricity without changing the land use and without competing with other activities such as agriculture in the case of agrivoltaics.

As seen also in Figure 13, module prices are directly influenced by the polysilicon price as it is an essential raw material in the PV manufacturing sector. The increase of polysilicon price has influenced module prices as well. After a particularly low price in July 2020 (USD 6.8/kg), polysilicon shortage in 2021 and 2022 caused significant price increases. The peak polysilicon price was met in December 2022 (USD 37/kg) and then prices started decreasing during 2023, reaching a USD 9/kg price in June 2023 (slightly higher than the January 2021 price) (Bernreuter Research, 2023b).

Figure 13. Spot market price trends for poly-Si, mono-Si wafers, cells and modules between 2018 and 2022.



Source: (VDMA, 2023)

Accordingly, mainstream module prices have experienced a similar spot market price increase from EUR 0.22/W_p in July 2020 to EUR 0.35/W_p in October 2022 and ultimately a decrease to EUR 0.22/W_p in September 2023 (PVxchange, 2023). Since then, polysilicon prices have dramatically decreased to USD 5.63/kg (May 2024) due to oversupply (several manufacturers increased their capacities and new players, attracted by the rising demand for PV, entered the sector) (Bernreuter Research, 2024). This has led to the lowest ever spot market price of mainstream PV modules (EUR 0.11/W_p), as shown in Table 3.

Table 3. EU spot market module prices by technology in September 2024.

PV module technology	EUR/W_p
High efficiency[6]	0.15 *0.31 (September 2023)* *0.43 (September 2022)*
Mainstream[7]	0.11 *0.22 (September 2023)* *0.34 (September 2022)*
Low cost[8]	0.07 *0.14 (September 2023)* *0.21 (September 2022)*

Source: (Pvxchange, 2022; PVxchange, 2023, 2024)

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[6] Crystalline modules with mono- or bifacial HJT, N-type TOPCon or IBC (Back Contact) cells and combinations thereof, which have efficiencies higher than 21 %.

[7] Standard modules, typically with poly- or monocrystalline cells (also PERC), which are mainly used in commercial PV systems and which have an efficiency of up to 21 %.

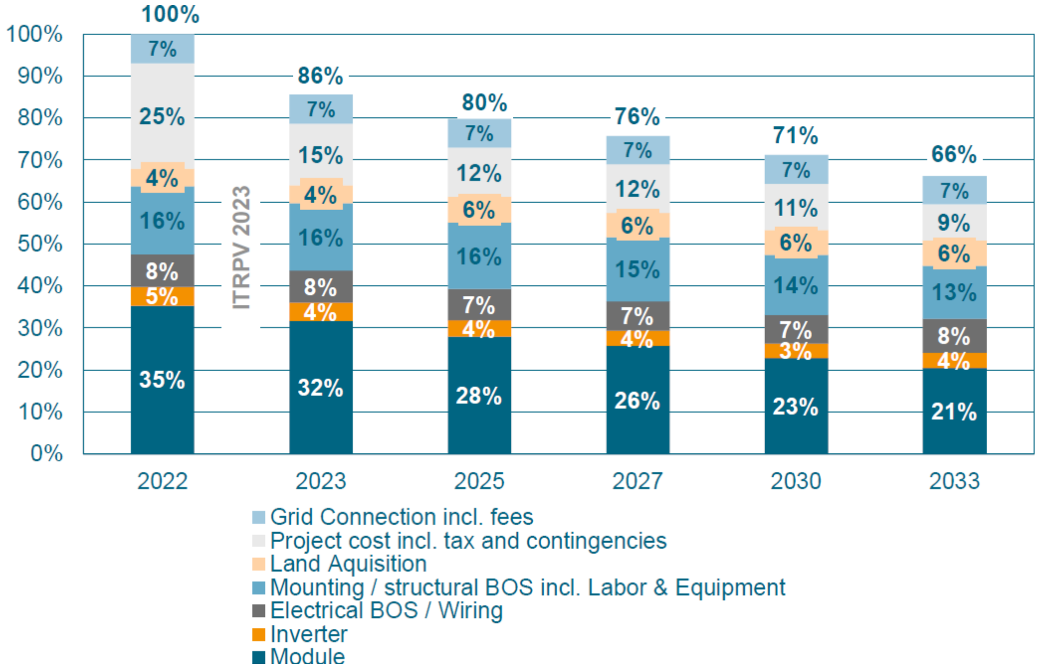
[8] Factory seconds, insolvency goods, used or low-output modules (crystalline), products with limited or no warranty, which usually also have no bankability.

Previous research, conducted by IRENA, has shown that the total installed costs between 2010 and 2023 decreased between 44 % (in the Netherlands) and 88 % in Australia, India and Spain (IRENA, 2024). Between 2018 and 2023, cost reductions in Europe were between 1 % (United Kingdom) and 48 % (Greece), with the exception of Italy. Regarding Asian countries, reduction was between 5 % (Japan) and 13 % (South Korea), with the exception of India for which costs increased by 7 %. The United States and Brazil had cost reductions of 4 % and 5 % respectively between 2018 and 2023 (IRENA, 2024).

In 2022, inverter costs represented only 4 % of the total cost of a large-scale system (>10 MWAC) (VDMA, 2023), down from 9 % (Ribeyron, 2020). According to (former) IHS Markit, already in 2021, inverter prices were lower than what was projected (Ribeyron, 2020).

As module and inverter costs have significantly decreased, nowadays other BoS costs account for a larger share of the system's total costs. This is because the learning rate of modules proved to be higher than that of BoS and OPEX. On average, in 2023, balance of system (BoS) costs (excluding inverters) made up about 61 % of total installed costs of utility-scale PV plants (IRENA, 2024). Soft costs[9] are varying significantly depending on the country. For utility-scale PV systems in the United States, in 2022, they were close to USD 0.50/W_{DC} (around USD 0.09/W_{DC} higher than in the EU and Asia) (VDMA, 2023).

Figure 14. Large-scale system component costs in 2022 and projections.



Source: (VDMA, 2023)

In 2022, the capital cost for a utility-scale PV system was estimated at USD 770/kW_{DC} in the EU, USD 705/kW_{DC} in the Asia and USD 1 410/kW_{DC} in the United States (VDMA, 2023). An estimated worldwide average for 2023 is at USD 700/kW_{DC}, with projections of reduction to USD 530/kW_{DC} in 2034 (VDMA, 2024). As far as inverters are concerned, no significant cost reductions are expected in the next ten years impacting the total capital cost of the PV systems (Figure 14). The 2023 ITRPV report projected that capital cost reductions will be in the range of 35 % and will effectively be a result of module price and soft costs reductions (VDMA, 2023). Projections for worldwide average utility-scale system costs suggested USD 504/kW_{DC} in 2034 (VDMA, 2024).

Other work regarding the projected capital cost in Europe is shown in Figure 15. For rooftop installations, the capital costs may fall to an average value of EUR 1 280/kW_p in 2030 from approximately EUR 1 620/kW_p in 2024, while the projection for 2050 is a compound average decrease of 3 % over the 2024-2050 period (from EUR 1 620/kW_p to EUR 810/kW_p from 2024 to 2050). Utility-scale capital costs are expected to decrease from EUR 460/kW_p in 2024 to EUR 230/kW_p in 2050.

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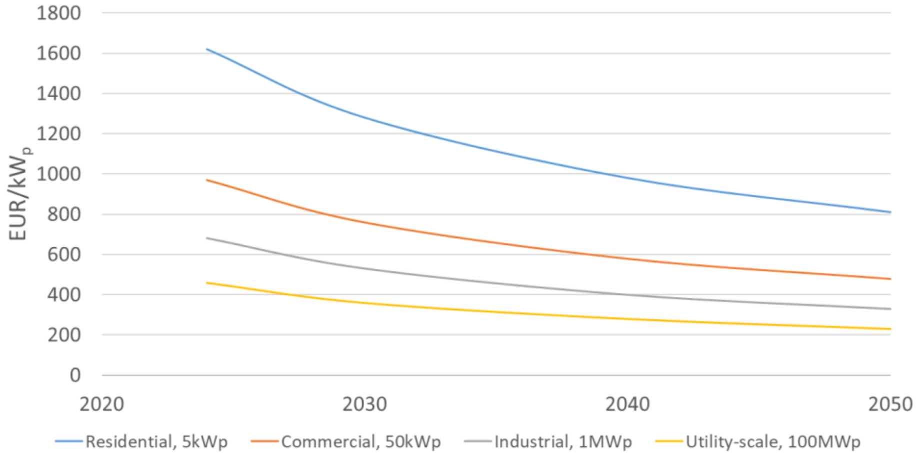
[9] Include project developer costs, overhead and profit, sales tax and permitting fees.

Figure 15. Capital cost projections for rooftop, commercial, industrial and utility-scale PV installations for 2030-2050.



Source: (ETIP-PV, 2024)

OPEX

The O&M benchmark costs in the US in 2020 are reported to be USD 18.7/kW$_{AC}$/year for commercial ground-mounted installations, USD 18.6/kW$_{AC}$/year for commercial roof-mounted installations, USD 28.9/kW$_{AC}$/year for residential installations, USD 16.3/kW$_{AC}$/year for fixed utility-scale installations and USD 17.5/kW$_{AC}$/year for 1-axis tracking utility-scale installations (IRENA, 2020b). In 2023 and depending on the market, O&M costs range between USD 3.6/kW/year (China) and USD 13.9/kW/year (Japan) (IRENA, 2024).

In 2023, average O&M costs for Europe were USD 7.9/kW/year, representing a decrease of 10 % (the highest among all regions) compared to 2022. Respectively, for Oceania O&M costs were USD 7.1/kW/year (7 % compared to 2022). Costs in Eurasia and South America were USD 6.9/kW/year and USD 7.3/kW/year, respectively (IRENA, 2024).

An evaluation of solar energy costs at EU level revealed that the average EU O&M costs[10] for utility-scale installations are between EUR 6.8/kW$_p$/year and EUR 14.8/kW$_p$/year. The lowest O&M costs are in Bulgaria in the range of EUR 5.2-11.2/kW$_p$/year and the highest in Germany between EUR 8.7/kW$_p$/year and EUR 18.9/kW$_p$/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.

LCoE

After the increase of the global benchmark LCoE[11] (Levelised Cost of Electricity) for electricity produced by PV systems at the end of 2021 and in 2022, it continued to decrease for non-tracking systems to a record low of USD$_{2022}$ 41/MWh at the end of 2023 (Jäger-Waldau, 2024). The main reason for this was the lower module prices due to the oversupply along the value chain. The full range of LCoE for non-tracking PV systems varied between USD 34 and 174/MWh. On the other hand, the global cost benchmark for tracking PV systems increased by about 9% in 2023 to USD$_{2022}$ 48/MWh. This was due mainly to higher costs for labour, balance of systems and financing in the USA. After freight costs peaked in Q3 2021 (six fold increase compared to H1 2020), they were in the same range as 2020 for most of 2023 with a tendency to fall towards the end. In the beginning of 2024, the shipping disruptions in the Red Sea have already increased freight costs by 20% for solar modules shipped from Asia to Europe (Mercom, 2024). Between 2022 and 2024, the global benchmark LCoE for utility-scale PV decreased by 10 % due to higher Weighted Average Cost of Capital (WACC) (IEA, 2024d).

IRENA estimates the global weighted average LCoE of utility-scale PV plants in 2023 to be USD 44/MWh (90 % decrease compared to the USD 460/MWh in 2010) (IRENA, 2024). The main contributors to this cost-reduction were: (i) the 45 % reduction of module costs, (ii) the 18 % reduction of inverters, racking and mounting and other BoS costs, (iii) the 28 % 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, 2024).

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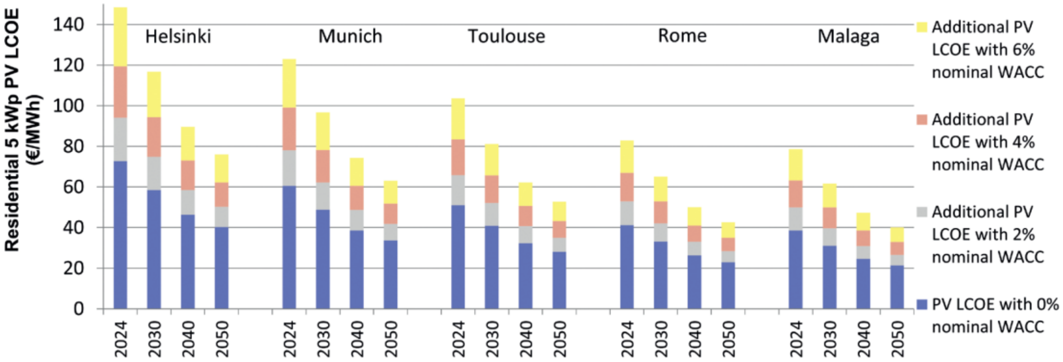
[10] O&M costs are calculated as a percentage of the initial investment (I_0). For fixed angle PV systems: 1 % of I_0 and for 2-axis tracking system: 1.5 % of I_0.

[11] The global benchmark is calculated by BNEF with capacity-weighted averages using their latest country estimates.

A comparative analysis of calculated LCoE values at different EU locations and with different Weighted Average Costs of Capital (WACC) rates (ETIP-PV, 2024) has shown that for a residential rooftop installation (Figure 16) when applying a 6 % WACC, the around EUR 150/MWh of LCoE in 2024 will decrease to EUR 75/MWh of LCoE in 2050 in Finland. For southern locations, like in Spain, for the same conditions, the 2024 LCoE of EUR 80/MWh will be reduced to EUR 40/MWh 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).

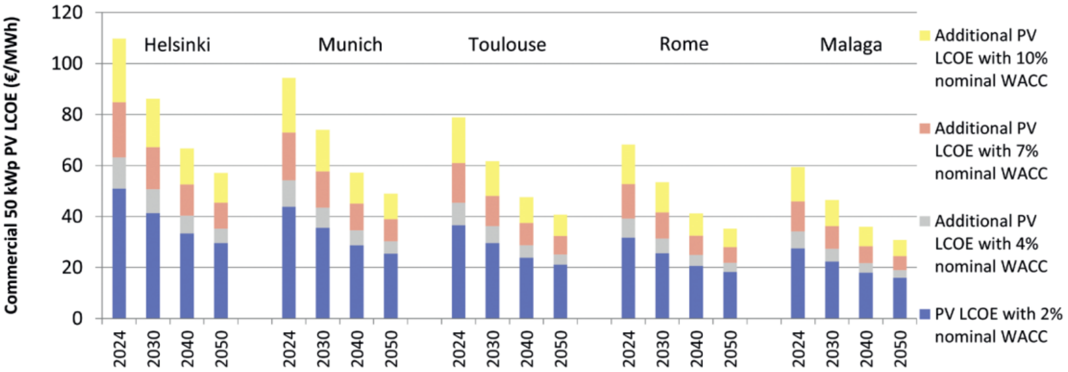
Figure 16. PV LCoE at six European locations with different nominal WACCs for 5 kW_p residential rooftop PV installation.



Source: (ETIP-PV, 2024)

The relevant LCoE values for a commercial rooftop installation presented in Figure 17 are lower than for the residential installation in Figure 16. In Finland from EUR 110/MWh in 2024 the LCoE will decrease to EUR 55/MWh in 2050, whereas in Spain in 2050 it will drop by approx. EUR 12/MWh from EUR 60/MWh in 2024.

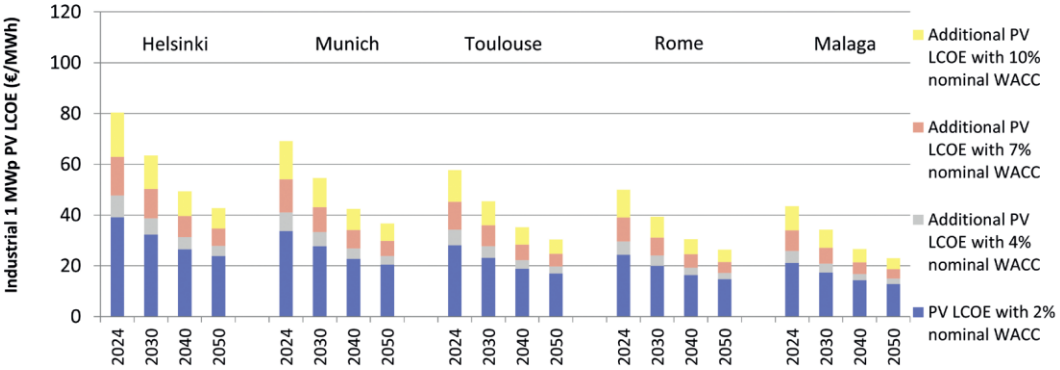
Figure 17. PV LCoE at six European locations with different nominal WACCs for 50 kW_p commercial rooftop PV installation.



Source: (ETIP-PV, 2024)

A decrease of approx. EUR 37/MWh between 2024 and 2050 (from EUR 80/MWh to EUR 43/MWh) is projected for the LCoE of industrial installations in Finland. In Spain, the LCoE will drop by EUR 21/MWh in 2050 in comparison to 2024 (EUR 43/MWh) (Figure 18).

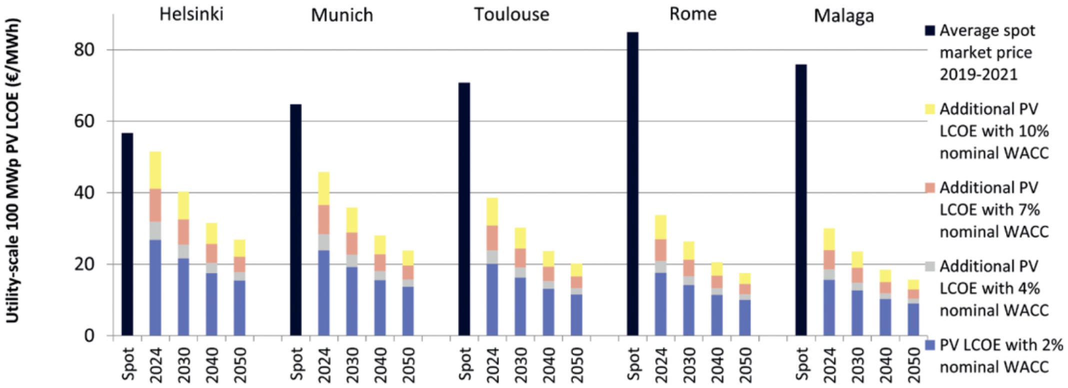
Figure 18. PV LCoE at six European locations with different nominal WACCs for 1 MW_p industrial PV installation.



Source: (ETIP-PV, 2024)

In the case of utility-scale installations and taking into consideration the wholesale electricity prices, the cost of electricity produced from PV in 2024 was already competitive for all locations even with the application of a WACC as high as 10 % (Figure 19).

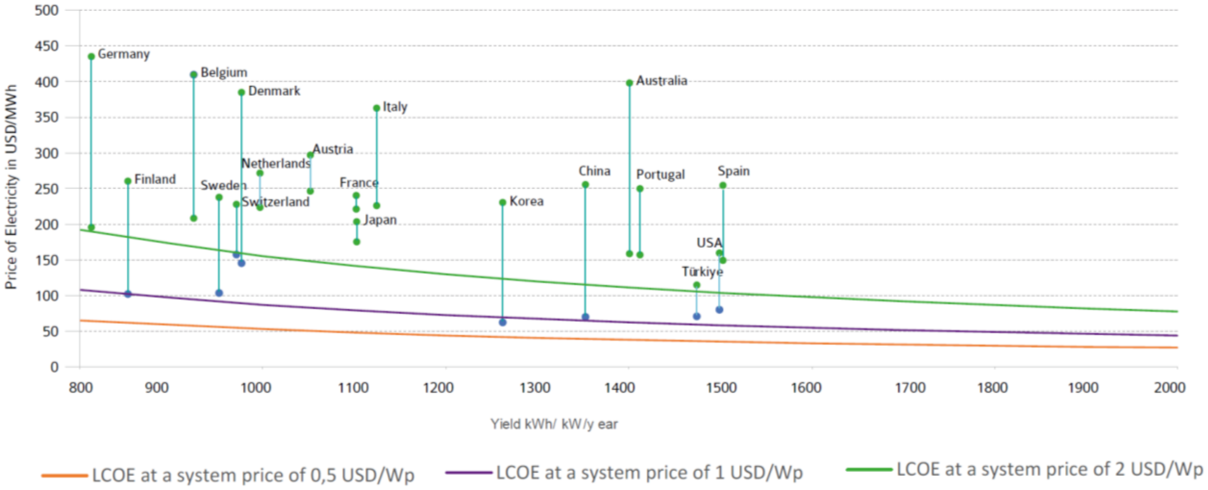
Figure 19. PV LCoE five European locations with different nominal WACCs for 100 MW_p utility-scale PV installation compared with average spot market electricity price of 2019-2021.



Source: (ETIP-PV, 2024)

According to Figure 20 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 (IEA PVPS, 2024b).

Figure 20. LCoE as a function of solar irradiance and retail prices in key PV markets.



Source: (IEA PVPS, 2024b)

2.4 Public RD&I Funding and Investments

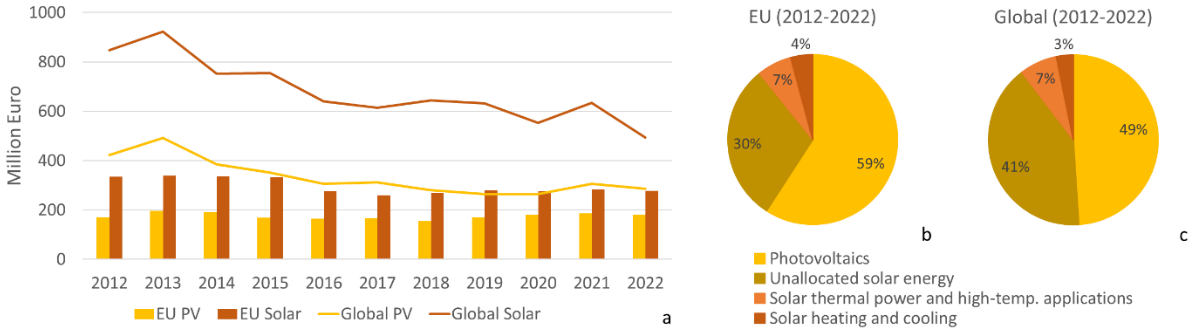
The public investment in solar energy and PV (treated as a sub-category) at EU and global level from 2012 until 2022 is illustrated in Figure 21a. It must be noted that data for 2022 are provisional and that the 2021 and 2022 values do not include funding reported from Italy. Furthermore, in 2021 Spain has changed the methodology for collecting the data, resulting in a break in the time series between 2020 and 2021 and in the same year, France has revised the data transmitted by the CNRS from 2002 to improve the coverage.

Overall, EU public investments in solar increased by 118 % between 2005 and 2011, year when they peaked. Thereafter they started decreasing gradually. Between 2011 and 2022 the decrease was 24 % at EU level. At global level, solar public investments increased by 130 % between 2005 and 2011 (peak year for investments) and decreased by 48 % between 2011 and 2022.

Regarding PV public funding, the EU experienced a 82 % increase between 2005 and 2013 (peak year for investments), following a slight decrease of 8 % for the period 2013-2022. Globally, PV public investments increased by 101 % in 2005-2009 and decreased by 46 % over the period 2009-2022.

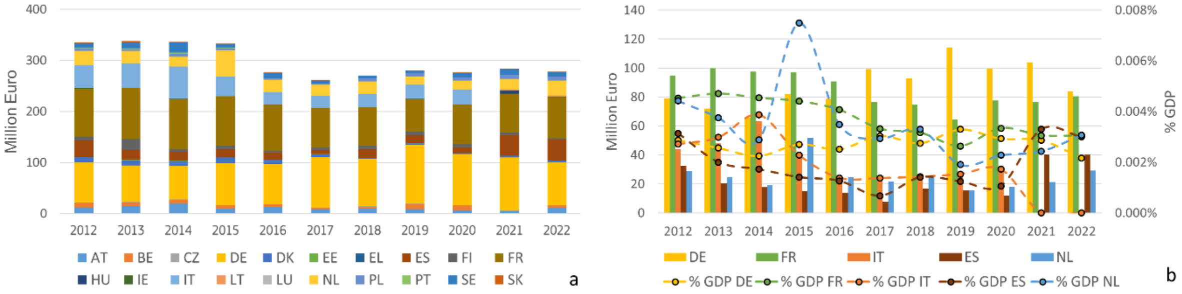
While 59 % of the total solar energy sector public investment was attributed to PV in the EU, the respective percentage at global level was 49 % for the period between 2012 and 2022 (Figure 21b and c). The total cumulative EU public investments in PV accounted for 53 % of the total cumulative global public investments in PV during the period 2012-2022, while in the case of the total cumulative public investments in solar, the EU accounted for 44 % of the global total cumulative public investments. The above-mentioned percentages are lower than expected since Italy is not included in the datasets for the years 2021 and 2022.

Figure 21. (a) EU and global public investments in Solar and PV R&D, (b) EU and (c) global allocation of solar energy technologies for the period 2012-2022.



Source: JRC analysis based on IEA

Figure 22. (a) EU public investments per MS and (b) EU public investments and % of GDP in Solar and R&D for the top five MS for the period 2012-2022.



Source: JRC analysis based on IEA and (The World Bank, 2023)

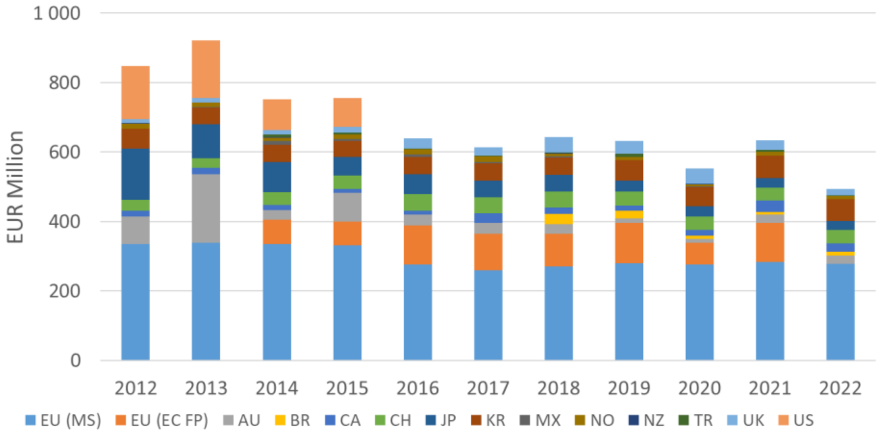
Data on PV public investments (IEA codes: 312 Solar photovoltaics) are not always reported from the EU MS and therefore are considered incomplete. For this reason, Figure 22a and b present MS' and the rest of the world countries' public investments in the broader technology group of solar energy rather than the specific technology of PV. This enables a more direct and fair comparison.

Germany, France, Italy, Spain and the Netherlands are the top five 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 at 0.003 % and between 0.003 % and 0.005 % of their GDP respectively. Spain's investments as a percentage of the country's GDP fluctuated between 0.001 % and 0.003 % throughout 2012 to 2022. The same applies also for Italy with 0.004 % of its GDP until 2014 and decreasing thereafter. In the case of the Netherlands, the public investment as a percentage of the country's GDP varied between 0.002 % and 0.004 % with a distinct peak in 2015 (0.007 % of GDP).

Regarding the thirteen major economies presented in Figure 23, caution for the interpretation of the results is advised as the United States have stopped reported their public investments to the IEA after 2015 and data on other countries is also missing. Based on the scarce data availability, the EU appears to account for 42 % of the total global public investments in solar cumulatively in the period from 2011 until 2021, while Japan for 9 % as between this period, the country appears to have reduced its investments by 75 %. When comparing the major economies for the period 2011-2015, the EU accounted for 40 % of the global public investments on solar, while the United States, Japan and Australia for 18 %, 12 % and 10 % respectively.

In Figure 23a and b, '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.

Figure 23. Global public investments per country in Solar and R&D for the period 2012-2022.



Source: JRC analysis based on IEA

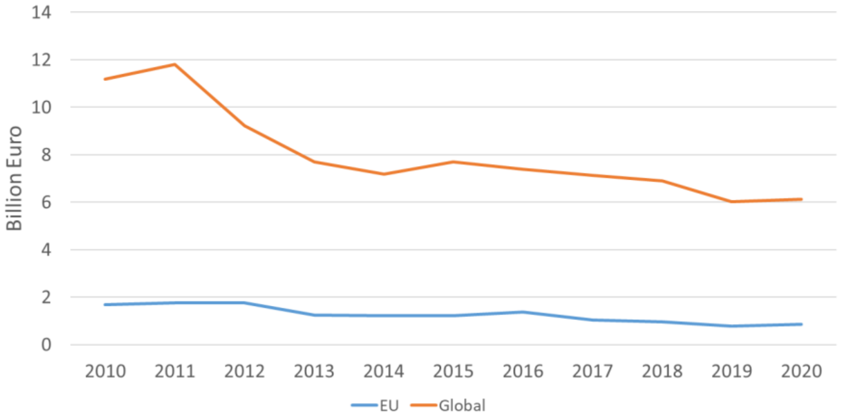
2.5 Private RD&I funding

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, 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 be interpreted with caution (especially for China). Unlike public investments, the analysis is performed from 2010 until 2020, since 2021 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 156 to 196 million and from EUR 264 to EUR 519 million respectively for the period 2010-2020, the private investments in the EU and globally ranged from EUR 0.8 to EUR 1.8 billion and from EUR 6 to EUR 11.8 billion respectively for the same period Figure 24. Analysing the relationship between public and private funding from 2010 until 2020 in the EU, it is observed that public R&D funding was between 9 % and 18 % of the total R&D funding. This suggests a much higher contribution of the private sector to the PV R&D funding (82 %-91 %). Private funding at global level is even more important as it covers between 94 % and 96 % of the total funding.

Figure 24. EU and global private investments in PV for the period 2010-2020.

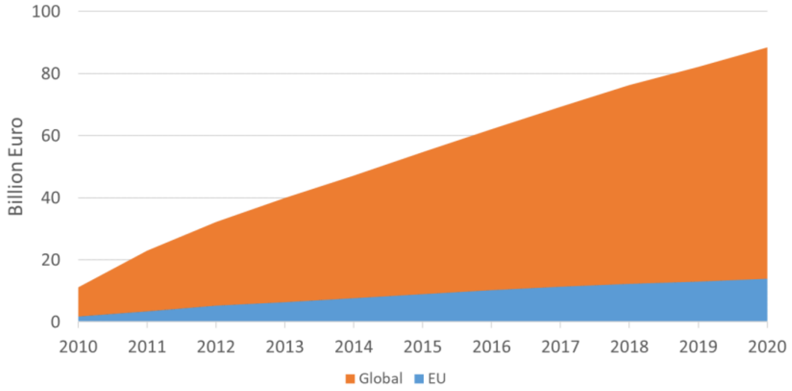


Source: JRC analysis based on (Fiorini et al., 2017; Pasimeni, Fiorini and Georgakaki, 2019)

Between 2010 and 2020, the indication for PV is that the EU exhibits a 49 % decrease in private investment and a 9 % increase in public investments. Over the same period, private investments at global level suffered a similar decrease to that of public investments (-45 % against -43 %). Regardless of the public or private nature of the investment, investments have suffered significant decreases both in the EU and globally. However, unlike the EU, the rest of the world is benefitting more from private rather than public investments.

As shown in Figure 25, at global level, the PV cumulative private investments were EUR 88 billion in 2020. In the same year, the EU private investments amounted to EUR 14 billion (16 % of the global private investments).

Figure 25. EU and global cumulative private investments in PV for the period 2010-2020.

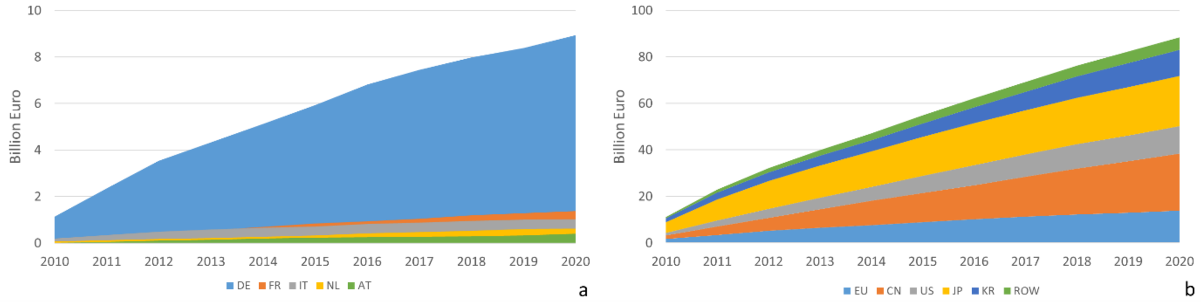


Source: JRC analysis based on (Fiorini et al., 2017; Pasimeni, Fiorini and Georgakaki, 2019)

Figure 26a presents the five EU countries with the highest levels of cumulative private investment in the EU. These five countries account for 89 % of the total cumulative private investments in the EU from 2010 to 2020. Germany had the highest level of private investment in PV, accounting for 64 % of the cumulative investments (2010-2020), followed by France with 10 % and Italy with 7 %.

Globally (Figure 26b), in 2020, the cumulative private investments in PV from Japan (24 %) and China (28 %) represent more than half of the global cumulative private investments. In 2019, Japan had the highest share in cumulative private investments (30 %), followed by China (23 %). However, it must be noted that 2020 dataset is near complete. The EU represents 16 % of the total cumulative private investments from 2010 to 2020, representing approximately EUR 14 billion out of a total of approximately EUR 88.5 billion. The next two regions are the US and South Korea (each 13 %).

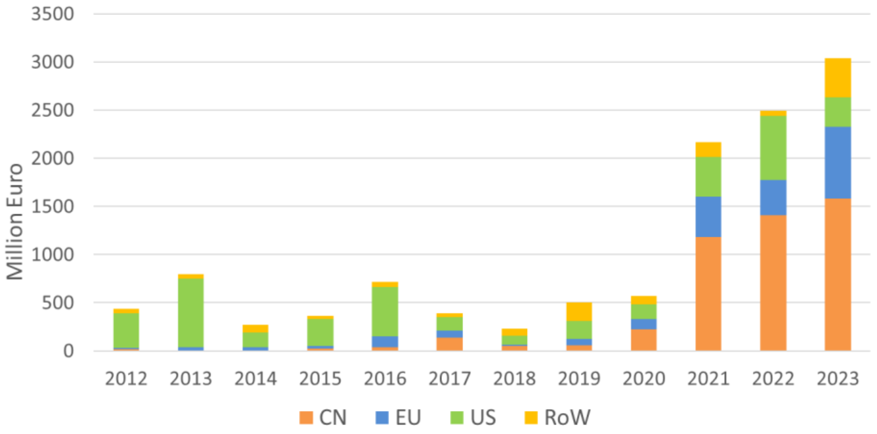
Figure 26. (a) EU cumulative private investments in PV per MS and (b) global cumulative private investments in PV EU and top five countries for the period 2010-2020.



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

Global VC investments[12] in photovoltaic companies increased sharply over the past 2 years, surpassing the highest levels seen in the early 2010s, and amounted to around EUR 3 billion in 2023 (Figure 27). This represents an increase of 22 % compared to 2022 levels, a five-fold growth compared to 2020, and puts an end to a period of lower investments whose beginning can be traced back in 2014. This trend is essentially driven by an outstanding growth of VC investments in Chinese firms in 2021 and 2022, both at early and later stages[13], and, to a smaller extent, by the rebound of later stage investments in US firms after a long period of lower investment levels.

Figure 27. EU and global total Venture Capital (VC) investments for the period 2012-2023.



Source: JRC analysis based on Pitchbook

China accounts for 84 % of global early-stage investments and 41 % of global later stage investments over 2018-2023. While later stage investments in Chinese companies decreased by 12 % between 2021 and 2022, 2023 has been proven a year of massive later stage investments with an increase of 70 %. However, as later stage investments in China increased significantly, early stage investments decreased by 50 % between 2022 and 2023 (between 2021 and 2022 they had increased, compensating for the later stage decrease).

The United States and the EU host respectively 40 % and 23 % of active venture capital companies over the 2018-2023 period. With 14 % of identified ventures, China has however taken a clear lead in the VC investment race with a high level of constant investment over the past 2 years. Regarding the total VC investments (early and later stage), China and the United States accounted for 50 % and 20 % respectively in the 2018-2023 period, while the EU accounted for 19 % of the global 2018-2023 total (see Figure 28).

Early-stage investments in EU VC companies amounted to EUR 130 million over the 2018-2023 period. They have continuously decreased after a peak in 2020 (EUR 60 million) and remained at half in 2021 and 2022. Over the 2018-2023 period, the EU accounted for 4 % of global early-stage investments (vs 9 % over 2017-2022) and its competitive positions further weakens in an accelerating global investment race. EU companies however only captured 10 % of the identified grant funding[14] over the 2018-2023 period behind the United States (34 %). The United Kingdom and Canada follow the EU 9 % and 8 % share of grant funding respectively. The remaining 39 % is attributed to the rest of the world, with most of it (78 %) for companies in Norway and 20 % in Australia. PitchBook only reports negligible (or none) amount of grant funding for Japanese, Korean or Chinese start-ups.

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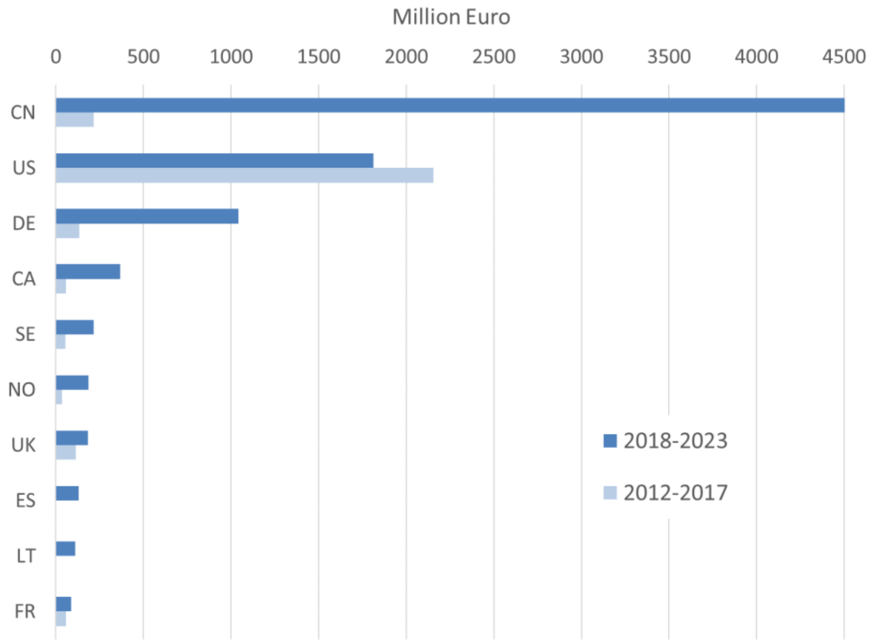
[12] Private Equity refers to capital investments (ownership or interest) made into companies that are not publicly traded. Venture capital (VC) is a form of private equity and a type of financing that investors provide to start-up companies and small businesses that have long-term growth potential. 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. Companies are selected based on their activity description (keyword selection and expert review).

[13] 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.

[14] Even though grant funding is not equity funding, grants are included among early VC stages because they are an import source of funding for start-ups.

Figure 28. Top ten countries total Venture Capital (VC) investments for all stages for the periods 2012-2017 and 2018-2023.



Source: JRC analysis based on Pitchbook

Later stages investments in EU companies amounted to EUR 1 billion over the 2018-2023 period. While they have decreased by 21 % between in 2021 and 2022, they increased again in 2023 (50 % compared to 2022), at a level of 15 times higher than in 2020. Accounting for 24 % of global later stage investments over 2018-2023 (vs 21 % over 2017-2022), the EU maintained its competitive position despite the increase of later stage investments for Chinese companies between 2022 and 2023. The EU increased its later stage investments by 50 % between 2022 and 2023 (respectively, China's later stage investments increased by 70 % during the same period). Late-stage VC investments in EU companies are essentially concentrated in Germany and France, which outrank the United Kingdom, but remain far behind the United States and China.

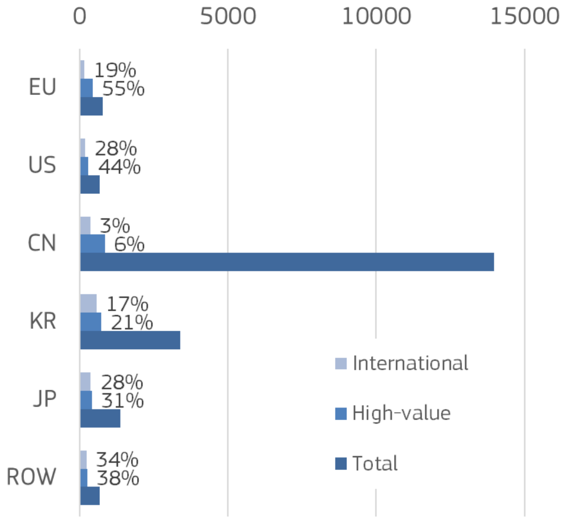
2.6 Patenting trends

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, 2023). It has to be noted though that data for 2021 is not complete.

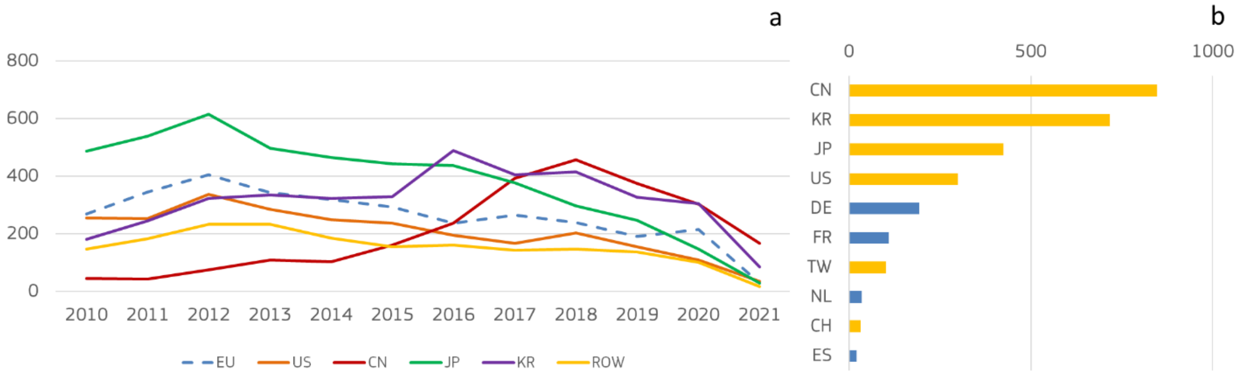
As depicted in Figure 29, China has the largest number of patents with almost 14 000 inventions, followed by South Korea and Japan. The EU is in 4th position with 790 inventions in total between 2019 and 2021.

Figure 29. Number of inventions and share of high-value and international activity for the period 2019-2021.



Source: JRC analysis based on EPO Patstat

Figure 30. (a) Number of high-value Inventions between 2010 and 2021 and (b) Top ten countries with high-value inventions for the period 2019-2021.



Source: JRC analysis based on EPO Patstat

However, when only the high-value inventions[15] are taken into consideration, the EU moves 1st with 55 % 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[16]. The same trend is evident also as far as international inventions[17] 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. The EU is surpassed by Japan and the United States regarding the international inventions. While Figure 29 shows the high-value inventions as a percentage of the total number of inventions, Figure 30a presents the number of high-value inventions in absolute numbers for each year from 2010 until 2021. Germany, France, the Netherlands and Spain are among the top ten countries with the highest number of high-value inventions between 2019 and 2021 (Figure 30b).

Table 4 and Table 5 respectively present the top ten entities globally and in the EU which filed the highest number of inventions in PV between 2019 and 2021.

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

[16] An invention is considered of high-value when it contains patent applications to more than one office.

[17] Patent applications protected in a country different to the residence of the applicant.

Table 4. Global top ten entities with high-value inventions in PV for the period 2019-2021.

Entities	Number of high-value inventions	Country
Samsung Display Co Ltd	299	KR
Boe Technology Group Co Ltd	128	CN
Wuhan China Star Optoelectronics Semiconductor Display Technology Co Ltd	111	CN
Samsung Electronics Co Ltd	57	KR
Lg Philips Lcd Co Ltd	56	KR
Panasonic Intellectual Property Management Co Ltd	32	JP
Shaanxi Lighte Optoelectronics Material Co Ltd	31	CN
Chengdu Boe Optoelectronics Technology Co Ltd	25	CN
Duk San Neolux Co Ltd	23	KR
Merck Patent Gmbh	23	DE

Source: JRC analysis based on EPO Patstat

In the top ten, global entities with high-value inventions are mostly based in China and South Korea. Japan and Germany conclude the ranking with one entity each. Merck Patent Gmbh (Germany), the only EU entity in this top ten, re-appears in this ranking after being absent during the period 2018-2020 (Chatzipanagi, Jaeger-Waldau, *et al.*, 2022; Chatzipanagi, Jaeger-Waldau, Cleret de Langavant, *et al.*, 2023)As far as the EU is concerned, the top ten list highlights the leadership of German entities in high-value inventions (Table 5). Cynora Gmbh fell to the 6th position and Merck Patent Gmbh re-emerged as 1st, as in the period 2017-2019 (Chatzipanagi, Jaeger-Waldau, *et al.*, 2022; Chatzipanagi, Jaeger-Waldau, Cleret de Langavant, *et al.*, 2023).

Table 5. EU top ten entities with high-value inventions in PV for the period 2019-2021.

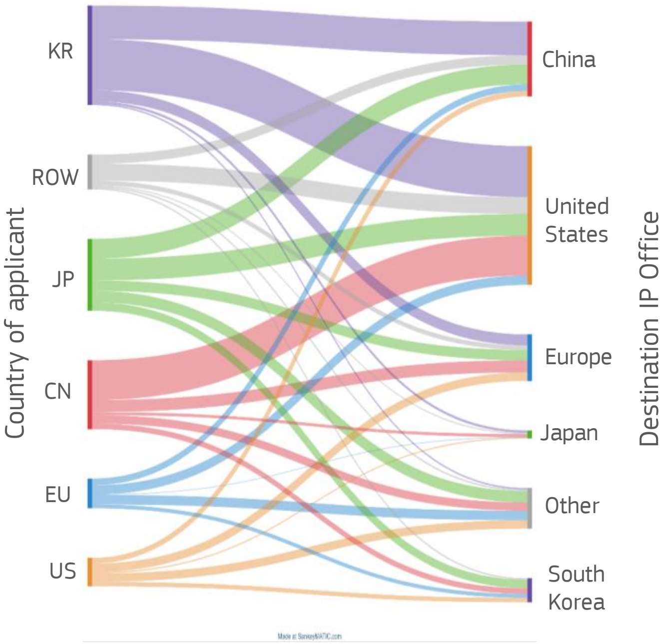
Entities	Number of high-value inventions	Country
Merck Patent Gmbh	23	DE
Azur Space Solar Power Gmbh	18	DE
Heliatek Gmbh	12	DE
Hanwha Q Cells Gmbh	12	DE
Novaled Gmbh	12	DE
Cynora Gmbh	12	DE
Isorg	7	FR
Total Sa	4	FR
Eni Spa	4	IT
Meyer Burger Germany Gmbh	4	AT

Source: JRC analysis based on EPO Patstat

Figure 31 presents the countries in which patents for high-value inventions were submitted, and subsequently enjoyed patent protection, between 2019 and 2021. 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. US inventors have split their patent applications evenly between China, Europe and other geographical areas. The same applies also for EU inventors, where patent applications are split evenly between US and others. However, patents in China appear to be slightly reduced compared to the period 2018-2020 (Chatzipanagi, Jaeger-Waldau, Cleret de Langavant, *et al.*, 2023). Applicants from South Korea are mainly applying in the US and China and to a lesser extent in Europe. In conclusion, the US is receiving the largest number of high-value invention applications. Europe is 3rd 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 2020 reveals a general decreasing trend for all PV technologies. More in particular, III-V group PV cell patents exhibit fluctuations (increases and decreases) between 2010 and 2021, with the United States being the leader and the EU improving its position in the last years. High-value patents related to the organic technology, have experienced an increase between 2010 and 2018 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 overall on II-VI group and III-V group PV cells and South Korea patented inventions mostly relating to organic PV cells, with China is following close South Korea in number of high-value patents after 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 2020.

Figure 31. International protection of high-value inventions for the period 2019-2021.



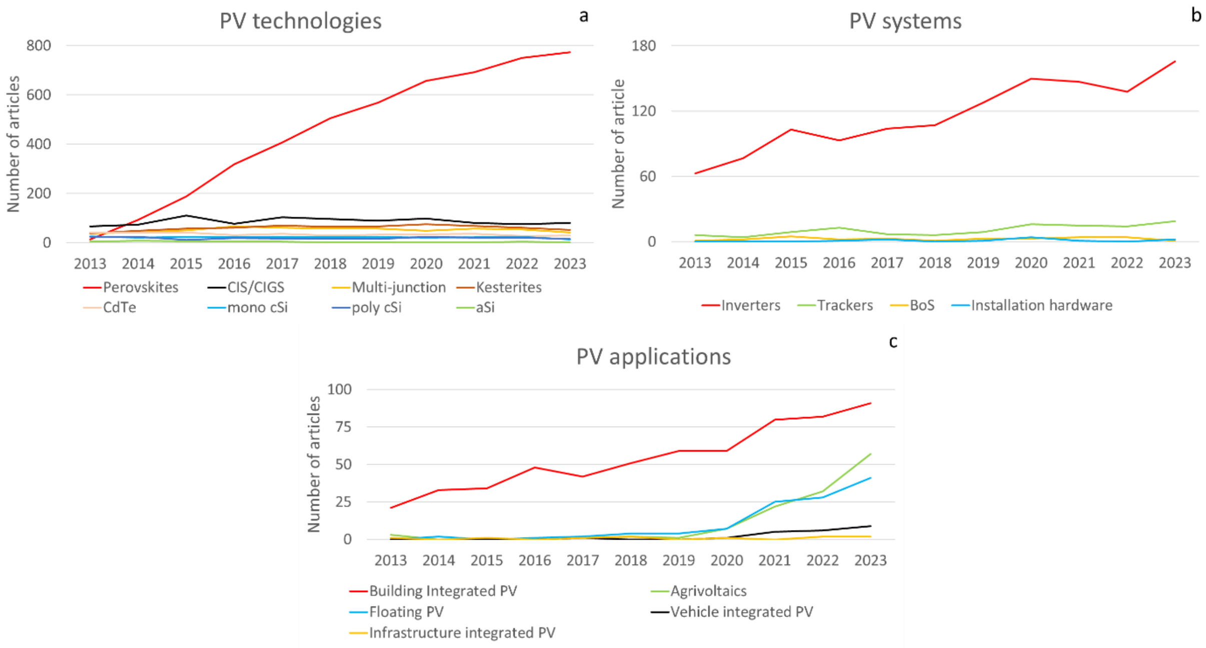
Source: JRC analysis based on EPO Patstat and Sankeymatic

2.7 Scientific publication trends

In the EU, the number of publications on PV technologies has increased steadily from 2013 to 2023 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 2014 onwards (Figure 32a), due to the promising outlooks of this technology. It is thanks to this intense research activity that the perovskites technology has reached such high efficiencies in recent years. The analysis of PV technologies publications at global level confirms the same trends as at EU level. In general, global publications dealing with the perovskite technology accounted for only 8 % of all technologies publications in 2013 but slowly increased, reaching an 83 % share in 2023. CdTe and CIS technologies publications decreased from around 22 % of all technologies publications in 2013 to 4 % in 2023. Publications related to kesterite and multi-junction technologies decreased from approx. 16 % in 2013 to 3 % in 2023. Those on mono cSi, poly cSi and a-Si are very limited, resulting to being at 1 % of total publications in 2023 from 8 % in 2013.

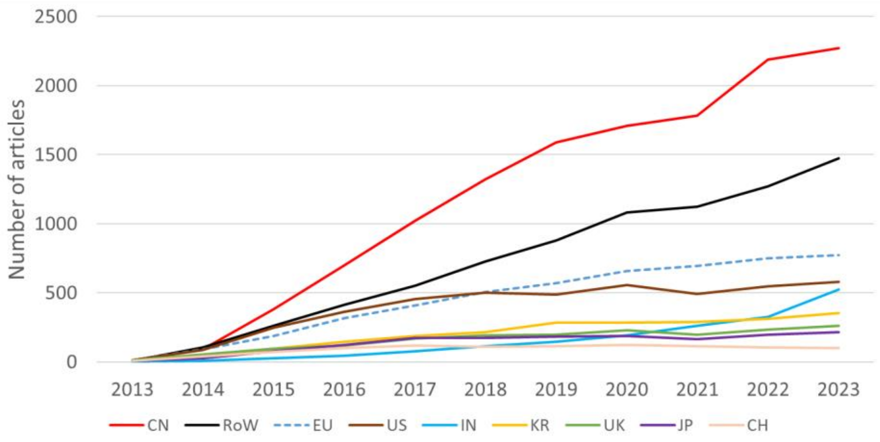
The number of publications on mono c-Si, a-Si, and kesterite technologies has been comparable for the EU and China from 2013 until 2023. On poly c-Si, CIS/CGS and multi-junction technologies, the EU has had more publications than other countries. As far as the CdTe technology is concerned, the leading country in publications is the United States for the period 2013-2023 (being the dominant country in the CdTe production and market). However, it must be noted that publications on CdTe technology in the United States have decreased after 2016. For the perovskite technology, which is the highest-trending topic, China has the highest number of papers between 2013 and 2023 (Figure 33).

Figure 32. EU publications on PV (a) technologies, (b) systems and (c) applications for the period 2013-2023.



Source: JRC analysis

Figure 33. Global publications on perovskites for the period 2013-2023.

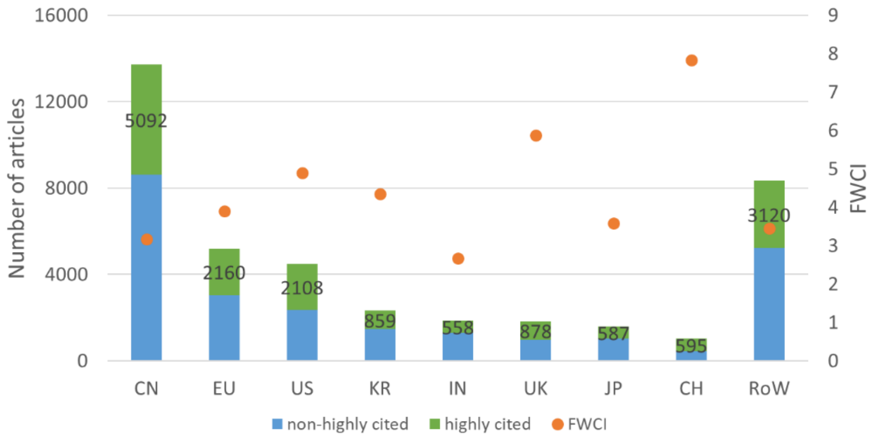


Source: JRC analysis

However, apart from the total number of publications, an analysis of the quality of publications is required. As depicted in Figure 34, the EU has less than half of China's publications on perovskites but the EU's highly cited publications are slightly more numerous than China's highly cited publications (41 % against 37 %). The best performing country is Switzerland, for which 58 % of its total number of publications is also highly cited. The United States and the United Kingdom follow with 48 %. In terms of Field Weighted Citation Impact (FWCI), China's FWCI is lower (3.2) than the EU's (3.9), meaning less frequent citations despite the large number of papers as a total. Almost half of the total number of publications on perovskites in the United States are highly cited publications and the country's FWCI is 4.9, 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 five are Spain, Italy, France and Sweden. In terms of collaboration networks for the publication of papers, China has strong bonds with the United States while the EU is mainly collaborating with the United Kingdom, Switzerland but also with India, Japan 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.

Figure 34. Global highly cited publications on perovskites and EU position for the period 2013-2023.



Source: JRC analysis

In the field of PV systems, publications in the EU as illustrated in Figure 32b evidence a predominance of literature on the topic of inverters. The same is true at global level as well. Globally, from 2013 until 2023, approximately 9 774 papers on inverters were published. Papers dealing with PV tracking systems were only 615. For BoS and hardware installation, there were around 130 and 66 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 16 % of the EU's papers. In 2013, 14 % of the papers on inverters globally were published by institutions based in the EU. This share remained stable until 2023. China also has a high number of publications in this field and its share in scientific publications remained stable around 30 % between 2013 and 2023, thus holding the first position. India, having a tradition in power systems research, is the 3rd country in the ranking with a share of publications in 2023 comparable with the EU's. China has the greatest number of publications on inverters, followed by the EU, India and the United States but only 22 % of China's publications are highly cited, whereas EU's and United States' portion of highly cited publications is 25 % and 30 % respectively. China's FWCI is 2.1 against 2.3 for the EU and 3.0 for the United States. 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. For publications on inverters, China, the EU and the United States, 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 -between France-Italy-Spain-Finland and Sweden-the Netherlands-Belgium. Germany is collaborating mainly with non-EU countries like the United Kingdom and Switzerland.

Building integrated photovoltaics is the PV application that attracted the highest number of publications to date, as illustrated in Figure 32c. The interest in floating photovoltaics has increased over the past 4 years and so has the number of related publications. Agrivoltaics-related publications surpassed publications related to floating PV after 2021 and vehicle integrated photovoltaics has started attracting more attention after the same year. The EU, from 2013 until 2023, has published the highest number of papers on building integrated photovoltaics making up for 22 % of the total number of papers on the topic globally. China follows with 18 %. More than 22 % of the EU's publications on building integrated photovoltaics come from Italy. Spain followed with 16 % and Germany with 12 % of the EU's building integrated photovoltaics publications. Even though the EU has the highest number of papers on building integrated photovoltaics, the highly-cited ones represent only 24 % of the total. By comparison, China's highly-cited papers on building integrated photovoltaics represent 34 % of the total. China has a higher FWCI than the EU (2.5 against 1.9). The United Kingdom's and the United States' highly cited publications are 33 % and 30 % of the global building integrated photovoltaics publications respectively and the countries have FWCIs of 2.8 and 2.1 respectively. In this field, collaborations are multiple and different depending on the specific application. In the field of vehicle integrated photovoltaics strong collaborations are identified between EU-Japan, EU-United States, EU-Switzerland and China-South Korea-India. At EU level, Spain and France are co-publishing several papers on building integrated photovoltaics, just like the Netherlands and Germany on vehicle integrated photovoltaics.

2.8 Assessment of R&I project developments

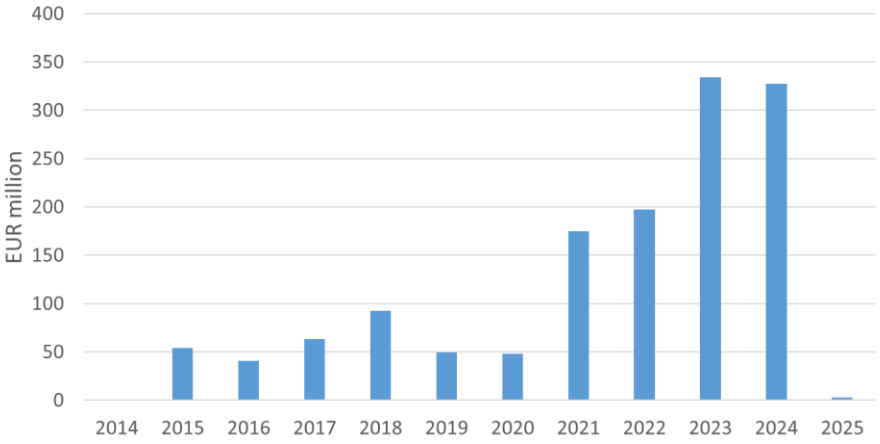
The assessment of the R&I developments covers the 2014 to 2024 period and includes projects from Horizon 2020, Horizon Europe, LIFE, LIFE2027, Innovation Fund (IF), Connecting Europe Facility (CEF), Connecting Europe Facility 2027 (CEF2027), Renewable Energy Financing Mechanism (RENEWFM), European Maritime and Fisheries Fund/European Maritime, Fisheries and Aquaculture Fund (EMFF/EMFAF) and European Research Council (ERC).

From 2014, a total of approximately EUR 1.4 billion has been invested in three hundred and forty four PV projects. Of this amount, EUR 309 million were granted to projects that were concluded by 2023 and the remaining EUR 1 072 million concern ongoing projects that will be concluded after 2024. Of the overall EU funding, almost 30 % of the project budget is directed to research on innovation, followed by budget for fellowships awarded by the Marie Skłodowska-Curie programmes (24 %). Coordination actions accounted for 15 % of the overall EU funding, grants to researchers provided by the European Research Council (ERC) attracted another 12 % and actions for SMEs another 10 %. Other actions under the Connecting Europe Facility-Energy, LIFE and the Renewable Energy Financing Mechanism attracted the remaining 9 %.

Small projects receive below EUR 1 million in funding whereas large projects receive funding over EUR 1 million. There have been 264 large projects identified which received approximately EUR 1 365 million in funding, corresponding to 99 % of the total EU financial contribution and 80 small projects which received around EUR 17 million, corresponding to the remaining 1 % of the total EU financial contribution to projects.

Funding in 2014 was only EUR 50 000 and is not visible in Figure 35. The year with the highest EU financial contribution was 2023 when EUR 330 million were granted to PV-related projects. In 2024 the EU financial support to projects amounted to EUR 327 million, of which 63 % (EUR 206 million) were through the Innovation Fund (IF). The biggest contribution went to HOPE project (EUR 200 million). Also in 2021 (the second year of the programme), 70 % of the EUR 174 million presented in Figure 35, came from the IF and were dedicated to TANGO project.

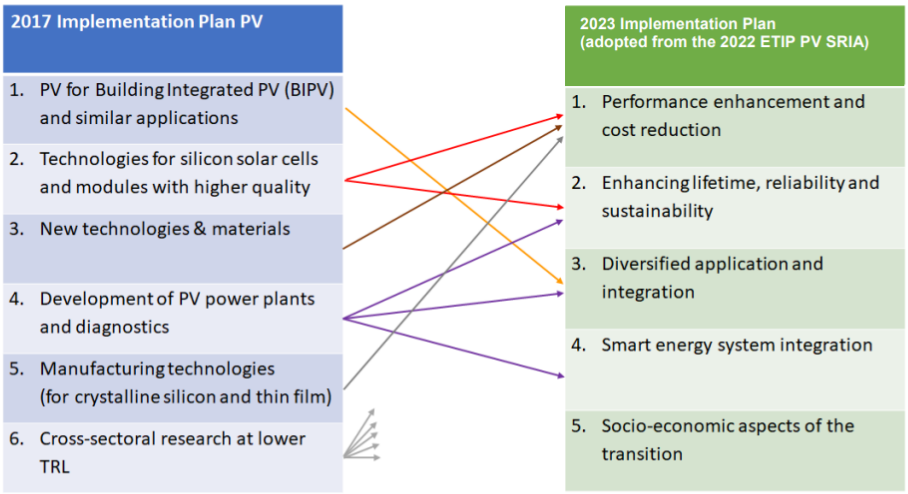
Figure 35. EU funding contribution for the period 2014-2025.



Source: JRC analysis based on data compilation

The 2023 revised PV Implementation Plan (Figure 36) adopts the challenges and corresponding targets and R&I topics from the 2022 ETIP-PV SRIA (SNETP, 2022). This will contribute to a common understanding of PV R&I priorities at European and Member State levels and facilitate the alignment of R&I and cross-border collaboration aimed for (IWG PV-Implementation Working Group on Photovoltaics, 2023).

Figure 36. Transfer of the 2017 PV Implementation Plan activities to the 2023 PV Implementation Plan activities.



Source: (IWG PV-Implementation Working Group on Photovoltaics, 2023)

According to Table 6, half of the EU funding was dedicated to research on enhancing the performance of PV modules and/or reducing their costs. R&I on different applications and integrations of PV received 20 % of the EU's funding budget, while one-fourth was given to projects related to lifetime enhancement, reliability and sustainability together with research on how PV can be smartly integrated into the energy system.

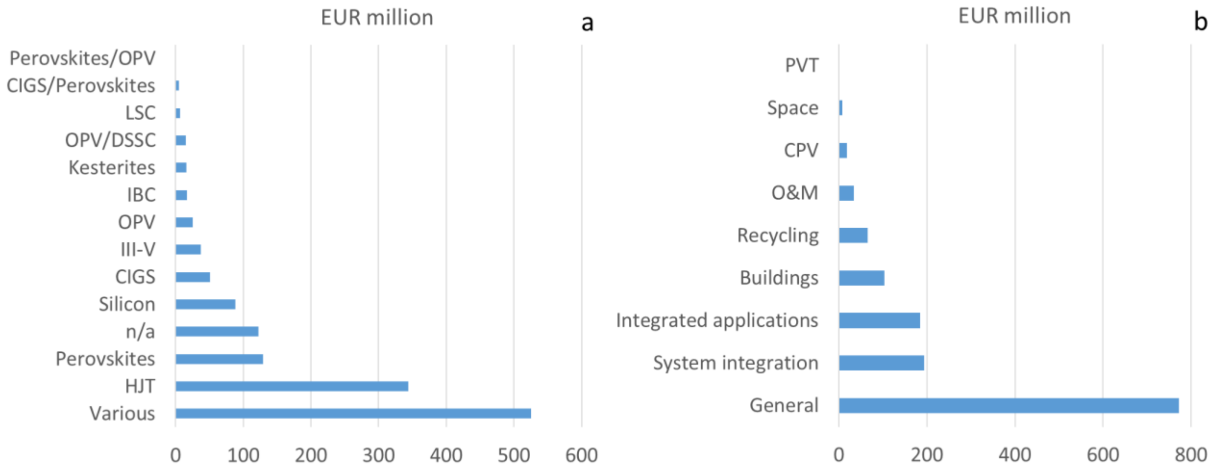
Table 6. EU contribution per 2023 SET Plan PV IWG priorities.

Priority		**EU funding [EUR million]**	**EU funding [% of total]**
1	Performance enhancement and cost reduction	693	50 %
2	Enhancing lifetime, reliability and sustainability	161	12 %
3	Diversified application and integration	273	20 %
4	Smart energy system integration	184	13 %
5	Socio-economic aspects of the transition	39	3 %
1 & 2	Performance enhancement and cost reduction & Enhancing lifetime, reliability and sustainability	32	2 %
Total		1 383	100 %

Source: JRC analysis based on data compilation

In terms of PV technology (Figure 37a), projects for HJT modules received approx. EUR 344 million (25 % of the total EU contribution for the period 2014-2025), mainly due to the TANGO and HOPE projects (EUR 318 million together). However, it must be noted that these two projects were funded through the IF funding scheme as big flagship projects with European added value. The second most funded technology is that of perovskites. Perovskite technology (as pure perovskite or in combination with other technologies), received EUR 134 million or 10 % of the EU's total funding budget. Silicon technology remains a higher priority in R&I in comparison to other less promising technologies such as CIGS, kesterites or organic PV, with 6 % of the funding. According to Figure 37b, applications characterised as "general" account for most of the funding (TANGO and HOPE projects included in this category), followed by system integration and integrated applications (EUR 194 million and EUR 185 million respectively). Building applications, with EUR 104 million in total, accounted for 7 % of the total EU funding, whereas recycling for 5 % with approx.. EUR 65 million being dedicated to research for end-of-life PV.

Figure 37. EU contribution per (a) PV technology and (b) application.



Source: JRC analysis based on data compilation

The breakdown to country level finds Germany being the country participating in most H2020 and Horizon Europe projects (155) from 2014 until 2025, followed by Spain, Italy and France with 125, 117 and 99 projects respectively. Germany, Spain, Italy and France together, account for approximately 66 % of the total H2020 and Horizon Europe funding for the period 2014-2025 (EUR 715 million). The individual funding received was EUR 161 million for Germany, EUR 138 million for Spain, EUR 85 million for Italy and EUR 91 million for France.

From the total number of 344 projects, 87 were used for a TRL analysis. From these 87 projects, 28 started at TRLs 4-5 (prototype) receiving 20 % of the EUR 813 million, while 31 started at a TRL 6-7 (validation) receiving 33 % of the budget. Projects of higher TRL 8-9 (production) represent 17 % of the total number of projects but received the most EU funding (40 %). The evaluation of the target TRL is more difficult as there are several other projects for which a stating target TRL is missing. Table 7 presents the 87 projects with their starting and target TRLs, in combination with the received EU funding.

Table 7. EU funding in EUR million and number of projects () with starting and target TRLs for 87 EU funded projects.

Starting TRL	**Target TRL**										
	n/a	TRL1	TRL2	TRL3	TRL4	TRL5	TRL6	TRL7	TRL8	TRL9	Total
TRL1											
TRL2					12 (3)						12 (3)
TRL3						38 (9)	5 (1)				43 (10)
TRL4						8 (2)	13 (2)	6 (1)			27 (5)
TRL5	69 (16)							64 (7)			133 (23)
TRL6	7 (1)							38 (2)	43 (4)		88 (7)
TRL7	183 (24)										183 (24)
TRL8	21 (6)										21 (6)
TRL9	308 (9)										308 (9)
Total	587 (56)				12 (3)	46 (11)	18 (3)	107 (10)	43 (4)		813 (87)

Source: JRC analysis based on data compilation

As far as the PV technologies and the related TRLs are concerned, it is identified that most of the EU funding is directed to projects related to CIGS technology start from TRL5 and those for IBC and HJT technology between TRL5 and TRL7. Perovskites exhibit a wider range of TRLs, from 3 to 7. The mature silicon technology projects are with TRLs from 7 to 9. In the case of PV applications, most of the EU funding is directed to projects related to integrated applications with TRLs between 7 and 8, recycling with TRL5-7 and projects related to system integration that exhibit the highest TRLs (8-9).

A list of the concluded, as well as the ongoing projects receiving EU financial funding, can be found in Annex 4. The list includes R&I projects with a starting date from 2014 until 2025.

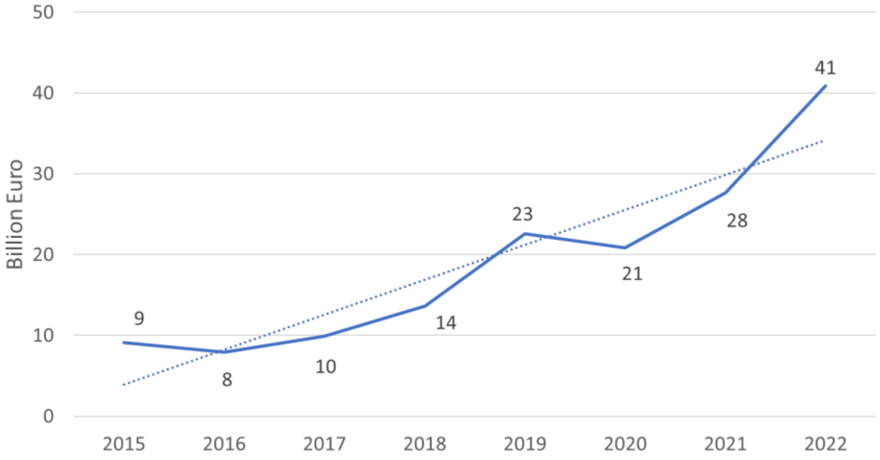
The second Horizon Europe Strategic Plan includes the “European Co-Programmed Partnership on Solar Photovoltaics (PV)”. The Partnership will promote the industrial engagement in PV R&I to support the innovation ecosystem across the full PV value chain. It will represent the R&I pillar of the EU Solar PV Industry Alliance (European Commission, 2024c).

3 Value Chain Analysis

3.1 Turnover

The EU PV turnover in 2022 was approximately EUR 41 billion, growing from EUR 28 billion in 2021. The slight decrease in turnover between 2019 and 2020, as depicted in Figure 38 was 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 PV turnover in the EU was 24 % between 2015 and 2022. Globally, the PV market is estimated to have reached a turnover of approximately USD 235 billion (EUR 223 billion[18]) in 2022 (Fortune Business Insights, 2023) and thus, the EU's share is 18.4 % of the total. In 2021 the EU's share was 16.5 %. The global turnover of the PV sector in 2023 amounts to USD 254 billion (EUR 238 billion[19]) (Fortune Business Insights, 2024).

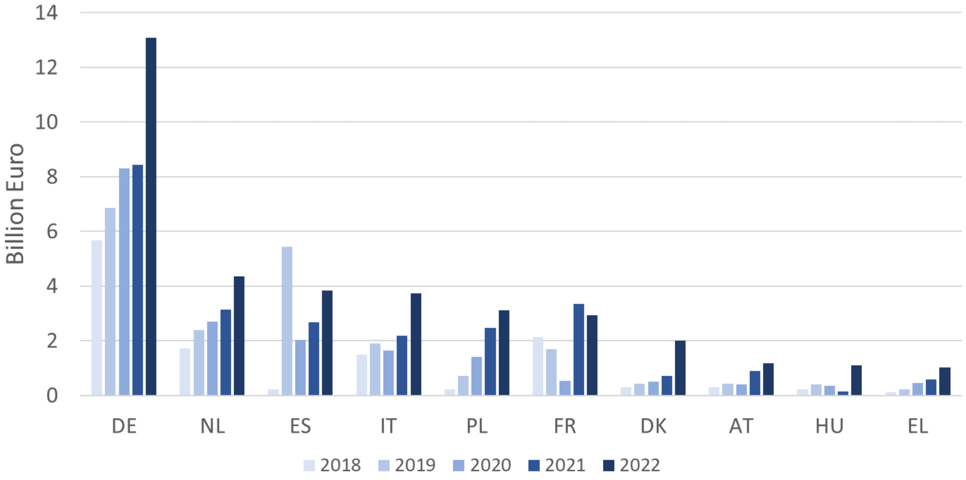
Figure 38. EU turnover in PV for the period 2015-2022.



Source: JRC analysis based on (EurObserv'ER, 2024a)

Germany, the Netherlands and Spain accounted for half of the EU's turnover in 2022, whereas the aggregated turnover of the top five countries in Figure 39 (Germany, the Netherlands, Spain, Italy and Poland) makes up for more than two-thirds of the EU's turnover in the same year.

Figure 39. EU turnover in PV for the top EU countries for the period 2018-2022.



Source: JRC analysis based on (EurObserv'ER, 2024a)

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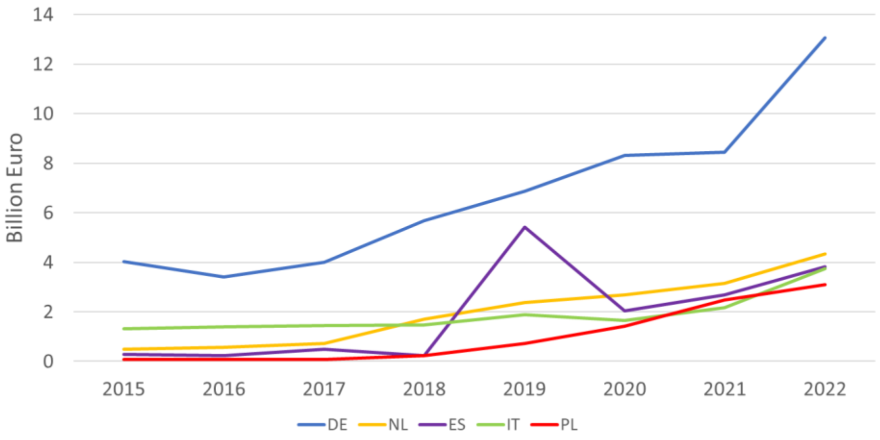
[18] Euro foreign exchange reference rates: 1 USD_{2022} = 0.9497 EUR_{2022} (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

[19] Euro foreign exchange reference rates: 1 USD_{2023} = 0.9371 EUR_{2023} (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

Germany and Netherlands have steadily increased their turnover from 2015 to 2022 with market compound annual growth rates of 18 % and 37 % respectively. The Spanish market recovered from the 2020's decrease in turnover, with CAGR of 37 % between 2020 and 2022, without though managing to reach its 2019 of EUR 5.5 billion turnover. France, on the other side, after reverting its market to higher than 2019 levels, has experienced another decrease (-13 %) in turnover between 2021 and 2022. While the above-mentioned countries are traditionally in the top five list for all the years, Poland constitutes an emerging market with a compound annual growth rate of 69 % between 2015 and 2022 (Figure 40).

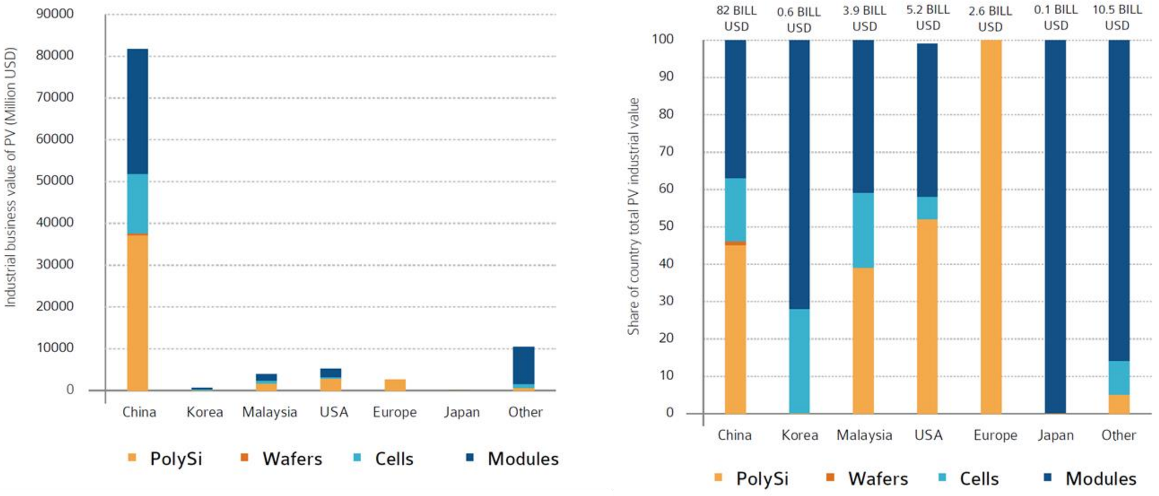
Figure 40. Turnover in PV for the top five EU countries for the period 2015-2022.



Source: JRC analysis based on (EurObserv'ER, 2024a)

In addition to Poland, Lithuania and Sweden are two emerging markets with strong CAGRs of 56 % and 50 % respectively for the period 2015-2022. Italy demonstrates a rather low CAGR in turnover (16 %) between the same years.

Figure 41. (a) Absolute and (b) share of turnover along the upstream (polysilicon to module) value chain for major economies in 2023.



Source: (IEA PVPS, 2024b)

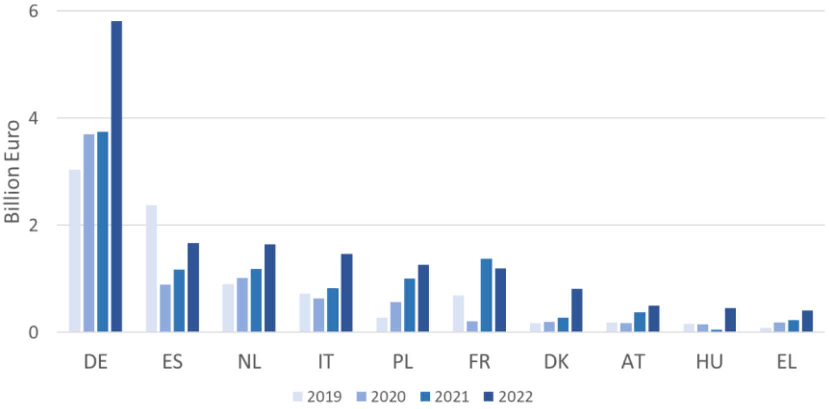
According to Figure 41a, China is dominant in all segments of the upstream (Annex 5) PV value chain (from polysilicon to modules production), accounting for 78 % of the global turnover in 2023. South Korea and Japan's turnover in the upstream (polysilicon to module) PV sector is attributed to modules, whereas Europe's turnover relies entirely on polysilicon (Figure 41b). Approx. 0.8 % of 2023 global GDP is due to the PV manufacturing sector. For China, the PV industry is responsible for 0.46 % of its GDP, while for Malaysia the respective percentage is around 1 % (IEA PVPS, 2024b).

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.

EU's GVA in PV exhibited a CAGR of 24 % between 2016 (EUR 4.6 billion) and 2022 (EUR 17 billion). At EU level and similarly to turnover, Spain had a remarkably high gross value added in 2019 that reached EUR 2.4 billion and then decreased to around EUR 0.9 billion in 2020 and ultimately followed an increasing trend to reach EUR 1.7 billion in 2022. France has decreased its gross value added by -13 % between 2021 and 2022. By contrast, most EU countries have increased their gross value added in 2022 compared to the previous years. Germany is again the leading EU market (Figure 42).

Figure 42. Gross Value Added (GVA) in PV for the top ten EU countries for the period 2019-2022.

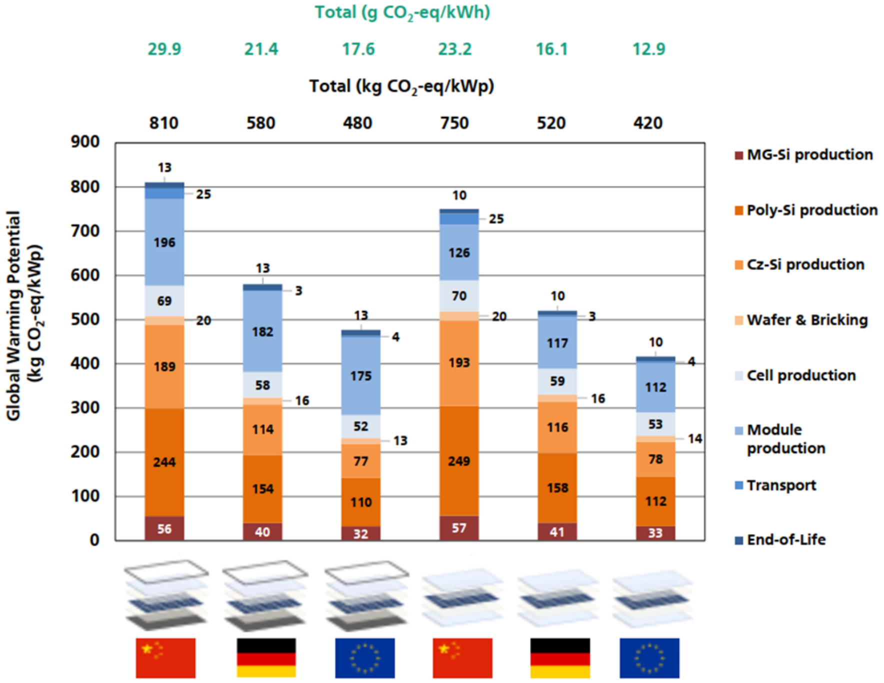


Source: JRC analysis based on (EurObserv'ER, 2024a)

3.3 Environmental and socio-economic sustainability

PV modules produced in China have a higher carbon footprint than those in the EU. PV modules manufactured in the EU produce 40 % less CO_2 than PV modules manufactured in China (Fraunhofer ISE, 2021). This is mainly attributed to the polysilicon (poly-Si) and the monocrystalline Czochralski silicon (Cz-Si) production. Regarding the different PV module configurations, the glass-glass PV modules have a slightly lower carbon footprint compared to the traditional backsheet and framed PV modules (Figure 43).

Figure 43. Carbon footprint of different PV module configurations in different countries.



Source: (ETIP-PV, 2023)

A fully-fledged and adapted methodology for PV module carbon footprint calculation, with particular regard to the manufacturing and shipping phases, has been proposed in 2023 (Polverini *et al.*, 2023). This method has the potential of being adapted to consider the full life cycle of PV modules, including end-of-life phase. It is a basis for the market requirements of the 'ecological profile' of products, according to the Ecodesign Directive (European Commission, 2022c).

Additional information environmental sustainability (Sustainability Assessment Framework (SAF) table) can be found in Annex 6.

3.4 Role of EU Companies

The analysis of the EU companies in the PV value chain is performed based on the structure presented in Figure 44.

Figure 44. PV value chain structure.

Source: JRC 2023

In June 2023, Norwegian Crystals, the mono c-Si ingot producer has declared bankruptcy, weakening the efforts for rebuilding the EU PV supply chain (Bernreuter Research, 2023a). In addition, in September 2023, NorSun SA announced a temporary suspension of its production, and ultimately also related employee layoffs, as a result of the pressure from the module oversupply in Europe (PV Magazine, 2023). The company has recently announced its intention to build 5 GW_p ingot and wafer manufacturing plant in the United States (PV Tech, 2024). At the end of 2023 and throughout 2024, several other manufacturers in the different steps of the PV supply chain like REC Silicon ASA, Exasun BV and Systovi SAS have closed their manufacturing facilities. Meyer Burger Technology AG is also considering a permanent closure of its production plant in Germany. Several other European companies are facing difficulties and are at risk of closure (Solitek, Voltec Solar, Bisol, Belga Solar, etc.) (S&P Global, 2024).

Regarding the raw materials of PV manufacturing the EU leading company in polysilicon is Wacker Chemie, while the main companies for solar glass are Interfloat Corporation (Germany), ENF Ltd. (Germany), Euroglas GmbH (Germany), Saint-Gobain (France) and Alliaverre (France). Endurans (the Netherlands), Coveme (Italy), Dunmore (Germany) and Aluminium Feron (Germany) are the main producers of backsheets and foils (ETIP-PV, 2023). Apart from the Austrian company Borealis, encapsulant producers are mainly located outside the EU, while silver paste producers in the EU are Heraeus (Germany), DuPont and Dycotec Materials (United Kingdom) (ETIP-PV, 2023).

Annex 7 presents the main EU companies for production equipment for polysilicon, ingot, wafer, cell and module as well as for module components, tracking systems and inverters. The information has been obtained from SolarPower Europe (SolarPower Europe, 2023c).

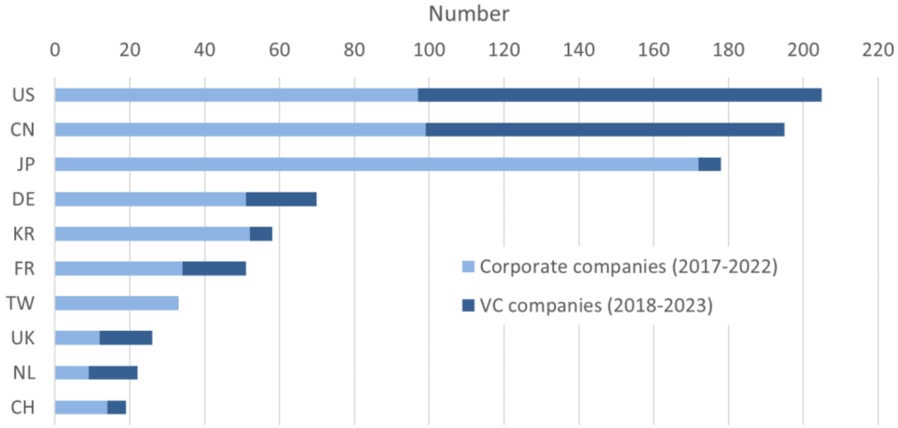
Some of the most important EU players in the "Monitoring & Controls" field are Green Power Monitoring, AlsoEnergy (which is a United States based company that operates partially in the EU), Solar-log and Meteo&Control. Regarding the Engineering, Procurement and Construction (EPC) segment, there are numerous companies and the market is highly fragmented. The same applies also for the deployment segment with major companies such as Enel Green Power, Engie and BayWa.re leading the market. In the recycling segment, the EU counts more than 15 recycling companies. Some, indicatively, that are dealing with direct recycling of PV modules are Envaris, Reiling, Rieger & Kraft Solar and Rinovasol in Germany, La Mia Energia and Yousolar in Italy, Euresi and Solucciona Energia in Spain. Regarding the rest of the world, Switzerland and the United Kingdom also have PV recycling facilities, while the United States have an extended recycling market with more than 20 companies (CEM, Cleanlites Recycling, Dynamic Lifecycle, Echo Environmental, Exotech, Fab Tech, First Solar, Green Lights Recycling, Mitsubishi Electric, We Recycle Solar and others) (ENF, 2023).

As far as the promising perovskite technology is concerned, the material provision market is dominated by companies in the United States and Japan. Among the approximately twenty global material providers there is also Dyenamo in Sweden (Perovskite-info, 2023b). Two major EU module developers; Enel Green Power in Italy and Evolar in Sweden are among the twenty global market players for the perovskite technology, with the United States dominating. Oxford PV is an important company in the sector and is based in the United Kingdom (Perovskite-info, 2023c). The EU is a leader in the equipment manufacturing for the perovskite technology. Seven major companies are active in the sector: MBRAUN, Aixtron and Bergfeld Lasertech in Germany, FOM

Technologies and infinityPV in Denmark, SparkNano in the Netherlands and JACOMEX in France (Perovskite-info, 2023a).

Figure 45 presents the global innovating corporate and VC companies in the field of PV. However, it must be noted that the corporate companies included in the graph are the identified innovators between 2017 and 2022 unlike the VC innovators that are active in the period 2018 and 2023. The reason for this is that the updated patent dataset used to derive to the results is only an intermediary release and cannot be used to identify corporate innovators over the period 2018-23 in a way that is comparable with last year's report (Chatzipanagi, Jaeger-Waldau, Cleret de Langavant, *et al.*, 2023).

Figure 45. Innovating companies in the period 2017-2023.



Source: JRC analysis based on compilation of sources

Ten countries host almost 85 % of identified innovators globally (Figure 45). The United States concurs the first position with 20 % of the world's innovating companies, followed by China with a share of 19 %. Three EU countries are included in the top ten countries of innovating companies: Germany (4th), France (6th) and the Netherlands (9th). The United States (1st) and China (2nd) have a very strong base of venture capital companies while most of the innovators in Japan (3rd), Germany (4th) and South Korea (5th) are corporate innovators (Figure 45). Within the EU (hosting 21 % of the globally identified innovating companies), the Netherlands and Sweden report a stronger share of venture capital companies.

3.5 Employment

Employment in the PV sector is another parameter reflecting its market growth. Employment data differ based on the source as can be seen in Box 2. The discrepancies encountered in the different sources are a result of different methodological approaches in estimating the employment, both at EU as well as global level. From the 826 000 PV jobs in the EU in 2023, SPE estimates that 362 000 were direct. IEA-PVPS's estimation for the direct jobs created in 2022 is 500 000. IRENA reports direct and indirect jobs and estimates the EU PV jobs in 2023 to have amounted to 720 000. Taking these differences into consideration, caution is advised when evaluating the data. The present analysis uses data from EurObserv'ER and IEA-PVPS and completes where necessary with data from IRENA, namely for the global numbers. For the EU jobs of the different segments in the PV value chain, SPE data was used.

Between 2008 and 2016, the PV sector suffered a dramatic decrease in jobs. The compound decrease in total PV jobs in the EU was 15 %. 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_p of ground-mounted systems that were not maintained afterwards (EY, 2017).

Globally, PV jobs reached 7.2 million at the end of 2023 (IEA PVPS, 2024b) from 5.8 million in 2022 (IRENA and ILO, 2023) (IEA-PVPS, 2023). EU's PV jobs represented 10 % of the global PV jobs in 2023. EU's position in the world for the number of total PV jobs between 2020 and 2023 is depicted in Figure 46. According to IEA-PVPS, China, that has the largest PV market in the world, accounted for 65 % of the world PV jobs in 2023 (4.6 million jobs) (IEA PVPS, 2024b). In 2020, the EU was in the 4th place globally, after China, the United States and Japan. However, in 2023, the EU conquered the 2nd position behind China.

Box 2. Differences in EU and global PV employment data (PV jobs).

EU

	2020	**2021**	**2022**	**2023**
SolarPower Europe:	357 000	466 000	648 000	826 000
EurObserv'ER:	165 700	223 100	346 900	Not available yet
IEA-PVPS:	185 000	185 000	330 000	500 000
IRENA:	166 000	236 000	517 000	719 900

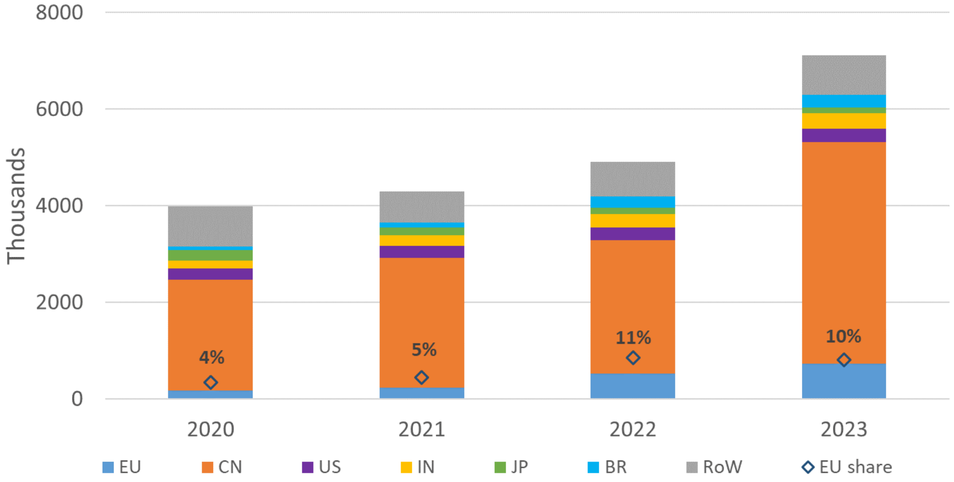
World

	2020	**2021**	**2022**	**2023**
IRENA:	3 980 000	4 290 000	4 900 000	7 100 000
IEA-PVPS:	3 980 000	4 290 000	5 800 000	7 200 000

Source: (SolarPower Europe, 2021a, 2022, 2023b, 2024a; IEA-PVPS, 2021, 2022, 2023; IRENA and ILO, 2021, 2022, 2023, 2024; EurObserv'ER, 2022, 2024a; IEA PVPS, 2024b)

In 2023, the share of jobs in the upstream segment was 26 % (vs. 74 % share of jobs in the downstream activities) (IEA PVPS, 2024b). A 2022 report from Fraunhofer ISE (Fraunhofer ISE, 2022) suggests that 7 500 full-time equivalents (FTEs) are needed for the production of 10 GW_p of PV generation assets from silicon ingot via wafer and cell to module, whereas the installation of 10 GW_p of PV requires 46 500 FTEs, suggesting a standard ratio of 14 % for upstream versus 86 % for downstream activities (Fraunhofer ISE, 2022). In general, small scale PV generates more jobs than utility-scale PV (IEA-PVPS, 2023).

Figure 46. Global direct and indirect PV jobs and EU share between 2020 and 2023.

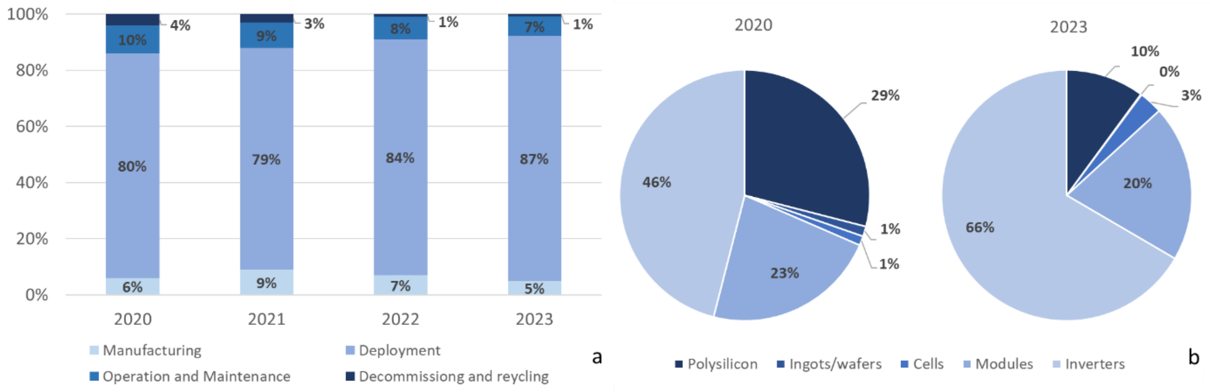


Source: JRC analysis based on (IEA-PVPS, 2019, 2020, 2021; IRENA and ILO, 2021; IEA-PVPS, 2022; IRENA and ILO, 2022; EurObserv'ER, 2022; IEA-PVPS, 2023; IRENA and ILO, 2023)*(EurObserv'ER, 2024a)*(IRENA and ILO, 2024)(IEA PVPS, 2024b)

Figure 47a and b present the disaggregated shares in the different segments of the PV value chain from 2020 until 2023. Throughout the four previous years, the majority of EU jobs was on PV deployment, growing from 80 % share in 2020 to 87 % in 2023 (Figure 47a). In the manufacturing segment, inverter manufacturing jobs grew from 46 % share in 2020 to 66 % share in 2023, while jobs in polysilicon manufacturing decreased from 29 % share to 10 % share in the same years (Figure 47b).

As far as PV jobs with relation to applications are concerned, in 2023, 68 % (from 73 % in 2022) of the jobs in the EU were for rooftop and 32 % for utility applications. The country with the highest proportion (68 %) of jobs in the utility-scale sector for 2023 was Spain. For rooftop applications, the highest proportion of jobs can be found in Italy and Romania (close to 85 %) as well as Poland, Germany, France and the Netherlands (close to 70 %) (SolarPower Europe, 2024a).

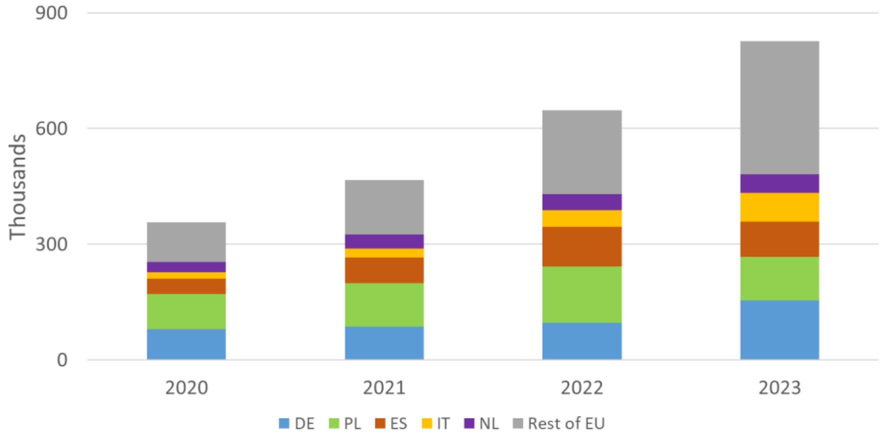
Figure 47. (a) Employment in PV value chain segments and (b) employment in manufacturing segment share between 2020 and 2023.



Source: JRC analysis based on (SolarPower Europe, 2023b)(SolarPower Europe, 2024a)

As depicted in last year's report (Chatzipanagi, 2022), there was a decrease in EU PV jobs between 2019 and 2020, mainly due to the significant respective decreases which took 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 power installed decreased from about 5 GW_p in 2019 to 3 GW_p in 2020. As the annual PV installations increased between 2020 and 2021 by 4.5 GW_p, so did the related jobs by 33 %. Of course, it has to be noted that 2020 was the year when Covid-19 occurred and disruptions took place both in the upstream as well as the downstream activities. In absence of employment data for 2023 from EurObserv'ER, this report presents EU direct and indirect jobs based on SolarPower Europe (SPE) (Figure 48). Despite the difference in absolute numbers between SPE and EurObserv'ER (SPE reports double the PV jobs compared to EurObserv'ER due to the different assumptions in methodology), the ranking and share of EU countries is in good accordance between the two different data sources, enabling a qualitative analysis of the EU situation. Most PV jobs have been created in Germany, the country with the biggest PV market and the largest installed PV power in the EU. For 2023, in Germany, the total number of jobs increased by 61 % compared to 2022. Germany is followed by Poland. Poland was the leading EU country in terms of PV jobs in 2021 and 2022 but decreased its PV jobs by 20 % in 2023 compared to 2022 mainly due to the country's shift from residential to utility-scale installations. Nevertheless it still has a significantly strong PV jobs market in the EU. Favorable policies for residential installations have resulted in an 80 % increase of PV jobs in Italy between 2022 and 2023.

Figure 48. EU direct and indirect PV jobs between 2020 and 2023.



Source: JRC analysis based on (SolarPower Europe, 2021b, 2022, 2023b, 2024a)

Regarding projections for 2028, SPE devised 3 different scenarios. These are the low, medium and high scenarios that are based on different assumptions[20]. Growth projections for 2028 range between a reduction of 19 % according to the low scenario and an increase of 70 % in PV jobs according to the high scenario. The medium scenario projects an increase of a bit more than 20 % PV jobs increase in 2028.

According to SPE's above-mentioned medium scenario jobs are expected to more than double in 2028 in the manufacturing sector, increase by 20 % in the deployment sector and by 87 % in the O&M sector. Jobs related to recycling activities are expected to grow by 89 % in 2027 (SolarPower Europe, 2024a). SPE also projects that the portion of rooftop-related jobs will decrease from 68 % in 2023 to 60 % in 2028 (SolarPower Europe, 2024a).

In the manufacturing sector, according to (ETIP-PV, 2023), the number of employees for the mg-Si and polysilicon process are estimated at 144 and 672 full-time equivalent jobs, respectively and include operators, technicians and engineers, with operators being the profession with the highest share in both processes (approx. 75 %). For the rest of the manufacturing segments and considering a 10 GW_p TOPCon manufacturing plant, for the ingot and the wafer processes, the number of jobs required are 1 715 and 1 808 respectively. For the cell and module production, the 1 441 and 3 179 full-time equivalent jobs are necessary. Again, operators make up for most of the jobs in comparison to technicians and engineers. Of course, it has to be noted that the level of automation is constantly increasing. Regarding the deployment sector, jobs may be less stable than in the manufacturing sector but can benefit local communities and economies. According to SPE, for a 10 MW_p ground-mounted system 2-4 design engineers, 1-2 electricians and approx. 45 construction workers are needed. For a 10 kW_p rooftop system 1 electrician and 4 construction workers are needed (SolarPower Europe, 2024a).

One third of the total jobs in renewable energies is in the PV sector (IEA PVPS, 2024b). Women represent 40 % of the total employees in the PV sector, the highest share in all renewable energies and oil and gas sector. Most women in the PV sector are employed in administrative positions (58 %), followed by non-STEM (science, technology, engineering and mathematics) technical positions. The share of women in STEM jobs is 32 % (the global average is 35 %) (IRENA and ILO, 2023).

Reskilling and upskilling workers is fundamental for the PV sector, as many workers are shortly going into retirement. At the same time, the needs for workers will continue to grow along with the planned manufacturing expansions as well as the planned installations in the next years.

Concerns have risen over the years regarding forced labour particularly in the Uyghur Region in China, which now accounts for approximately 35 % of the world's polysilicon (down from 45 %) and as much as 32 % of global metallurgical grade silicon production. The vast majority of modules produced globally continues to have exposure to the Uyghur Region (Crawford and Murphy, 2023).

3.6 Energy intensity and labour productivity

3.6.1 Energy intensity

The Energy Return on Investment (EROI) (in terms of electricity) of different PV technologies and at different irradiation levels can be seen in Figure 49. The highest EROI is observed for the CdTe technology in the United States, whereas the lowest for CIGS PV systems in Japan.

According to Fraunhofer ISE, in the past 24 years, the Energy Payback Time (EPBT) of PV has experienced a decrease of 12.8 %. Depending on the location and the technology used for the PV system, its EPBT can be as low as 0.9 years (South Europe), while in the Northern European countries it slightly exceeds the one year (Fraunhofer ISE, 2024). EPBT for PV systems produced in Europe is shorter than for those produced in China because of better grid efficiency[21] in Europe (Fraunhofer ISE, 2024). Additional information can be found in Annex 6. Figure 50 shows presents an EPBT comparison between different PV technologies at different irradiation levels in different global locations.

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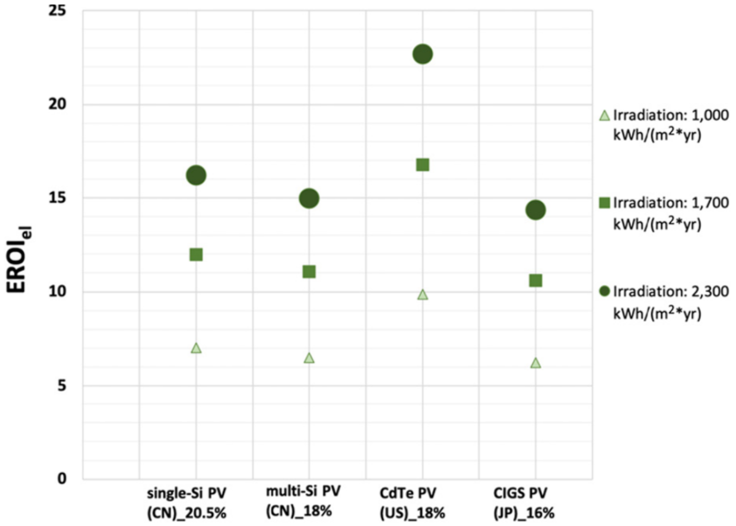
[20] Low Scenario: policymakers halt solar support and other issues arise, including interest rate hikes and severe financial crisis situations. Medium Scenario: most likely development given the current state of play of the market. High Scenario: best optimal case in which policy support, financial conditions and other factors are enhanced.

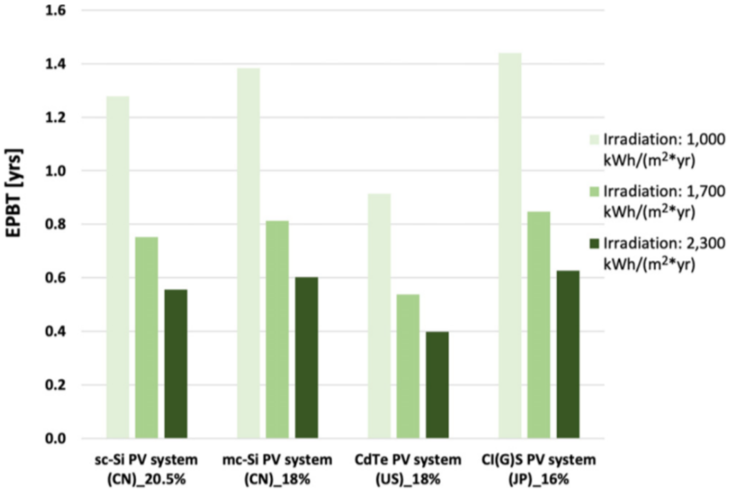
[21] The higher, the better in countries where upstream production is located; (better energy mix to generate electrical power; less losses in the electrical transmission network). At downstream (where PV is installed) a low grid efficiency reduces the EPBT (Fraunhofer ISE, 2023).

Figure 49. Energy Return on Investment of different technology PV systems, under three irradiation levels in different global locations.



Source: (Fthenakis and Leccisi, 2022)

Figure 50. Energy Pay Back Times of different technology PV systems, assuming three irradiation levels in different global locations.

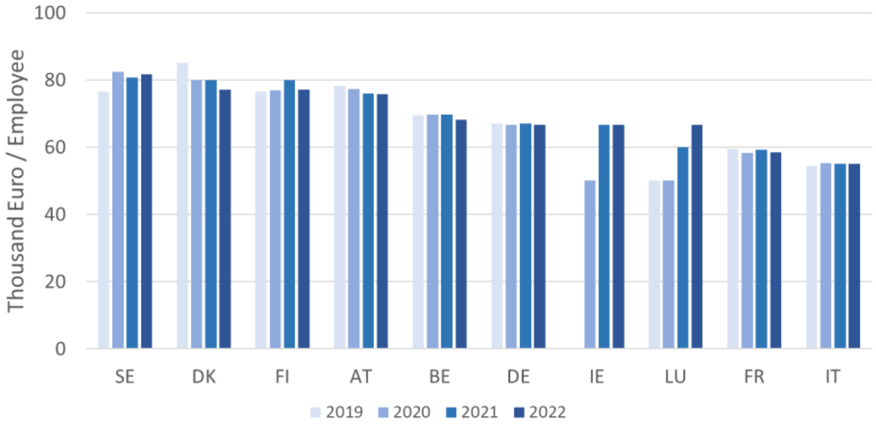


Source: (Fthenakis and Leccisi, 2022)

3.6.2 Labour productivity

The labour productivity of the entire PV value chain for the years 2019, 2020, 2021 and 2022 is presented in Figure 51. The most job-intensive segments along the upstream PV supply chain are module and cell manufacturing. Over the last decade, however, the use of automation and automated guided vehicles has increased labour productivity, thereby reducing labour intensity (IEA, 2022b). Sweden has been has been the leader in PV labour productivity in 2020, 2021 and 2022. Germany demonstrates a stable labour productivity while Ireland and Luxemburg have demonstrated an increasing labour productivity in 2021 and 2022.

Figure 51. PV labour productivity in the EU between 2019 and 2022.



Source: JRC analysis based on EurObserv'ER

3.7 EU Production Data

No production codes are explicitly associated with photovoltaics. The selected Prodcom[22] codes, (Table 8) correspond to vague product groups that include solar cells, semiconductor devices and photovoltaic cells. However, they can be used as a proxy for understanding the trends.

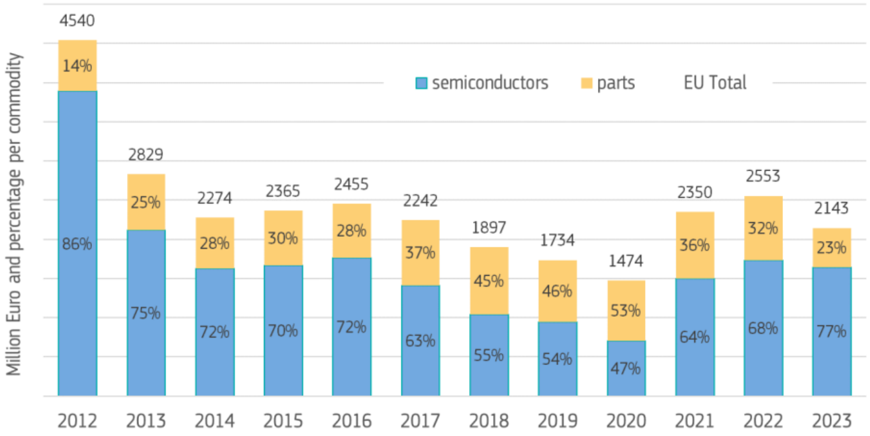
Table 8. Prodcom codes as a proxy for PV production.

HS code	Description	Alias
26114070	Parts of diodes, transistors and similar semiconductor devices, photosensitive semiconductor devices and photovoltaic cells, light-emitting diodes and mounted piezo-electric crystals	Semiconductors
26112240	Photosensitive semiconductor devices; solar cells, photo-diodes, photo-transistors, etc.	Parts

Source: JRC analysis based on PRODCOM

Figure 52 shows the EU production in value. Over the past twelve years (2012-2023), the overall production value demonstrated a compound decrease of 7 % with an average value of EUR 2.4 billion. In 2023, the total value had a 16 % increase compared to the previous year, reaching EUR 2.1 billion. Semiconductors occupy the biggest share of the EU production value, while, in 2023, the production value of parts decreased by -40%, reaching EUR 500 million. Germany and Italy were the top EU producers (Figure 53), holding one third of the total EU production together (three-year average), without Germany reporting its production value for 2023.

Figure 52. EU production value per commodity for the period 2012-2023.



Source: JRC analysis based on PRODCOM

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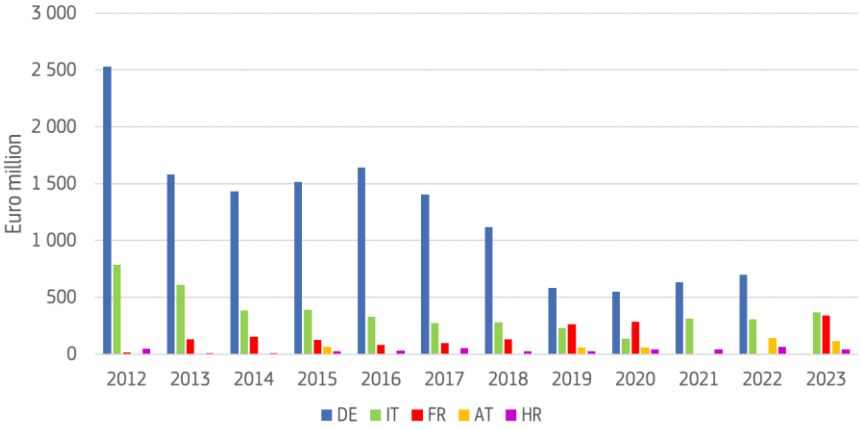
[22] PROduction COMmunautaire (Community Production)

Figure 53. Top five EU PV producers for the period 2012-2023.



Source: JRC analysis based on PRODCOM

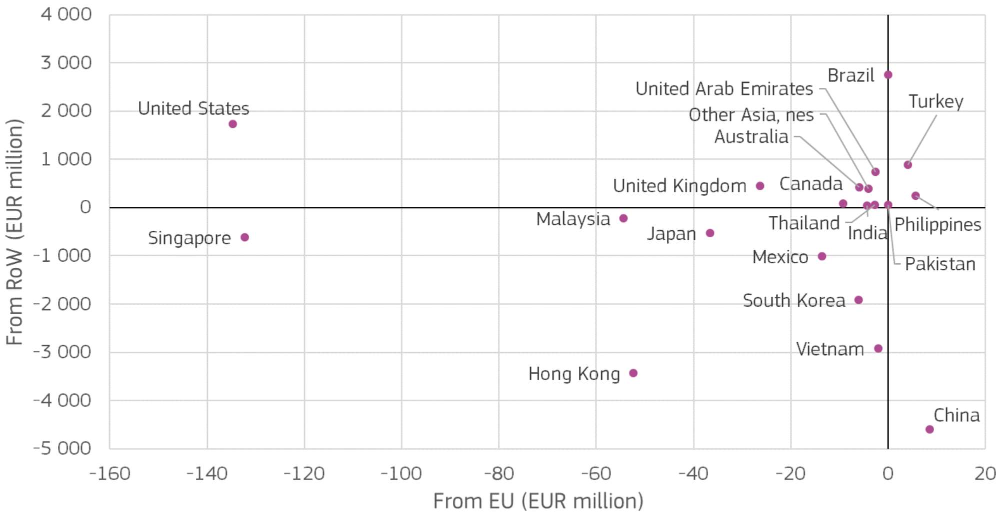
4 EU Market Position and Global Competitiveness

4.1 Global & EU market leaders

Figure 54 demonstrates EU's position in different markets for the period 2020-2022. The horizontal axis shows the 2-year average of net import change from the EU and the vertical axis shows the 2-year average of the net import change from the rest of the world. Countries in quadrant I (above the horizontal axis and right of the vertical axis) are considered to have a growing market (increase of imports). Countries in quadrant III (below the horizontal axis and left of the vertical axis) have less imports.

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 10 % lower than in India, 30 % lower than in the United States and 60 % lower than in Europe. This is due to China's lower energy, labour and investment costs, higher investments and implementation of vertical integration. These above mentioned cost differences may increase to 70 % for India, 100 % for the United States and 140 % for the EU by 2028 (IEA, 2024c). In Europe, rising energy prices following the geopolitical circumstances of years 2021-2022 widened the cost gap with China. In 2022, EU industrial energy prices are more than triple those of China, India and the United States (IEA, 2022a).

Figure 54. EU positioning in different markets with 2-year average (2020-2021 and 2021-2022) of change in import from the EU and RoW.



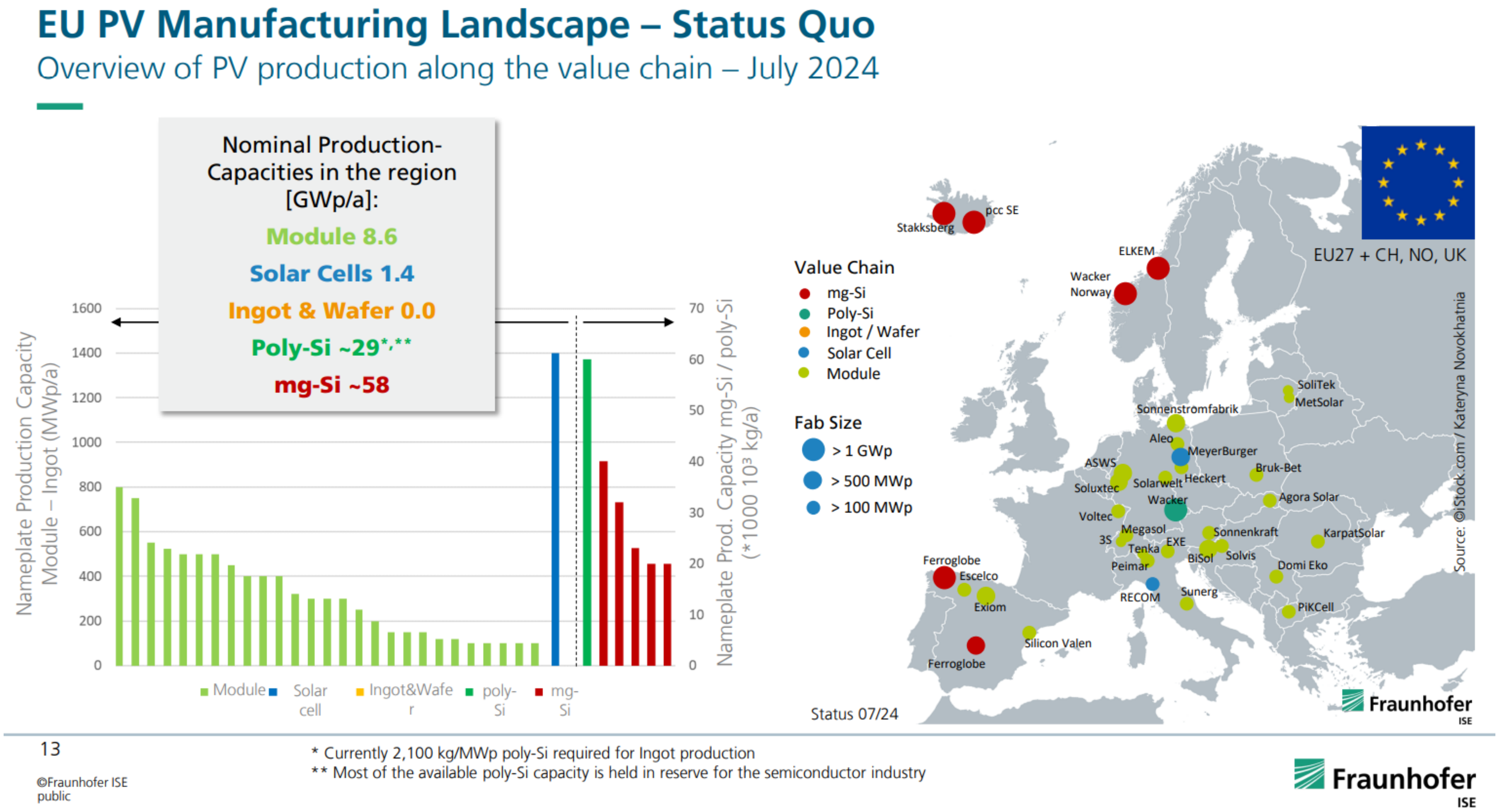
Source: JRC based on UN Comtrade data

In the EU, at the end of 2023, the polysilicon manufacturing was between 28 GW_p and 29 GW_p, depending on the source of information. The manufacturing capacity of ingots and wafers varied between 0 and 0.25 GW_p, while that of cells between 1 GW_p and 1.5 GW_p. As far as modules are concerned, production capacity was determined between 8.5 GW_p and 11 GW_p (Figure 55) (Bloomberg New Energy Finance, 2024f; Fraunhofer ISE, 2024; Sinovoltaics, 2024). However, taking into consideration the most recent announcements of closures and re-organisations ((S&P Global, 2024), the production capacity in the EU reduces to approx. 6 GW_p, (the rest are characterised as unmodern sleeping module lines, not been operational in 2023). According to the European Solar Manufacturing Council's (ESMC) estimations only around 2 GW_p of PV modules were actually produced in 2023, with 0.8–1 GW_p of them remaining still in the manufacturers' inventories unsold, while the surplus of imported modules is currently between 70 and 85 GW_p (ESMC, 2024).

The commissioned manufacturing facilities globally reached 963 GW_p for polysilicon, 1 871 GW_p for ingots and wafers, 994 GW_p for cells and 1 154 GW_p for modules. As seen also in Figure 56, EU's market share is significantly small in polysilicon and module production and almost inexistent in ingot, wafer and cell production (Bloomberg New Energy Finance, 2024f).

In 2015 China accounted for 65 % and 69 % of the global PV cell and module (crystalline and thin-film) production capacity respectively (IEA PVPS, 2016). In 2023, the country increased its share to 87 % and 82 % for cell and module production capacity respectively while the EU accounted for only 0.3 % and 0.9 % respectively (Bloomberg New Energy Finance, 2024f).

Figure 55. PV manufacturing capacities in the EU in July 2024.



EU PV Manufacturing Landscape – Status Quo

Overview of PV production along the value chain – July 2024

Nominal Production-
Capacities in the region
[GWp/a]:

Module 8.6

Solar Cells 1.4

Ingot & Wafer 0.0

Poly-Si ~29*,**

mg-Si ~58

Status 07/24

EU27 + CH, NO, UK

* Currently 2,100 kg/MWp poly-Si required for Ingot production

** Most of the available poly-Si capacity is held in reserve for the semiconductor industry

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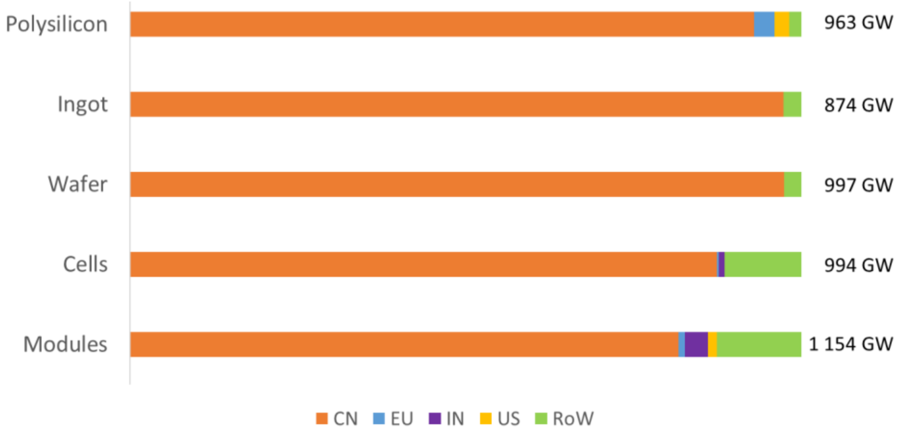
Source: (Fraunhofer ISE, 2024)

Vietnam and Malaysia hold a significant and increasing share in cell and module manufacturing capacities (5 % of the global manufacturing for each in 2023 (Bloomberg New Energy Finance, 2024f)) as countries in which major Chinese solar cell manufacturers have built production lines in an attempt to overcome the barrier of the USA antidumping duties and countervailing duties imposed on Chinese products (IEA-PVPS, 2023).

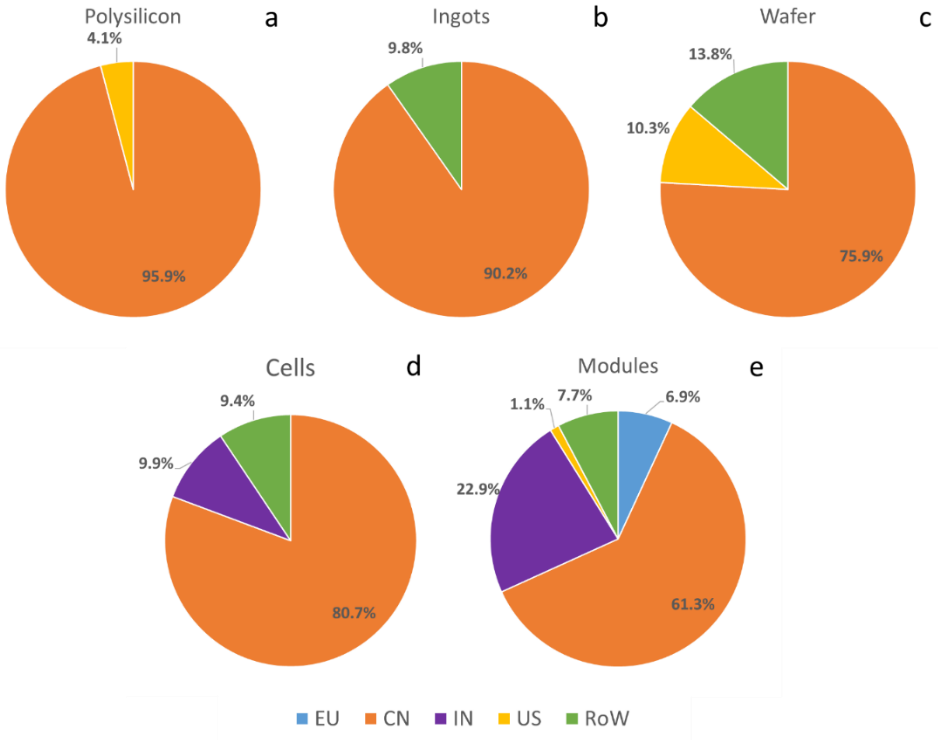
Figure 56. Commissioned manufacturing capacities in the PV supply chain in 2023.



Source: (Bloomberg New Energy Finance, 2024f)

Figure 57 shows the shares of major PV economies regarding the manufacturing capacities under construction. The EU is stepping up with manufacturing plants accounting for 7 % of the global module capacities under construction. India holds a 23 % share in the same segment and China a 61 %. India is constructing more facilities for the production of cells, with a share of 10 % of the global total. On the other hand, the United States is investing on under construction capacities mostly for polysilicon (REC Silicon) and wafers (Bloomberg New Energy Finance, 2024f).

Figure 57. Under construction manufacturing capacities share in the PV supply chain in 2023.



Source: (Bloomberg New Energy Finance, 2024f)

The announced future manufacturing capacities for different countries and regions in the different steps of the PV chain are more uncertain as they are highly dependent on the investment availability, overcapacity and market competition. However, also in the case of future planned capacity additions, China is leading the way with share between 70 % and 98 % depending on the segment. The United States plan to expand their manufacturing capabilities in all segments, with a particular emphasis on cells and modules (6.5 % and 15.3 % of the global announced cell and module capabilities) (Bloomberg New Energy Finance, 2024f). According to Bloomberg, the EU plans on expansion for cell and module manufacturing capacities, accounting for almost 2 % and 3.5 % of the global announced capabilities respectively (Bloomberg New Energy Finance, 2024f). More recent information regarding the planned expansions in the EU include 2 GW$_p$ (0.7 % of global announcements) for ingots, 10 GW$_p$ (3.5 % of global announcements) for wafers, almost 20 GW$_p$ (5 % of global announcements) for cells and around 30 GW$_p$ (9.5 % of global announcements) for modules (Sinovoltaics, 2024).

The global players in polysilicon, cell and module production are presented in Table 9.

Table 9. Top five global manufacturers for polysilicon, wafer, cell and module production in the period 2020-2023.

Company	**2020**	**2021**	**2022**	**2023**
	Polysilicon production (MT)			
Tongwei	86,195	109,341	266,900	389,000
GCL Tech	75,300	104,506	169,224	232,256
DAQO	77,288	86,587	133,812	197,800
TBEA (Xinte)	65,000	78,200	125,900	191,300
Asia Silicon	22,000	22,000	50,000	105,000
	Wafer production (GW)			
TCL Zhonghuan				133.7
Longi				127.5
Jinko				76
GCL Tech				51.1
JA Solar				50.1
	Cell production (GW$_p$)			
Tongwei	21.4	32.9	49.2	80.8
Jinko	11.0	13.0	32.7	63.9
Longi	18.0	25.0	36.2	55.0
Trina Solar	7.9	18.9	33.6	44.3
Aiko	13.3	19.5	33.7	40.1
	Module production (GW$_p$)			
Jinko	18.8	23.0	45.0	83.9
Longi	26.6	38.5	48.2	72.8
Trina	16.4	24.8	45.4	60.7
JA Solar	15.9	25.8	40.0	60.0
Canadian Solar	10.3	14.5	21.1	31.4

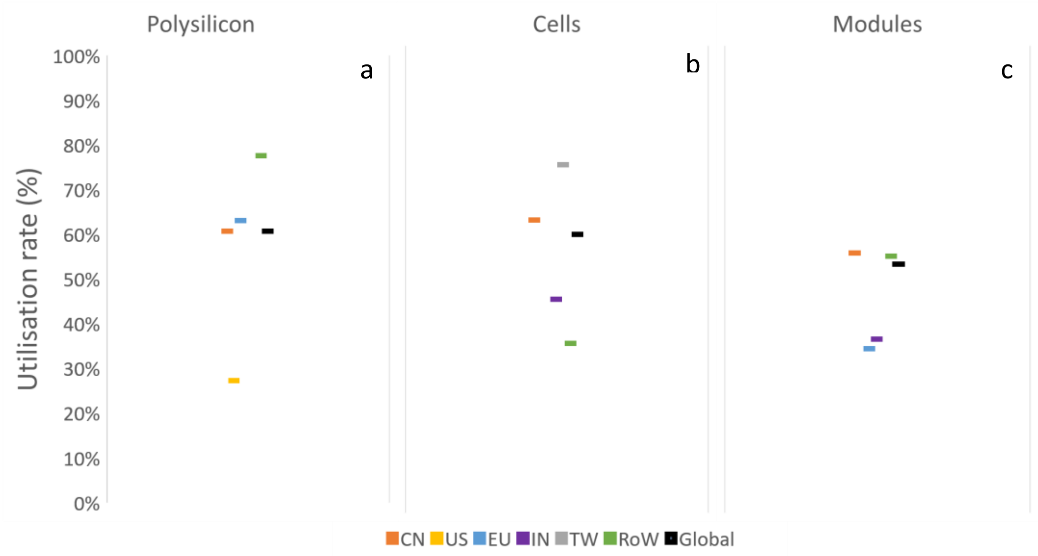
Source: (Bloomberg New Energy Finance, 2024e)(IEA PVPS, 2024b)

The top five polysilicon producers are all Chinese and accounted for 73 % of the global polysilicon production in 2023. The German Wacker Chemie (7th in the top ten list) decreased its production share from 15 % in 2020 to 4 % in 2023. Tongwei, the leading company in polysilicon manufacturing, increased its share from 19 % in 2020 to 28 % in 2023. The global top five cell manufacturers accounted for 48 % of the cell production in 2023, by producing 64 % more cells than in 2022. All companies in the top ten list are Chinese based companies and together accounted for 75 % of the global cell manufacturing. The top five module manufacturers present in Table 9 accounted for 50 % of the global module production in 2023, a rather stable share since 2020. These leading companies are all based in China apart from Canadian Solar which is headquartered in Canada but has most of its factories in China. Canadian Solar maintained a stable 5 % of market share in 2023 (Bloomberg New Energy Finance, 2024e).

Other major companies in the sector are Hanwha QCELLS (South Korea), First Solar (United States), BrightSource Energy, Inc. (U.S.), SunPower Corporation (U.S.)[23], 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).

However, besides the actual manufacturing capacities, the utilisation rates[24] in major countries and how they have evolved in the recent years are relevant for the analysis of the PV manufacturing landscape. Figure 58 presents the utilisation rates in polysilicon, cell and module manufacturing in 2023. The following analysis may underestimate actual utilisation rates as not all decommissioned production capabilities are considered and there may be differences on the nameplate capacities assumed (24/7 or one shift).

Figure 58. Utilisation rates for (a) polysilicon, (b) cells and (c) modules in 2023.



Source: (Bloomberg New Energy Finance, 2024e, 2024f)

The most pronounced utilisation rate decrease is observed for polysilicon. The global polysilicon utilisation rate of manufacturing decreased from 86 % in 2022 to 61 % in 2023 (decrease of 29 %). In China polysilicon manufacturing utilisation rates decreased from 91 % in 2022 to 61 % in 2023. The respective decrease for the EU was 22 %, from 81 % in 2022 to 63 % in 2023 (Bloomberg New Energy Finance, 2024e, 2024f).

Global utilisation rates in cell manufacturing remained rather stable in the past two years, around 60 % in 2023. Chinese cell manufacturing utilisation rate experienced an 11 % decrease between 2022 and 2023, similar to the global situation. India increased its utilisation rate by from 31 % in 2022 to 46 % in 2023 and Taiwan exhibited a utilisation rate of 74 % in 2023 from 64 % in 2022 (Bloomberg New Energy Finance, 2024e, 2024f).

The utilisation rate for module manufacturing in China was at 56 % in 2023, following a similar trend to that at global level (53 %). The IEA reports global actual utilisation rates of around 55 % globally for cell and module manufacturing and close to 70 % for polysilicon and wafers (IEA, 2024d, 2024a). In 2023, according to projections, utilisation rates for modules, cells and wafers will be at 50 %, 55 % and 80 % respectively, while for polysilicon they are expected to decrease to 65 % (IEA, 2024d). Based on ESMC's estimations, the EU's utilisation rates in module manufacturing in 2023 was 33 % (approx. 2 GW_p actual production and approx. 6 GW_p production capacity) (ESMC, 2024). India exhibited a 37 % utilisation rate for module manufacturing (Bloomberg New Energy Finance, 2024e, 2024f).

As far as global PV inverter production is concerned, between 2019 and 2023, the segment experienced an approx. 50 % CAGR, from 123.4 GW_{AC} in 2019 to 586.5 GW_{AC} in 2023. This increase may be overestimated due

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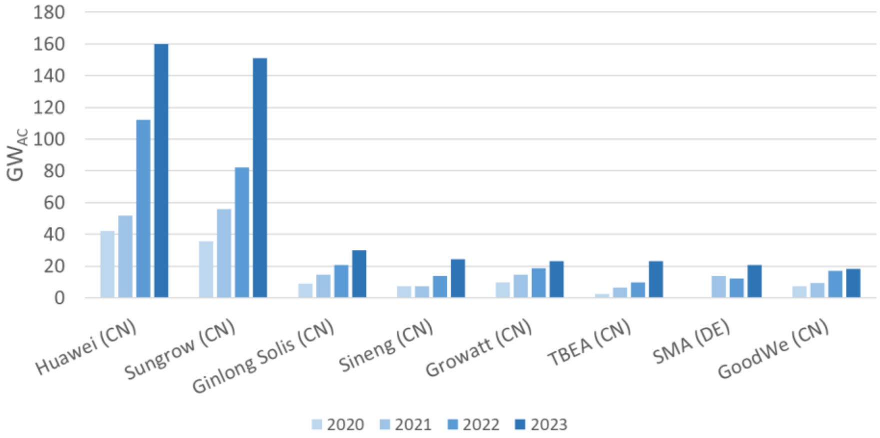
[23] Total Energies acquired a 60% stake in the company (all commercial and manufacturing activities) in 2011 but it remained listed as a US company (https://www.reuters.com/business/energy/totalenergies-buy-sunpowers-commercial-industrial-business-250-mln-2022-02-10/).

[24] Utilisation rate is the actual production compared to the production capability of the plants.

to non-disclosure of actual production volumes by the manufacturers. China led the way with a CAGR of 62 % and an increase in production share to 90 % in 2023 from 60 % in 2019. The EU on the other hand, saw its market share decreasing from 23 % in 2019 to 6 % in 2023 and a CAGR of only 7 % in the period 2019-2023. However, it must be noted that the above analysis is based on manufacturer's headquarters and not necessarily manufacturing location. SMA is known to produce its smaller single phase inverters in China (SMA China), opposed to the large 3 phase inverters that are produced in Germany (Solarquotes, 2017). The United States demonstrated a 33 % CAGR for the period 2019-2023, while Israel, with a market share of 2 % in 2023 experienced a CAGR increase of 23 % (Bloomberg New Energy Finance, 2024e).

The top ten of inverter companies includes nine Chinese companies and only one European, namely SMA (Germany) (Figure 59). In 2023, the top two companies, Huawei and Sungrow, with annual inverter productions of 160 GW_{AC} and 150 GW_{AC} respectively, accounted for half of the PV inverter production, whereas, the top ten for 82 %. SMA accounted for only 3 % of the global PV inverter production in 2023, from a 6 % in 2021. The German company's CAGR for the period 2021-2023 was 23 %. The Chinese company Huawei exhibited a CAGR of 75 % for the same period (Bloomberg New Energy Finance, 2024e).

Figure 59. PV inverter production by manufacturers for the period 2020-2023.



Source: (Bloomberg New Energy Finance, 2024e)

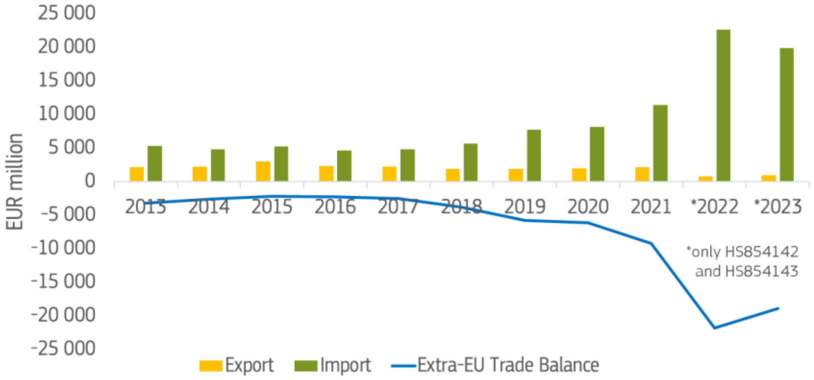
Between 2019 and 2023, the EU domestically produced PV modules could not compete with the Chinese ones. Despite the announcement of several energy policies, such as the Green Deal Industrial Plan (GDIP) and the Net Zero Industry Act (NZIA), that aim to boost the domestic manufacturing and decrease dependency on China, the EU imported from China a 88 GW_p capacity of PV modules between 2021 and 2022 (EMBER, 2024a) (96 % increase of imports) but managed to install less than half, remaining therefore with 47 GW_p of PV module stacked in warehouses. In 2023 the EU imports from China amounted to 102 GW_p, an increase of 16 % from 2022 (EMBER, 2024a). The annual EU deployment in 2023 was 55 GW_p, thus remaining with a surplus of another 47 GW_p in 2023. At the same time, EU manufacturers have around 1 GW_p of PV modules remaining in their inventories (ESMC, 2024). The manufacturing boom in China and the created overcapacity have decreased costs to unprecedented low levels with manufacturer selling at prices even below their production cost. The market pressures will inevitably bring to bankruptcy several companies in the sector globally, before its stabilisation. Module prices are expected to stabilise in the end of 2024 or early 2025 (PV Magazine, 2024b). However, the coveted European re-build of PV manufacturing is threatened as a result of the created oversupply and continuous lowering prices of Chinese PV modules. As several European companies have either bankrupted and ceased production or reduced significantly their capacities and/or flee to other countries with more favourable market and investment conditions, in September 2023, the European Solar PV Alliance released a document with recommendations regarding the financial mechanisms to fill the cost gap and restore the PV industry in Europe (ESMC, 2023).

The value chain disruptions experienced in the previous years as well as the concentration of supply in China has led major economies to adopt manufacturing policies in an effort to diversify their supply chain and boost their domestic manufacturing capabilities. The United States' Inflation Reduction Act (IRA), India's Product Linked Incentive (PLI) Scheme and EU's Net Zero Industry Act (NZIA) are expected to increase PV production capabilities outside China, however this might not be sufficient (Financial Times, 2024) and China could maintain its 80 % - 90 % (depending on the segment) global share in 2030 (IEA, 2024d). In addition, several countries have introduced non-price criteria into PV utility-scale project auctions as policy measures to boost supply chain diversification, local economic development and the sustainability of imported or domestically manufactured equipment used. More in particular and regarding the major PV economies, India has introduced the prequalification criterion that the modules can originate from producers on the Approved List of Models and Manufacturers (for the moment the list features companies with manufacturing capacities only in India) (IEA, 2024d). At EU level, through the NZIA, sets mandatory non-price criteria, namely the auction's sustainability and resilience contribution, cybersecurity, responsible business conduct, and ability to deliver projects fully and on time (European Commission, 2024a). Other prequalification criteria at Member State level are already in place (IEA, 2024d).

4.2 Trade (Import/export) and trade balance

In 2023, the EU imports of photovoltaic cells[25] shrunk by 12 % compared to 2022, reaching almost EUR 20 billion, equally reducing the trade deficit at about EUR 19 billion (Figure 60). In 2021-2023, the extra-EU share in global exports (3 %) and imports from outside the EU (31 %) remained similar to the levels of last year's report (2020-2022) (Chatzipanagi, Jaeger-Waldau, Cleret de Langavant, *et al.*, 2023).

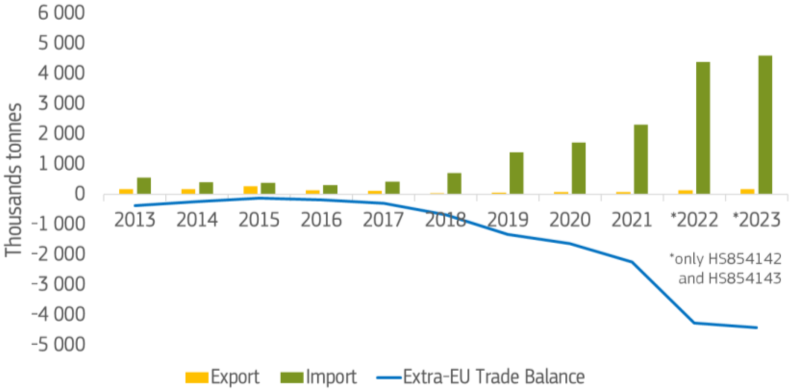
Figure 60. Extra-EU trade for photovoltaic cells for the period 2013-2023 (monetary).



Source: JRC based on COMEXT data

In terms of quantities, in 2023, the EU imports saw a small increase of 5 %, reaching almost 4.6 MT, compared to 4.4 MT in 2022 (Figure 61). This shows a -16% drop in the cost of imports from EUR 5.15 /kg to EUR 4.32 /kg or from EUR 0.26 /W to EUR 0.22 /W[26], which is in line with the average price for mainstream PV modules in the EU (SolarPower Europe, 2024c).

Figure 61. Extra-EU trade for photovoltaic cells for the period 2013-2023 (weight).



Source: JRC based on COMEXT data

In 2021-2023, China remained the main importing partner holding 94 % of total extra-EU imports in value (98 % in 2023), while the EU exported mainly to the United Kingdom, Switzerland and the United States (Figure 62a and b).

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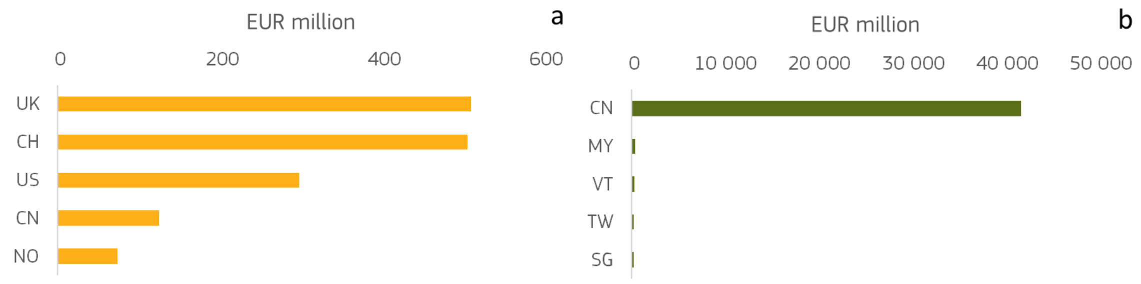
[25] As of 2022 (Chatzipanagi, Jaeger-Waldau, Cleret De Langavant, *et al.*, 2023):
854140 [Photosensitive semiconductor devices, incl. photovoltaic cells whether or not assembled in modules or made up into panels; light emitting diodes (excl. photovoltaic generators)] is discontinued
854190 [Photosensitive semiconductor devices, incl. photovoltaic cells] has been restructured to "Parts, diodes, transistors"
854142 [Photovoltaic cells not assembled in modules or made up into panels] is newly introduced
854143 [Photovoltaic cells not assembled in modules or made up into panels] is newly introduced

[26] When assuming an average power-to-weight ratio of 20W/kg, https://www.goosolarpower.com/2023/06/solar-panel-weigh-size.html

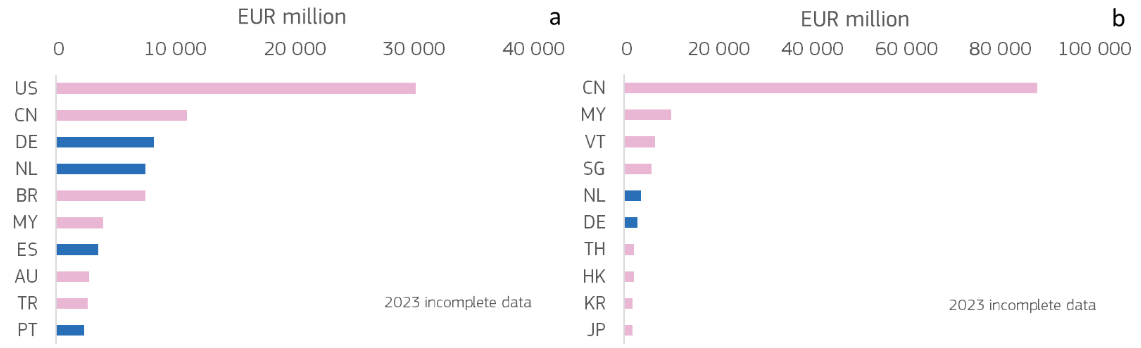
Figure 62. Top five countries (a) importing from and (b) exporting to the EU for the period 2021-2023.



Source: JRC based on COMEXT data

The EU maintained its presence amongst the top ten global exporters and importers (Figure 63a and b). Germany climbed up one rank in the top exporters and importers ranking. The Netherlands advanced four positions among the top exporters and one among the top importers. Portugal also appeared among the top global importers.

Figure 63. Top ten global (a) importers and (b) exporters for the period 2021-2023.



Source: JRC based on COMTRADE data

Since 2021, no Member State has a positive trade balance. In 2021-2023, Germany brought 78 % of its extra-EU imports from China, while 52 % of its total imports were from Netherlands. However, Netherlands brought 95 % of its extra-EU imports from China (89 % of its total imports) for the same period.

Regarding the growing markets[27] during 2020-2022[28], Brazil had the largest net import increase followed by Turkey and the United Arab Emirates. However, the EU failed to capture any of those three growing markets. The EU captured only the market in UK with a 24 % share of imports, losing ground compared to the 36 % of the previous study (2019-2021) (Table 10).

Table 10. Growing markets based on a 2-year average of net import change.

Country	Total import (2020-2022) [EUR Million]	% import from the EU	2-year average of net import change
Brazil	7 132	0%	1 379
Turkey	1 960	3%	446
United Arab Emirates	1 145	1%	367
United Kingdom	1 586	24%	202
Australia	3 757	1%	202

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[27] Calculated as $net\ import\ change = [(import_{2021} - import_{2020}) + (import_{2022} - import_{2021})]/2$

[28] Latest year data (2023) may be incomplete for Comtrade, because it does not provide estimates for the missing values as Comext does.

Country	Total import (2020-2022) [EUR Million]	% import from the EU	2-year average of net import change
Other Asia, nes	3 258	5%	192
Philippines	1 778	5%	126
Canada	1 261	7%	31
Pakistan	1 147	0%	27
Thailand	3 359	1%	25
India	6 289	0%	15

Source: JRC based on COMTRADE data

4.3 Resource 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.

The European Commission's proposal for the Critical Raw Materials Act (CRMA) (European Commission, 2023c), identifies and distinguishes between strategic raw materials (SRMs), that are essential according to the demand projections, and the critical raw materials (CRMs), that pose a high risk of supply disruption and are considered important for the EU's competitiveness.

The EU's dependency on China, a leading producer and user of many critical minerals (including rare earths), for critical materials used in the PV value chain must be taken seriously into consideration.

The materials that have a high supply risk and are defined as CRMs for the EU are silicon metal, gallium, and borates while copper, cadmium, selenium, silver, aluminium, indium and tellurium are considered materials with a lower supply risk (Carrara *et al.*, 2023). In the same report, the authors identify the supply risk for the processed materials as high for the crystalline technology due to China's domination and as lower for the thin-film technologies. 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). The final assembly is characterised by higher risk for the crystalline silicon than for the thin-film modules (Carrara *et al.*, 2023).

However, the above-mentioned analysis that identifies a high-risk supply of primary raw materials does not directly influence the EU since it is currently importing the final product (e.g. cadmium telluride) rather than the primary raw materials (e.g. tellurium). However, it will become crucially relevant in the short-term given the planned large-scale EU domestic PV manufacturing.

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

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 and high demand) and the market share of each technology. Taking into account that the crystalline technology will remain the dominant PV technology in the forthcoming years, the projections for 2030 report that the silicon and silver demand will increase 1.8 times compared to 2020. The increase in demand in 2050 (compared to 2020) will be 1.4 times for silicon and silver, reflecting the accomplished material efficiency (Carrara *et al.*, 2023). Copper demand will increase by 2 and 2.3 times compared to 2020 in the years 2030 and 2050 respectively. Other projections report that the demand for silicon, for the Net Zero emissions by 2050 scenario, will be 1.7 times the 2022 demand. For copper, the respective demand for 2050 will be 2.5 times the 2022 demand (IEA, 2023).

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 (European Commission, 2022f).

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. In addition, the manufacturing of solar glass is particularly energy-intensive and therefore also costly and this may limit investment initiatives from companies already in the sector or new players attempting to enter the market.

Overall, modern module designs using circular manufacturing concepts and material reduction for the balance of system is of equal importance to achieve the required growth of the PV industry (Jäger-Waldau, 2024).

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 1.6 TW_p in 2023 and estimates for 2024 vary from a shrinking market to a significant increase to over 550 GW_p, which would bring the total cumulative installed PV capacity to over 2 TW_p. The EU alone reached a cumulative installed PV capacity 271 GW_p at the end of 2023 and a cumulative electricity generation of approx. 230 TWh from PV systems. According to projections, the EU capacity will increase to approx. 400 GW_p in 2025, between 650 GW_p and 1 TW_p in 2030 and between 7 TW_p and 8.8 TW_p in 2050, whereas the projected global installed capacity will increase between 4.3-6 TW_p in 2030 and 22-60 TW_p in 2050.

The average PV module efficiency has increased from 9.0 % in 1980 to 14.7 % in 2010 and 21.8 % in 2023. 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 19.2 % while the record cell efficiency is 25.2 ± 0.8 %). Two of the most promising and efficient technologies are silicon-based tandems with III-V top material (currently at 32.65 ± 0.7 % module efficiency) and perovskite-silicon tandem devices. The market's tendency towards the replacement of Passivated Emitter and Rear Contact (PERC) architecture (currently at ~21 % module efficiency with projections reaching 22 % in 2034) by the n-type Tunnel Oxide Passivated Contact (TOPCon) (currently at 23 % module efficiency with projections reaching 24 % in 2034) is bringing further efficiency increases. Heterojunction modules are expected to exceed efficiencies of 24 % (currently around 23 %) by 2034, while modules with silicon-based tandem cells may reach over 30 % efficiency by 2034. 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 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 90 % between 2010 and 2023 from USD 417/MWh to USD 45/MWh. Projections for the EU indicate that it will further decrease from the 2024 values of EUR 53/MWh (Northern Europe) and EUR 30/MWh (Southern Europe) to EUR 30/MWh (Northern Europe) and EUR 18/MWh (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.

Almost all leading solar cell and module production companies are Chinese and they dominate the PV module shipments. In 2023, China accounted for 87 % (from 65 % in 2015) of the global cell production and 82 % (from 69 % in 2015) of the global module production. The respective share for the EU was 0.3 % for cells and 0.9 % for modules. However, to the above mentioned shares, it is essential to consider that manufacturing utilisation rates have decreased considerably in 2023. The most pronounced decrease occurred in the polysilicon segment (61 % in 2023 against 86 % in 2022 globally). More in particular, China changed its polysilicon utilisation rate from 91 % in 2022 to 61 % in 2023, while the EU decreased from 81 % in 2022 to 63 % in 2023. The global utilisation rate for cell manufacturing remained rather stable, around 60 %. The global module manufacturing utilisation rate in 2023 was 53 %, whereas the EU was 33 %.

For 2023, the top five module manufacturing companies, include four Chinese and one Canadian company and they accounted for 50 % of the global module production.

With regard to manufacturing capacities under construction, the EU is investing mostly in module capacities, accounting for 7 % of the global module capacities under construction and remains behind in the other segments. China's under construction capacities range between 60-96 % (depending on the segment) of the global total. China is expected to maintain its dominance in market share of global supply chains (80-95 % depending on the segment).

Additionally, the costs for PV manufacturing in China are considerably lower than in other regions. According to a 2022 IEA report, costs in China are 10 % lower than in India, 30 % lower than in the United States, and 60 % lower than in Europe. The Agency draws attention to the possibility that these cost differences will increase to 70 % for India, 100 % for the United States and 140 % for the EU by 2028, despite the adopted policies aiming to strengthen their domestic manufacturing market.

EU's recent competitiveness regarding the inverter market has suffered a considerable hit in 2022 as more Chinese companies have entered the market and surpassed the European companies in market share. The European companies SMA (Germany) and Power Electronics (Spain) reduced their combined market share from 14 % in 2018 to 7 % in 2022. In 2023, SMA held a 3 % share of the global inverter production, whereas Huawei and Sungrow (top two global inverter manufacturers), accounted for half of the PV inverter production. The EU saw its market share in inverter manufacturing decrease from 23 % in 2019 to 6 % in 2023.

China's impressive manufacturing capacity expansions are enabled by, firstly, 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.

Recent scientific findings suggest that global warming needs to be limited to 1.5 °C and therefore more ambitious decarbonisation and renewable energy targets are needed. The current ambitions for PV in the EU are not sufficient enough to effectively contribute to the necessary future renewable energy supply. PV deployment to achieve these ambitions needs to come through innovative forms of deployment (agrivoltaics, floating photovoltaics, dual use of traffic infrastructure, vehicle integrated photovoltaics, etc.) in addition to traditional deployment (utility-scale and rooftop).

The already announced support schemes for solar PV manufacturing in Europe, attempting to boost EU's domestic manufacturing capacities and rebuilt its competitiveness in the global PV value chain, are encouraging, but not in line with the global market growth (projections refer to over 5.8 TW_p of PV installed capacity globally and over 1 TW_p in the EU by 2030). The establishment of a resilient supply chain in connection to the EU PV manufacturing base is of primary importance. Last, but certainly not least, the political interest and promotion for manufacturing expansion will play a significant role.

The current trend of the EU market shows that it is growing faster than anticipated in the 2022 EU Solar Strategy Communication. As the overall global demand for PV components is growing even faster than in the EU and trade frictions can occur, precaution has to be taken to avoid a fallout of international supply chain disruptions on the deployment of PV in the EU. To hedge such a risk, the EU value chain should be able to supply at least 25-35 % of the EU market. At the moment, this is possible for the production of polysilicon, backsheets, contact materials, inverters and balance of system components. Additional new capacities for wafers, cells and solar glass production are needed.

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

References

Ardente, F., Latunussa, C.E.L. and Blengini, G.A. (2019) ‘Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling’, *Waste Management*, 91, pp. 156–167. Available at: https://doi.org/10.1016/j.wasman.2019.04.059.

Bernreuter Research (2023a) *Insolvency of Norwegian Crystals is a blow to PV supply in EU*. Available at: https://www.bernreuter.com/newsroom/polysilicon-news/article/insolvency-of-norwegian-crystals-is-a-blow-to-pv-supply-in-eu/ (Accessed: 11 September 2023).

Bernreuter Research (2023b) *Polysilicon Price Trend*. Available at: https://www.bernreuter.com/polysilicon/price-trend/ (Accessed: 20 June 2023).

Bernreuter Research (2024) *Polysilicon Price Trend*. Available at: https://www.bernreuter.com/polysilicon/price-trend/#current-polysilicon-spot-price (Accessed: 30 May 2024).

Bloomberg New Energy Finance (2024a) *1 Q 2024 Global PV Market Outlook*.

Bloomberg New Energy Finance (2024b) *3 Q 2024 Global PV Market Outlook*.

Bloomberg New Energy Finance (2024c) *Energy Transition Investment Trends 2024*.

Bloomberg New Energy Finance (2024d) *Global Installed Capacity (historical & forecast)*.

Bloomberg New Energy Finance (2024e) *Solar Manufacturer Production 2023 - Tracking the suppliers in the world’s solar market*.

Bloomberg New Energy Finance (2024f) *Solar PV Equipment Manufacturers dataset*.

Bobba, S. *et al.* (2020) *Critical Raw Materials for Strategic Technologies and Sectors in the EU - a Foresight Study*, *European Commission*. Available at: https://doi.org/10.2873/58081.

Carrara, S. *et al.* (2023) *Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU: A foresight study*, *Publications Office of the European Union*. Available at: https://doi.org/10.2760/334074.

Chatzipanagi, A., Taylor, N., *et al.* (2022) *Agri-photovoltaics (Agri-PV): how multi-land use can help deliver sustainable energy and food*. Available at: https://publications.jrc.ec.europa.eu/repository/handle/JRC129225.

Chatzipanagi, A., Jaeger-Waldau, A., *et al.* (2022) *Clean Energy Technology Observatory: Photovoltaics in the European Union – 2022 Status Report on Technology Development, Trends, Value Chains and Markets*. Available at: https://publications.jrc.ec.europa.eu/repository/handle/JRC130720.

Chatzipanagi, A., Jaeger-Waldau, A., Cleret De Langavant, C., *et al.* (2023) *Clean Energy Technology Observatory: Photovoltaics in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets*. Available at: https://doi.org/10.2760/732675.

Chatzipanagi, A., Jaeger-Waldau, A., Cleret de Langavant, C., *et al.* (2023) *Clean Energy Technology Observatory: Photovoltaics in the European Union - 2023 Status Report on Technology Development Trends, Value Chains and Markets*. Available at: Under publication.

Chatzipanagi, A. et al. (2022) *Clean Energy Technology Observatory: Photovoltaics in the European Union – 2022 Status Report on Technology Development, Trends, Value Chains and Markets*, *Publications Office of the European Union*. Available at: https://doi.org/10.2760/812610.

Chatzipanagi, A., Taylor, N. and Jaeger-Waldau, A. (2023) *Overview of the Potential and Challenges for Agri-Photovoltaics in the European Union*. Available at: https://doi.org/10.2760/208702.

Council of the EU (2024) *Industrial policy: Council gives final approval to the net-zero industry act*. Available at: https://www.consilium.europa.eu/en/press/press-releases/2024/05/27/industrial-policy-council-gives-final-approval-to-the-net-zero-industry-act/#:~:text=Firstly%2C manufacturing capacity of net,of world production by 2040. (Accessed: 11 July 2024).

Crawford, A. and Murphy, L.T. (2023) ‘Over-exposed: Uyghur Region Exposure Assessment for Solar Industry Sourcing’, (August). Available at: https://www.shu.ac.uk/-/media/home/research/helena-kennedy-centre/projects/over-exposed/crawford-murphy-et-al----over-exposed-xuar-assessment-aug-2023.pdf.

Després, J. *et al.* (2018) *POLES-JRC model documentation*. Available at: https://doi.org/10.2760/814959.

Dodd, N. *et al.* (2020) *Preparatory study for solar photovoltaic modules, inverters and systems*. Available at: https://doi.org/10.2760/852637.

EMBER (2024a) *China solar PV exports*. Available at: https://ember-climate.org/data-catalogue/china-solar-pv-exports/ (Accessed: 26 June 2024).

EMBER (2024b) *Electricity Data Explorer*. Available at: https://ember-climate.org/data/data-tools/data-explorer/ (Accessed: 20 June 2024).

ENF (2023) *Solar Recycling Companies*. Available at: https://www.enfsolar.com/directory/service/manufacturers-recycling (Accessed: 7 September 2023).

ESMC (2023) *Release: ESIA Recommendation paper on financial mechanisms to fill the cost gap and restore the PV industry in Europe*. Available at: https://esmc.solar/release-esia-recommendation-paper-on-financial-mechanisms-to-fill-the-cost-gap-and-restore-the-pv-industry-in-europe/ (Accessed: 5 October 2023).

ESMC (2024) *Letter to the European Commission - Request for emergency measures for EU PV module producers*. Available at: https://esmc.solar/wp-content/uploads/2024/02/Letter-to-the-European-Commission-Request-for-emergency-measures-for-EU-PV-module-producers.pdf (Accessed: 30 May 2024).

ETIP-PV (2023) *PV Manufacturing in Europe: Understanding the value chain for a successful industrial policy*. Available at: https://etip-pv.eu/publications/etip-pv-publications/download/pv-industry-white-paper-6.

ETIP-PV (2024) 'Low-cost PV - The Key for Sustainable Future Energy System'. Available at: https://etip-pv.eu/publications/etip-pv-publications/.

EurObserv'ER (2022) *Online Database*. Available at: https://www.eurobserv-er.org/online-database/ (Accessed: 17 October 2023).

EurObserv'ER (2024a) *22nd annual overview barometer*. Available at: https://www.eurobserv-er.org/22nd-annual-overview-barometer/.

EurObserv'ER (2024b) *Photovoltaic barometer 2023*. Available at: https://www.eurobserv-er.org/photovoltaic-barometer-2023/.

European Commission (2018a) 'Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)', *Official Journal of the European Union*, 2018(L 328), pp. 82–209.

European Commission (2018b) *Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844.

European Commission (2019) *Product Environmental Footprint Category Rules (PEFCR) Photovoltaic Modules*. Available at: https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_PV_electricity_v1.1.pdf.

European Commission (2020a) *Communication From the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, EU Biodiversity Strategy for 2030 Bringing nature back into our lives*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0380.

European Commission (2020b) *New European Bauhaus*. Available at: https://new-european-bauhaus.europa.eu/index_en.

European Commission (2022a) *Communication From the Commission To the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, EU Solar Energy Strategy*. Available at: https://eur-lex.europa.eu/resource.html?uri=cellar:516a902d-d7a0-11ec-a95f-01aa75ed71a1.0001.02/DOC_1&format=PDF.

European Commission (2022b) *Communication From the Commission To the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, REPowerEU: Joint European Action for more affordable, secure and sustainable energy*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A108%3AFIN.

European Commission (2022c) *Ecodesign and Energy Labelling*. Available at: https://ec.europa.eu/growth/single-market/european-standards/harmonised-standards/ecodesign_en.

European Commission (2022d) *EU strategic dependencies and capacities: second stage of in-depth reviews*

COMMISSION STAFF WORKING DOCUMENT. Available at: http://www.ncbi.nlm.nih.gov/pubmed/19097363.

European Commission (2022e) *Fit for 55*. Available at: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/ (Accessed: 5 September 2023).

European Commission (2022f) *Raw Materials Information System (RMIS)*. Available at: https://rmis.jrc.ec.europa.eu/?page=green-energy-transport-85d456 (Accessed: 15 June 2022).

European Commission (2022g) *Regulation of the European Parliament and of the Council laying down harmonised conditions for the marketing of construction products, amending Regulation (EU) 2019/1020 and repealing Regulation (EU) 305/2011*. Available at: https://ec.europa.eu/docsroom/documents/49315.

European Commission (2023a) *Clean Energy Technology Observatory*. Available at: https://setis.ec.europa.eu/publications/clean-energy-technology-observatory-ceto_en (Accessed: 5 September 2023).

European Commission (2023b) *Commission staff working document for a regulation of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act)*. Available at: https://single-market-economy.ec.europa.eu/system/files/2023-06/SWD_2023_219_F1_STAFF_WORKING_PAPER_EN_V9_P1_2785109.PDF.

European Commission (2023c) *European Critical Raw Materials Act*. Available at: https://single-market-economy.ec.europa.eu/publications/european-critical-raw-materials-act_en (Accessed: 7 September 2023).

European Commission (2023d) *European Solar Industry Alliance*. Available at: https://single-market-economy.ec.europa.eu/industry/strategy/industrial-alliances/european-solar-photovoltaic-industry-alliance_en (Accessed: 5 September 2023).

European Commission (2023e) *Proposal for a sustainability assessment framework for energy technologies*. Available at: https://setis.ec.europa.eu/proposal-sustainability-assessment-framework-energy-technologies_en (Accessed: 23 October 2024).

European Commission (2024a) *Commission welcomes political agreement to make clean technology manufacturing in the EU resilient and competitive*. Available at: https://ec.europa.eu/commission/presscorner/detail/en/ip_24_680.

European Commission (2024b) *European Solar Charter*. Available at: https://energy.ec.europa.eu/topics/renewable-energy/solar-energy/european-solar-charter_en (Accessed: 11 July 2024).

European Commission (2024c) *The second strategic plan 2025-2027 sets direction to the future of R&I*. Available at: https://doi.org/10.2777/518974.

European Council (2023) *Renewable energy: Council adopts new rules - Press Release*. Available at: https://www.consilium.europa.eu/en/press/press-releases/2023/10/09/renewable-energy-council-adopts-new-rules/?utm_source=dsms-auto&utm_medium=email&utm_campaign=Renewable+energy%3A+Council+adopts+new+rules (Accessed: 17 October 2023).

European Patent Office (2023) *Cooperative Patent Classification*. Available at: https://www.cooperativepatentclassification.org/cpcSchemeAndDefinitions/table (Accessed: 1 April 2022).

EY (2017) *Solar PV Jobs & Value Added in Europe*. Available at: https://resources.solarbusinesshub.com/images/reports/177.pdf.

Feldman, D. *et al.* (2021) *U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020*. Available at: https://www.nrel.gov/docs/fy21osti/77324.pdf.

Financial Times (2024) *US solar manufacturers in 'dire situation' as imports soar*. Available at: https://www.ft.com/content/9afeb8a2-ee25-4455-b917-5f06486abe5b (Accessed: 26 June 2024).

Fiorini, A. *et al.* (2017) *Monitoring R&I in Low-Carbon Energy Technologies Methodology for the R&I indicators in the State of the Energy Union Report-2016 edition*, *JRC Science for Policy report*. Available at: https://doi.org/10.2760/434051.

Fortune Business Insights (2022) *Solar Photovoltaic (PV) market size*. Available at: https://www.fortunebusinessinsights.com/industry-reports/solar-pv-market-100263 (Accessed: 1 April 2022).

Fortune Business Insights (2023) *Solar Power Market Size*. Available at: https://www.globenewswire.com/en/news-release/2023/01/16/2589219/0/en/Solar-Power-Market-Size-2022-2029-worth-USD-373-84-Billion-by-2029-Exhibiting-CAGR-of-6-9.html#:~:text=The global solar power market,period of 2022 to 2029. (Accessed: 16 January 2023).

Fortune Business Insights (2024) *Solar Power Market Size Summary*. Available at: www.fortunebusinessinsights.com/industry-reports/solar-power-market-100764#summary (Accessed: 10 June 2024).

Fraunhofer ISE (2021) *European Glass-Glass Photovoltaic Modules Are Particularly Climate-Friendly*. Available at: https://www.ise.fraunhofer.de/en/press-media/press-releases/2021/european-glass-glass-photovoltaic-modules-are-particularly-climate-friendly.html (Accessed: 10 March 2023).

Fraunhofer ISE (2022) *Aktuelle Fakten zur Photovoltaik in Deutschland*. Available at: https://www.ise.fraunhofer.de/de/veroeffentlichungen/studien/aktuelle-fakten-zur-photovoltaik-in-deutschland.html.

Fraunhofer ISE (2023) 'Photovoltaics Report 2023', (February). Available at: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf.

Fraunhofer ISE (2024) *Photovoltaics Report 2024*. Available at: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf.

Frischknecht, R. and Krebs, L. (2021) *IEA PVPS Environmental life cycle assessment of electricity from PV systems*. Available at: https://iea-pvps.org/fact-sheets/factsheet-environmental-life-cycle-assessment-of-electricity-from-pv-systems/.

Fthenakis, V. and Leccisi, E. (2021) 'Updated sustainability status of crystalline silicon-based photovoltaic systems: Life-cycle energy and environmental impact reduction trends', *Progress in Photovoltaics: Research and Applications*, 29(10), pp. 1068–1077. Available at: https://doi.org/10.1002/pip.3441.

Fthenakis, V.M. and Leccisi, E. (2022) *Environmental Impacts of Photovoltaic Life Cycles*, *Comprehensive Renewable Energy, Second Edition: Volume 1-9*. Elsevier Ltd. Available at: https://doi.org/10.1016/B978-0-12-819727-1.00090-X.

Gebhardt, P. *et al.* (2022) 'Lead-Free PV Modules: Industrial Realization and Evaluation of Environmental Impact', in *WCPEC-8, 8th World Conference on Photovoltaic Energy Conversion, 26-30 September 2022, Milan, Italy*, pp. 26–30.

Gholami, H., Nils Røstvik, H. and Steemers, K. (2021) 'The Contribution of Building-Integrated Photovoltaics (BIPV) to the Concept of Nearly Zero-Energy Cities in Europe: Potential and Challenges Ahead', pp. 1–22. Available at: https://doi.org/10.3390/en14196015.

Green, M.A. *et al.* (2024) 'Solar cell efficiency tables (Version 64)', *Progress in Photovoltaics: Research and Applications*, 32(7), pp. 425–441. Available at: https://doi.org/10.1002/pip.3831.

IEA-PVPS (2019) *Trends in Photovoltaic Applications 2019*. Available at: https://doi.org/10.1021/ac50054a041.

IEA-PVPS (2020) *Trends in Photovoltaic Applications 2020*.

IEA-PVPS (2021) *Trends in Photovoltaic Applications 2021*. Available at: https://iea-pvps.org/trends_reports/trends-in-pv-applications-2021/.

IEA-PVPS (2022) *Trends in Photovoltaic Applications 2022*. Available at: https://iea-pvps.org/wp-content/uploads/2023/02/PVPS_Trend_Report_2022.pdf.

IEA-PVPS (2023) *Trends in Photovoltaic Applications 2023*. Available at: http://www.iea-pvps.org/.

IEA (2022a) 'Renewables 2022, Analysis and forecast to 2027', p. 158. Available at: https://www.iea.org/reports/renewables-2022.

IEA (2022b) 'Special Report on Solar PV Global Supply Chains', *Special Report on Solar PV Global Supply Chains* [Preprint]. Available at: https://doi.org/10.1787/9e8b0121-en.

IEA (2023) *Critical Minerals Data Explorer*. Available at: https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer (Accessed: 7 September 2023).

IEA (2024a) 'Advancing Clean Technology Manufacturing - An Energy Technology Perspectives Special Report'. Available at: https://www.iea.org/reports/advancing-clean-technology-manufacturing.

IEA (2024b) *Renewable Energy Progress Tracker*.

IEA (2024c) *Renewables 2023 - Analysis and forecast to 2028*. Available at: https://iea.blob.core.windows.net/assets/96d66a8b-d502-476b-ba94-54ffda84cf72/Renewables_2023.pdf.

IEA (2024d) *Renewables 2024 - Analysis and forecast to 2030*. Available at: https://iea.blob.core.windows.net/assets/88a07dd9-42fe-4232-842e-9015b4b647f8/Renewables2024.pdf.

IEA PVPS (2016) *Trends in Photovoltaic Applications 2015 - Survey Report of Selected IEA Countries between 1992 and 2014*. Available at: https://iea-pvps.org/wp-content/uploads/2020/01/IEA-PVPS_-_Trends_2015_-_MedRes.pdf.

IEA PVPS (2024a) *Snapshot of Global PV Markets 2024*. Available at: http://www.iea-pvps.org/fileadmin/dam/public/report/technical/PVPS_report_-_A_Snapshot_of_Global_PV_-_1992-2014.pdf.

IEA PVPS (2024b) *Trends in Photovoltaic Applications 2024*. Available at: https://iea-pvps.org/trends_reports/trends-in-pv-applications-2024/.

IFC (2015) *Utility-Scale Solar Photovoltaic Power Plants*. Available at: https://www.ifc.org/wps/wcm/connect/a1b3dbd3-983e-4ee3-a67b-cdc29ef900cb/IFC+Solar+Report_Web+_08+05.pdf?MOD=AJPERES&CVID=kZePDPG.

IIASA (2024) *GLOBIOM documentation*. Available at: https://globiom.org/documentation.html (Accessed: 4 October 2024).

IPCC (2022) *Climate Change 2022: Mitigation of Climate Change*. Available at: https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf.

IRENA (2020a) *Energy Technology Perspectives 2020*, *Energy Technology Perspectives 2020*. Available at: https://doi.org/10.1787/ab43a9a5-en.

IRENA (2020b) *Tracking Energy Innovation Impacts Framework*. Available at: https://cordis.europa.eu/project/id/899899/results.

IRENA (2024) *Renewable Power Generation Costs in 2023*. Available at: https://www.irena.org/Publications/2024/Sep/Renewable-Power-Generation-Costs-in-2023.

IRENA and ILO (2021) *Renewable Energy and Jobs – Annual Review 2021*. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Oct/IRENA_RE_Jobs_2021.pdf.

IRENA and ILO (2022) *Renewable energy and jobs: Annual review 2022*. Available at: https://www.ilo.org/global/publications/books/WCMS_856649/lang--en/index.htm.

IRENA and ILO (2023) *Renewable energy and jobs: Annual review 2023*. Available at: https://www.ilo.org/global/publications/books/WCMS_856649/lang--en/index.htm.

IRENA and ILO (2024) *Renewable Energy and Jobs: Annual Review 2024*. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Oct/IRENA_Renewable_energy_and_jobs_2024.pdf.

IWG PV-Implementation Working Group on Photovoltaics (2023) *Implementation plan and background documents*. Available at: https://www.iwg-pv.eu/implementation-plan (Accessed: 4 March 2024).

Jäger-Waldau, A. (2024) 'Snapshot of photovoltaics - February 2024', *EPJ Photovoltaics*, 15(21), p. 9. Available at: https://doi.org/10.1051/epjpv/2024018.

Kakoulaki, G., Gonzalez Sanchez, R., *et al.* (2023) 'Benefits of pairing floating solar photovoltaics with hydropower reservoirs in Europe', *Renewable and Sustainable Energy Reviews*, 171. Available at: https://doi.org/10.1016/j.rser.2022.112989.

Kakoulaki, G., Fahl, F., *et al.* (2023) 'Potential for transforming the European transport infrastructure into solar PV energy hub', *Renewable and Sustainable Energy Reviews, Submitted* [Preprint].

Lammerant, L., Laureysens, I. and Driesen, K. (2020) *Potential impacts of solar, geothermal and ocean energy on habitats and species protected under the birds and habitats directives.* Available at: https://op.europa.eu/en/publication-detail/-/publication/edf7213a-02c9-11eb-8919-01aa75ed71a1/language-en.

Latunussa, C.E.L. *et al.* (2016) 'Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels', *Solar Energy Materials and Solar Cells*, 156, pp. 101–111. Available at:

https://doi.org/10.1016/j.solmat.2016.03.020.

Lohrmann, A. *et al.* (2019) 'Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery', *Nature Energy*, 4(12), pp. 1040–1048. Available at: https://doi.org/10.1038/s41560-019-0501-4.

Lugo-laguna, D., Arcos-Vargas, A. and Nuñez-hernandez, F. (2021) 'A european assessment of the solar energy cost: Key factors and optimal technology', *Sustainability (Switzerland)*, 13(6), pp. 1–25. Available at: https://doi.org/10.3390/su13063238.

Manish, R. *et al.* (2020) *SolarPower Europe and LUT University (2020): 100% Renewable Europe: How To Make Europe's Energy System Climate-Neutral Before 2050.* Available at: https://www.solarpowereurope.org/insights/webinars/100-renewable-energy-in-europe-before-2050.

Mantzos, L. *et al.* (2017) 'POTEnCIA: A new EU-wide energy sector model', *International Conference on the European Energy Market, EEM* [Preprint]. Available at: https://doi.org/10.1109/EEM.2017.7982028.

Mantzos, L. *et al.* (2019) *The POTEnCIA Central scenario: an EU energy outlook to 2050*. Available at: https://doi.org/10.2760/32835.

Mercom (2024) *Red Sea Shipping Crisis Hits Key Trade Route for Solar Modules*. Available at: https://www.mercomindia.com/red-sea-shipping-crisis-hits-solar-modules (Accessed: 27 February 2024).

Moser, D. *et al.* (2021) 'Impact of Public and Private Funding on the Development of the Photovoltaic Sector and the Achievement of 2030 Energy Transition Targets', *Proceedings of 38th European Photovoltaic Solar Energy Conference and Exhibition*, pp. 1657–1661. Available at: https://doi.org/10.4229/EUPVSEC20212021-7EO.1.6.

Müller, A. *et al.* (2021) 'A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory', *Solar Energy Materials and Solar Cells*, 230(June). Available at: https://doi.org/10.1016/j.solmat.2021.111277.

Neuwahl, F. *et al.* (2024) *The POTEnCIA CETO 2024 Scenario (under publication)*.

Pasimeni, F. (2019) 'SQL query to increase data accuracy and completeness in PATSTAT', *World Patent Information*, 57(December 2018), pp. 1–7. Available at: https://doi.org/10.1016/j.wpi.2019.02.001.

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

Pasimeni, F., Fiorini, A. and Georgakaki, A. (2021) 'International landscape of the inventive activity on climate change mitigation technologies. A patent analysis', *Energy Strategy Reviews*, 36, p. 100677. Available at: https://doi.org/10.1016/j.esr.2021.100677.

Pasimeni, F. and Georgakaki, A. (2020) *Patent-Based Indicators: Main Concepts and Data Availability*. Available at: https://setis.ec.europa.eu/patent-based-indicators-main-concepts-and-data-availability_en.

Pehl, M. *et al.* (2017) 'Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling', *Nature Energy*, 2(12), pp. 939–945. Available at: https://doi.org/10.1038/s41560-017-0032-9.

Perovskite-info (2023a) *Perovskite equipment makers*. Available at: https://www.perovskite-info.com/companies-list/perovskite-equipment-makers (Accessed: 7 September 2023).

Perovskite-info (2023b) *Perovskite material providers*. Available at: https://www.perovskite-info.com/companies-list/pervoskite-material-providers (Accessed: 7 September 2023).

Perovskite-info (2023c) *Perovskite solar panels developers*. Available at: https://www.perovskite-info.com/companies-list/perovskite-solar-panels-developers (Accessed: 7 September 2023).

Polverini, D. *et al.* (2023) 'Assessing the carbon footprint of photovoltaic modules through the EU Ecodesign Directive', *Solar Energy*, 257(March), pp. 1–9. Available at: https://doi.org/10.1016/j.solener.2023.04.001.

PV Magazine (2023) *Norsun announces temporary wafer production halt, layoffs*. Available at: https://www.pv-magazine.com/2023/09/08/norsun-announces-temporary-wafer-production-halt-layoffs/ (Accessed: 5 October 2023).

PV Magazine (2024a) *Longi claims 34.6% efficiency for perovskite-silicon tandem solar cell*. Available at:

https://www.pv-magazine.com/2024/06/14/longi-claims-34-6-efficiency-for-perovskite-silicon-tandem-solar-cell/?utm_source=dlvr.it&utm_medium=linkedin (Accessed: 9 July 2024).

PV Magazine (2024b) *'We expect solar panel prices to stabilize in the second half of the year'*. Available at: https://www.pv-magazine.com/2024/06/25/we-expect-solar-panel-prices-to-stabilize-in-the-second-half-of-the-year/#:~:text=pv magazine International-,'We expect solar panel prices to stabilize in the second,and PV manufacturing outside China. (Accessed: 26 June 2024).

PV Tech (2024) *NorSun to build 5GW ingot and wafer manufacturing plant in Oklahoma*. Available at: https://www.pv-tech.org/norsun-to-build-5gw-ingot-and-wafer-manufacturing-plant-in-oklahoma/#:~:text=Norwegian ingot and wafer manufacturer,2024 and production in 2026. (Accessed: 26 June 2024).

PVEurope (2022) *'Scaling up is key'*. Available at: https://www.pveurope.eu/solar-modules/pv-manufacturing-europe-scaling-key (Accessed: 13 September 2022).

Pvxchange (2022) *Price Index - Market Analysis April 2022*. Available at: https://www.pvxchange.com/Market-Analysis-April-2022-An-ounce-of-prevention (Accessed: 15 June 2022).

PVxchange (2023) *Price Index*. Available at: https://www.pvxchange.com/Price-Index (Accessed: 4 September 2023).

PVxchange (2024) *Price Index - September 2024*. Available at: https://www.pvxchange.com/Price-Index (Accessed: 3 October 2024).

Ribeyron, P. (2020) *Business models and business plan in PV manufacturing value chain AMPERE-Deliverable report*. Available at: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c3dc0e53&appId=PPGMS.

Rózsai, M. *et al.* (2024) *JRC-IDEES-2021: the Integrated Database of the European Energy System – Data update and technical documentation*. Available at: https://doi.org/10.2760/614599.

S&P Global (2024) *Squeeze on European solar manufacturers curbs innovation, cementing China's lead*. Available at: https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/squeeze-on-european-solar-manufacturers-curbs-innovation-cementing-china-s-lead-81072375 (Accessed: 15 April 2024).

Schmitz, A. *et al.* (2024) *Impacts of enhanced learning for clean energy technologies on global energy system scenarios (under publication)*.

Sinovoltaics (2024) *Solar Supply Chain Maps*. Available at: https://sinovoltaics.com/sinovoltaics-solar-supply-chain-maps/ (Accessed: 17 October 2024).

SNETP (2022) *SNETP Strategic Research and Innovation Agenda*. Available at: https://etip-pv.eu/publications/sria-pv/.

Solar Energy Industries Association (2022) *Water use management*. Available at: https://www.seia.org/initiatives/water-use-management (Accessed: 12 October 2022).

SolarPower Europe (2021a) *EU Solar Jobs Report 2021 - Towards Higher Solar Ambitions in Europe*.

SolarPower Europe (2021b) *EU Solar Jobs Report 2021 – Towards Higher Solar Ambitions in Europe.* Available at: https://www.solarpowereurope.org/insights/thematic-reports/eu-solar-jobs-report-1.

SolarPower Europe (2022) *EU Solar Jobs Report 2022 - Addressing the solar skills challenge*.

SolarPower Europe (2023a) *EU Market Outlook For Solar Power 2023 - 2027*. Available at: https://api.solarpowereurope.org/uploads/Solar_Power_Europe_EU_Market_Outlook_2023_v03_deca570a83.pdf.

SolarPower Europe (2023b) *EU Solar Jobs Report 2023 - Bridging the solar skills gap through quality and quantity*.

SolarPower Europe (2023c) *EU Solar Manufacturing Map*. Available at: https://www.solarpowereurope.org/insights/interactive-data/solar-manufacturing-map (Accessed: 4 September 2023).

SolarPower Europe (2023d) *Global Market Outlook 2023-2027*. Available at:

http://www.solarpowereurope.org/insights/global-market-outlook/.

SolarPower Europe (2024a) *EU Solar Jobs Report 2024 - A solar workforce ready for stronger growth*.

SolarPower Europe (2024b) *Global Market Outlook 2024-2028*. Available at: https://www.solarpowereurope.org/insights/outlooks/global-market-outlook-for-solar-power-2024-2028/detail.

SolarPower Europe (2024c) *Record-low solar PV prices risk EU's open strategic autonomy*. Available at: https://www.solarpowereurope.org/press-releases/record-low-solar-pv-prices-risk-eu-s-open-strategic-autonomy (Accessed: 2 July 2024).

Solarquotes (2017) *SunPower And SMA Choose To (Very Discreetly) Manufacture In China*. Available at: https://www.solarquotes.com.au/blog/sunpower-sma-choose-discreetly-manufacture-china/ (Accessed: 30 May 2024).

Stolz, P. *et al.* (2017) *Water Footprint of European Rooftop Photovoltaic Electricity based on Re-gionalised Life Cycle Inventories*, *IEA PVPS Task 12*. Available at: https://iea-pvps.org/wp-content/uploads/2020/01/Water_Footprint_of_European_Rooftop_Photovoltaic_Electricity_based_in_Re-giornalised_Life_Cycle_Inventories_by_Task_12.pdf.

Szabó, S. *et al.* (2017) 'A methodology for maximizing the benefits of solar landfills on closed sites', *Renewable and Sustainable Energy Reviews*, 76(March), pp. 1291–1300. Available at: https://doi.org/10.1016/j.rser.2017.03.117.

Tawalbeh, M. *et al.* (2021) 'Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook', *Science of the Total Environment*, 759. Available at: https://doi.org/10.1016/j.scitotenv.2020.143528.

Tchognia Nkuissi, H.J.K. *et al.* (2019) 'Toxic Materials Used in Thin Film Photovoltaics and Their Impacts on Environment', *Environmental Impacts of Solar Panels* [Preprint]. Available at: https://doi.org/10.5772/intechopen.88326.

The World Bank (2023) *Gross Domestic Product (GDP) data*. Available at: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD (Accessed: 17 August 2023).

Thiel, C. *et al.* (2022) 'Impact of climatic conditions on prospects for integrated photovoltaics in electric vehicles', *Renewable and Sustainable Energy Reviews*, 158(December 2021), pp. 1–17. Available at: https://doi.org/10.1016/j.rser.2022.112109.

TNO (2023) *Zon op Dijken, Openbaar Eindrapport*. Available at: https://www.tno.nl/en/newsroom/2023/02/dykes-solar-panel/.

Vartiainen, E. *et al.* (2020) 'Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity', *Progress in Photovoltaics: Research and Applications*, 28(6), pp. 439–453. Available at: https://doi.org/10.1002/pip.3189.

VDMA (2023) *International Technology Roadmap for Photovoltaic (ITRPV) 2022 Results*. Available at: https://www.vdma.org/international-technology-roadmap-photovoltaic.

VDMA (2024) *International Technology Roadmap for Photovoltaics (ITRPV), Results 2023*. Available at: https://www.vdma.org/international-technology-roadmap-photovoltaic.

Wiatros-Motyka, M. *et al.* (2024) *Global electricity review 2024*.

Wilson, G.M. *et al.* (2020) 'The 2020 photovoltaic technologies roadmap', *Journal of Physics D: Applied Physics*, 53(49). Available at: https://doi.org/10.1088/1361-6463/ab9c6a.

WoodMackenzie (2023) *Global solar forecast gets an upgrade*. Available at: https://www.woodmac.com/news/opinion/global-solar-forecast/ (Accessed: 19 February 2024).

World Economic Forum (2023) *What were the key outcomes of COP28?* Available at: https://www.weforum.org/agenda/2023/12/cop28-key-outcomes-un-climate-summit/#:~:text=The UN climate summit%2C COP28,of energy efficiency by 2030. (Accessed: 11 July 2024).

List of abbreviations and definitions

General

BoS	Balance of System
CAPEX	Capital Expenditure
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
EPC	Engineering, Procurement and Construction
EPBT	Energy Payback Time
EROC	Energy Return On Carbon invested
EROI	Energy Return On energy Invested
ESIA	European Solar Industry Alliance
ESMC	European Solar Manufacturing Council
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
FTE	Full-Time Equivalent
FWCI	Field Weighted Citation Impact
GDP	Gross Domestic Product
GDIP	Green Deal Industrial Plan
GHG	Greenhouse Gases
GVA	Gross Value Added
H2020	Horizon 2020 funding programme
IF	Innovation Fund
IPCC	Intergovernmental Panel on Climate Change
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

NZIA	Net Zero Industry Act
O&M	Operation and Maintenance
OPEX	Operational Expenditure
Prodcom	PRODuction COMmunautaire (Community Production)
PV	Photovoltaics
RED	Renewables Energy Directive
R&D	Research and Development
R&I	Research and Innovation
SET-Plan	Strategic Energy Technology Plan
SPE	Solar Power Europe
SRIA	Strategic Research and Innovation Agenda
SRM	Strategic Raw Material
STEM	Science, Technology, Engineering and Mathematics
TIM	Tools for Information Monitoring
TRL	Technology Readiness Level
UN Comtrade	United Nations International Trade Statistics Database
VC	Venture Capital
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
HJT	Heterojunction technology
mono c-Si	Mono-crystalline silicon
MT	Mega tonne
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_{AC}	Watt alternating current
W_{DC}	Watt direct current
W_p	Watt peak
Wh	Watt hour

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Annexes

Annex 1 Summary Table of Data Sources for the CETO Indicators

Theme	Indicator	Main data source
Technology maturity status, development and trends	Technology readiness level	ITRPV, IEA-PVPS, Fraunhofer ISE, SNETP, scientific publications, EC reports, various
	Installed capacity & energy production	Eurostat, IRENA, Ember, JRC, IEA-PVPS
	Technology costs	IRENA, ITRPV, ETIP-PV, Bernreuter Research, JRC, various
	Public and private RD&I funding	IEA, JRC
	Patenting trends	EPO Patstat, JRC
	Scientific publication trends	JRC
	Assessment of R&I project developments	CINEA, DG RTD
Value chain analysis	Turnover	IEA-PVPS, EurObserv'ER
	Gross Value Added	EurObserv'ER
	Environmental and socio-economic sustainability	Scientific publications, JRC, various
	EU companies and roles	Pitchbook, Fraunhofer, various
	Employment	IRENA, EurObserv'ER, SolarPower Europe, Fraunhofer ISE, scientific publications, IEA-PVPS
	Energy intensity and labour productivity	Scientific publications, various
	EU industrial production	Prodcom, JRC
Global markets and EU positioning	Global market growth and relevant short-to-medium term projections	Various
	EU market share vs third countries share, including EU market leaders and global market leaders	Comtrade, IEA-PVPS, Bloomberg NEF, various
	EU trade (imports, exports) and trade balance	ESMC, Comext, UN Comtrade, JRC
	Resource efficiency and dependencies (in relation EU competiveness)	JRC, various

Annex 2 Countries, regions and continents coding

EU

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	The Netherlands
PL	Poland
PT	Portugal
RO	Romania
SK	Slovakia
SI	Slovenia
ES	Spain
SE	Sweden

WORLD

CODE	COUNTRY
BR	Brazil
CA	Canada
CN	China
CH	Switzerland
EU	European Union
HK	Hong Kong
IL	Israel
IN	India
JP	Japan
KR	South Korea
MY	Malaysia
RoW	Rest of World
SG	Singapore
TW	Taiwan
UK	United Kingdom
US	United States of America
VN	Vietnam

Annex 3 Energy System Models and Scenarios: POTEnCIA and POLES-JRC

A3.1 POTEnCIA Model

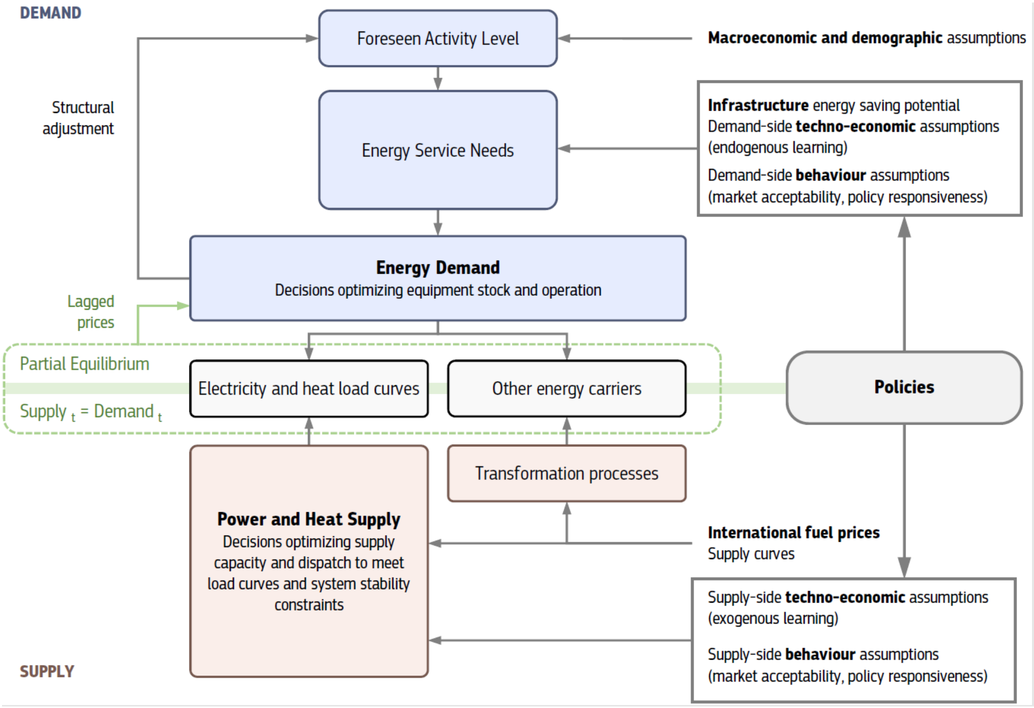
A3.1.1 Model Overview

The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed in-house by the European Commission's Joint Research Centre (JRC) to support EU policy analysis, POTEnCIA allows for the joint evaluation of technology-focused policies, combined with policies addressing the decision-making of energy users. To this end:

- By simulating decision-making under imperfect foresight at a high level of techno-economic detail, POTEnCIA realistically captures the adoption and operation of new energy technologies under different policy regimes;
- By combining yearly time steps for demand-side planning and investment with hourly resolution for the power sector, POTEnCIA provides high temporal detail to suitably assess rapid structural changes in the EU's energy system;
- By tracking yearly capital stock vintages for energy supply and demand, POTEnCIA accurately represents the age and performance of installed energy equipment, and enables the assessment of path dependencies, retrofitting or retirement strategies, and stranded asset risks.

The core modelling approach of POTEnCIA (Figure A3-1; detailed in the (Mantzos *et al.*, 2017, 2019)) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method. As such, for each sector of energy supply and demand, this approach assumes a representative agent seeking to maximize its benefit or minimize its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies.

Figure A3-1. The POTEnCIA model at a glance.



Source: Adapted from (Mantzos et al., 2019)

This core modelling approach is implemented individually for each EU Member State to capture differences in macroeconomic and energy system structures, technology assumptions, and resource constraints. The national model implementation is supported by spatially-explicit analyses to realistically define renewable energy potentials and infrastructure costs for hydrogen and CO_2 transport. Typical model output is provided in annual time steps over a horizon of 2000-2070; historical data (2000-2021) are calibrated to Eurostat and other official EU statistics to provide accurate initial conditions, using an updated version of the JRC Integrated Database of the European Energy System (Rózsai *et al.*, 2024).

A3.1.2 POTEnCIA CETO 2024 Scenario

The technology projections provided by the POTEnCIA model are obtained under a climate neutrality scenario aligned with the broad GHG reduction objectives of the European Green Deal. As such, this scenario reduces net EU GHG emissions by 55 % by 2030 and 90 % by 2040, both compared to 1990, and reaches net zero EU emissions by 2050. To model suitably the uptake of different technologies under this decarbonisation trajectory, the scenario includes a representation at EU level of general climate and energy policies such as emissions pricing under the Emissions Trading System, as well as key policy instruments that have a crucial impact on the uptake of specific technologies. For instance, the 2030 energy consumption and renewable energy shares reflect the targets of the EU's Renewable Energy Directive and of the Energy Efficiency Directive. Similarly, the adoption of alternative powertrains and fuels in transport is consistent with the updated CO_2 emission standards in road transport and with the targets of the ReFuelEU Aviation and FuelEU Maritime regulations. A more detailed description of the *POTEnCIA CETO 2024 Scenario* will be available in the forthcoming report (Neuwahl *et al.*, 2024).

A3.2 POLES-JRC Model

A3.2.1 Model Overview

POLES-JRC (Prospective Outlook for the Long-term Energy System) is a global energy model well suited to evaluate the evolution of energy demand and supply in the main world economies with a representation of international energy markets. It is a simulation model that follows a recursive dynamic partial equilibrium method. POLES-JRC is hosted at the JRC and was designed to assess global and national climate and energy policies.

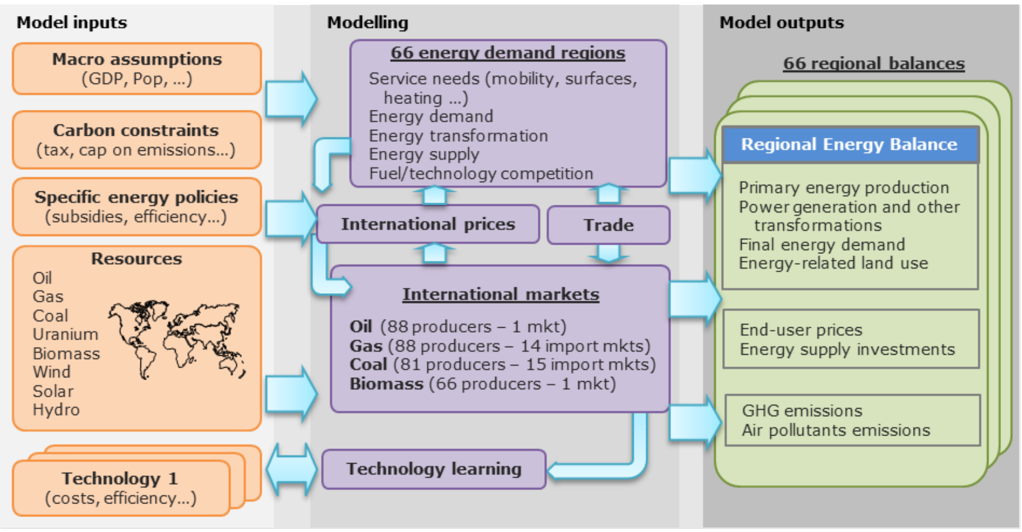
POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables) to transformation (power, biofuels, hydrogen and hydrogen-derived fuels such as synfuels) and final sectoral demand (industry, buildings, transport). International markets and prices of energy fuels are calculated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all detailed OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global frame: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2100 and is updated yearly with recent information.

The POLES-JRC model applied for the CETO project is specifically enhanced and modified to capture learning effects of clean energy technologies.

POLES-JRC results are published within the series of yearly publications "Global Climate and Energy Outlooks" – GECO. The GECO reports along with detailed country energy and GHG balances and an on-line visualisation interface can be found at: https://joint-research-centre.ec.europa.eu/scientific-activities-z/geco_en.

A detailed documentation of the POLES-JRC model is provided in (Després *et al.*, 2018) and a schematic representation can be seen in **Error! Reference source not found.**.

Figure A3-2. Schematic representation of the POLES-JRC model architecture.



Source: POLES-JRC model

A3.2.2 POLES-JRC Model description

Power System

The power system considers all relevant power generating technologies including fossil, nuclear and renewable power technologies. Each technology is modelled based on its current capacities and techno-economic characteristics. The evolution of cost and efficiencies are modelled through technology learning.

With regard to the power technologies covered by CETO, the model includes solar power (utility-scale and residential PV, concentrated solar power), wind power (on-shore and off-shore), hydropower and ocean power. Moreover, clean thermal power technologies are taken into account with steam turbines fuelled by biomass, biomass gasification, CCS power technologies and geothermal power. Furthermore, electricity storage technologies such as pumped hydropower storage and batteries are also included.

For solar and wind power, variable generation is considered by representative days with hourly profiles. For all renewables, regional resource potentials are considered.

Electricity demand

Electricity demand is calculated for all sectors taking into account hourly fluctuations through the use of representative days. Clean energy technologies using electricity consist of heat pumps (heating and cooling), batteries and fuel cells in transport, and electrolysers.

Power system operation and planning

Power system operation allocates generation by technology to each hour of representative days, ensuring that supplying and storage technologies meet overall demand, including grid imports and exports. Capacity planning considers the existing power mix, the expected evolution of electricity demand as well as the techno-economic characteristics of the power technologies.

Hydrogen

POLES-JRC takes into account several hydrogen production routes: (i) low temperature electrolysers using power from dedicated solar, wind and nuclear plants as well as from the grid, (ii) steam reforming of natural gas (with and without CCS), (iii) gasification of coal and biomass (with and without CCS), (iv) pyrolysis of gas and biomass as well as (v) high temperature electrolysis using nuclear power.

Hydrogen is used as fuel in all sectors including industry, transport, power generation and as well as feedstock for the production of synfuels (gaseous and liquid synfuels) and ammonia. Moreover, hydrogen trade is modelled, considering hydrogen transport with various means (pipeline, ship, truck) and forms (pressurised, liquid, converted into ammonia).

Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM-G4M model (IIASA, 2024). This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass-for-energy potential, production cost and reactivity to carbon pricing.

Biomass is used for power generation, hydrogen production and for the production of 1st and 2nd generation of liquid biofuels.

Carbon Capture Utilization and Storage (CCUS)

POLES-JRC uses CCUS technologies in:

- Power generation: advanced coal using CCS, coal and biomass gasification with CCS, and gas combined cycle with CCS.
- Hydrogen production: Steam reforming with CCS, coal and biomass gasification with CCS, and gas and biomass pyrolysis.
- Direct air capture (DAC) where the CO2 is either stored or used for the production of synfuels (gaseous or liquid).
- Steel and cement production in the industrial sector.
- Second generation biofuels production.

The deployment of CCS technologies considers region-specific geological storage potentials.

Endogenous technology learning

The POLES-JRC model was enhanced to capture effects of learning of clean energy technologies. To capture these effects, a one-factor learning-by-doing (LBD) approach was applied to technologies and technology sub-components, aiming at endogenising the evolution of technology costs.

POLES-JRC considers historical statistics and assumptions on the evolution of cost and capacities of energy technologies until the most recent year available (this report: 2022/2023). Based on the year and a capacities threshold, the model switches from the default time series to the endogeneous modelling with the one-factor LBD approach. Within the LBD, the learning rate represents the percentage change of the cost of energy technology based on a doubling of the capacity of the energy technology.

This generic approach is applied on a component level to capture spillover effects as well. For instance, a gasifier unit is used as component for several power generating technologies (e.g. integrated gasification combined cycle, IGCC) as well as for several hydrogen production technologies (e.g. gasification of coal and biomass). Therefore, the component-based LBD approach allows to model spillover effects not only across technologies, but also across sectors. Also, it allows to estimate costs for emerging technologies for which historical experience does not yet exist.

Moreover, for each component a floor cost is specified which marks the minimum for the component's investment cost and serves as limitation for the cost reduction by endogenous learning. Cost reductions by learning in POLES-JRC slow down when the investment cost approaches the floor cost.

The described method above applies not only for the overnight investment cost of energy technologies, but as well for operation and maintenance (OM) costs, which also decrease as technologies improve, and for efficiencies. In the model, OM costs diminish synchronously to the decrease of total investment cost of the technology. The efficiency of renewables is implicitly taken into account in the investment cost learning and the considered renewable potentials. For most technologies the efficiencies are endogenously modelled.

A3.2.3 Global CETO 2°C Scenario 2024

The global scenario data presented in the CETO technology reports 2024 refers to a 2°C scenario modelled by the POLES-JRC model in a modified and enhanced version to address the specific issues relevant for the CETO project.

The Global CETO 2°C scenario 2024 and its specific POLES JRC model configuration is described in detail in the forthcoming report "Impacts of enhanced learning for clean energy technologies on global energy system scenario" (Schmitz *et al.*, 2024).

The Global CETO 2°C scenario 2024 is designed to limit global temperature increase to 2°C at the end of the century. It is driven by a single global carbon price for all regions that reduces emissions sufficiently so as to limit global warming to 2°C. This scenario is therefore a stylised representation of a pathway to the temperature targets. This scenario does not consider financial transfers between countries to implement mitigation measures. This is a simplified representation of an ideal case where strong international cooperation results in concerted effort to reduce emissions globally; it is not meant to replicate the result of announced targets and pledges, which differ greatly in ambition across countries.

As a starting point, for all regions, it considers already legislated energy and climate policies (as of June 2023), but climate policy pledges and targets formulated in Nationally Determined Contributions (NDCs) and Long-Term Strategies (LTSs) are not explicitly taken into account. In particular, the EU Fit for 55 and RePowerEU packages are included in the policy setup for the EU. Announced emissions targets for 2040 and 2050 for the EU are not considered.

The Global CETO 2°C scenario 2024 differs fundamentally from the Global CETO 2°C scenario 2023 used in the CETO technology reports in 2023 in various aspects[29]:

- The version of the POLES-JRC model used for the Global CETO 2°C scenario has been further enhanced and modified to capture effects of endogenous learning of clean energy technologies and, furthermore, several technology representations were further detailed, e.g. DAC (composition of renewable technologies, batteries and DAC unit), fuel conversion technologies (for hydrogen transport) and batteries in transport.

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[29] A description of the *Global CETO 2°C scenario 2023* can be found in Annex 3 of (Chatzipanagi, Jaeger-Waldau, Cleret De Langavant, *et al.*, 2023)

- The techno-economic parameters have been thoroughly revised and updated taking into account the expertise of the authors of the CETO technology reports.

As a result, major scenario differences occur in the Global CETO 2°C scenario 2024 regarding DAC, synfuels, CCS power technologies, wind power and ocean power.

A3.3 Distinctions for the CETO 2024 Scenarios – POLES-JRC vs. POTEnCIA

The results of both models are driven by national as well as international techno-economic assumptions, fuel costs, as well as policy incentives such as carbon prices. However, on one side these two JRC energy system models differ in scope and level of detail, on the other side the definitions of the POTEnCIA and POLES-JRC scenarios presented in this document follow distinct logics, leading to different scenario results:

The Global CETO 2°C scenario 2024 (POLES-JRC) scenario is driven by a global carbon price trajectory to limit global warming to 2°C, where enacted climate policies are modelled, but long-term climate policy pledges and targets are not explicitly considered. Scenario results are presented for the global total until 2100.

The POTEnCIA CETO 2024 scenario is a decarbonisation scenario that follows a trajectory for EU27's net GHG emissions aligned with the general objectives of the European Climate Law (ECL) taking into consideration many sector-specific pieces of legislation. Scenario results are presented for the EU27 until 2050.

Annex 4 EU Supported R&I Projects for PV

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
758885	4SUNS	4-Colours/2-Junctions of III-V semiconductors on Si to use in electronics devices and solar cells	III-V	CPV	ERC	1,499,719	2018	2023
101059891	ACCELERATE-PER	Physics-informed machine learning to accelerate stability research on perovskite solar cells	perovskites	general	MSCA	199694,4	2023	2025
101129661	ADAPTATION	Adaptable bio-inspired polariton-polariton energy management	various	general	IA	3635137	2024	2028
666507	ADVANCED-buildings	New Generation of buildings glass with advanced integation properties	various	buildings	SME	1,887,121	2015	2017
101075709	AdvanSiC	AdvanSiC - Advances in Cost-Effective HV SiC Power Devices for Europe's Medium Voltage Grids	various	O&M	Coordination	3242373	2023	2025
101147383	AfricaEnergyParks	Improving energy access and climate resilience in Africa's fringe communities	various	integrated applications	Coordination	4994556,75	2024	2028
101069310	ALAMS	Atomic-layer additive manufacturing for solar cells	various	general	ERC	150000	2022	2023
774686	AlbaSolar	Developing perovskite-based solar panels	perovskites	general	SME	50,000	2017	2017
101147112	ALGAESOL	Sustainable aviation and shipping fuels from microalgae and direct solar BES technologies	various	general	Coordination	3997156,25	2024	2027
745601	AMPERE	Automated photovoltaic cell and Module industrial Production to regain and secure European Renewable Energy market	Silicon	general	Innovation	14,952,065	2017	2020
101101025	APERITIF	Dry-processing of metal halide perovskites into thin films	perovskites	general	ERC	150000	2023	2025
101122277	APOLLO	A Proactive Approach to the Recovery and Recycling of Photovoltaic Modules	various	recycling	R&I	5,325,755.76	2024	2026
763989	APOLO	SmArt Designed Full Printed Flexible RObust Efficient Organic HaLide PerOvskite solar cells	perovskites	general	R&I	4,997,191	2018	2022
101097337	ARCHIMEDES	Approaching 20% emission efficiency in the NIR-II region with radical chromophores	various	general	ERC	2499825	2023	2028
720887	ARCIGS-M	Advanced aRchitectures for ultra-thin high-efficiency CIGS solar cells with high Manufacturability	CIGS	buildings	RIA	4,498,701	2016	2020
101082517	ASCEND	Advanced Space Cloud for European Net zero emissions and Data sovereignty	various	space	R&I	2047882	2023	2024
101106002	ATACAMA	Affordable TAndem Cell Architecture by Multi-thin-epitaxy Approach	III-V	general	MSCA	211754,88	2024	2026
101136142	BAMBOO	Build scAled Modular Bamboo-inspired Offshore sOlar systems (BAMBOO)	various	integrated applications	IA	6,917,726.25	2024	2026
818009	Be-Smart	BE-Smart: Innovative Building Envelope for Sustainable, Modular, Aesthetic, Reliable and efficient construction	N/A	buildings	Coordination	8,155,173.37	2018	2022
101096516	BEST-Storage	BUILDING ENERGY EFFICIENT SYSTEM THROUGH SHORT AND LONG SPECTRUM THERMAL ENERGY STORAGE	various	system integration	IA	4797535	2023	2026

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
817991	BIPVBOOST	Bringing down costs of buildings multifunctional solutions and processes along the value chain, enabling widespread nZEBs implementation	various	buildings	Coordination	8,844,070	2018	2023
952911	BOOSTER	Boost Of Organic Solar Technology for European Radiance	OPV/DSSC	buildings	Coordination	6,106,623.75	2020	2024
101109054	BOOSTPV	Development of Bismuth Chalcogenide Sustainable Thin Film PV Technology	CIGS	buildings	MSCA	151901,76	2023	2025
101033809	BundleUP NEXT	Next-Level PDA Methodology to Enhance Public and Private Sustainable Energy Projects	N/A	general	Coordination	€996,375.00	2021	2024
101146684	BURST	Breaking limits Using Record enabling Silicon Technology with photonic management	IBC	general	Coordination	3,214,191.50	2024	2027
101088359	C2C-PV	Cradle-to-Cradle Design of Photovoltaic Modules	various	recycling	ERC	1962404	2023	2028
641972	CABRISS	Implementation of a CirculAr economy Based on Recycled, reused and recovered Indium, Silicon and Silver materials for photovoltaic and other applications	various	recycling	IA	7,844,565	2015	2018
101152844	CAPSELL	Chalcogenide Perovskites for Efficient, Stable, and non-toxic Solar Cells	perovskites	general	MSCA	230774,4	2024	2026
728894	CDRONE	Towards un-subsidised solar power – Cleandrone, the inspection and cleaning solution	N/A	O&M	SME	50,000	2016	2016
653296	CHEOPS	Production technology to achieve low Cost and Highly Efficient phOtovoltaic Perovskite Solar cells	perovskites	general	RIA	3,299,095	2016	2019
776680	CIRCUSOL	Circular business models for the solar power industry	various	recycling	IA	7,014,893	2018	2022
101135062	CisWEFE-NEX	Circular Systemic Water-Energy-Food-Ecosystems (WEFE) Nexus CCRI Demonstrator for Regions facing Severe Water Stress.	various	system integration	IA	9659285,15	2024	2029
101007084	CITYSOLAR	ENERGY HARVESTING IN CITIES WITH TRANSPARENT AND HIGHLY EFFICIENT WINDOW-INTEGRATED MULTI-JUNCTION SOLAR CELLS	Various	buildings	Coordination	3,779,242	2020	2023
101033682	CLEAR-X	Consumers Leading the EU's Energy Ambition Response, Expansion	N/A	general	Coordination	€1,999,750.00	2021	2024
640873	CPVMatch	Concentrating Photovoltaic modules using advanced technologies and cells for highest efficiencies	III-V	CPV	RIA	4,949,596	2015	2018
101113365	Cremoso	Cost-Effective Charge-Transport Materials for New-Generation Solar Cells	various	general	ERC	150000	2023	2024
699935	Crystal Tandem Solar	Single-Crystal Perovskite Tandem Solar Cells For High Efficiency and Low Cost	perovskites	general	MSCA	269,858	2017	2019
887915	cs-BIPV-FS	Next-generation transparent PV for Building Integrated Photovoltaics	Silicon	buildings	SME	50,000	2019	2020
952982	CUSTOM-ART	DISRUPTIVE KESTERITES-BASED THIN FILM TECHNOLOGIES CUSTOMISED FOR CHALLENGING ARCHITECTURAL AND ACTIVE URBAN FURNITURE APPLICATIONS	Kesterites	buildings	Coordination	6,999,745.25	2020	2024
790316	DeepSolar	Artificial Intelligence-based diagnostic system for Solar PV Plants	N/A	O&M	SME	50,000	2017	2018

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
101146984	DeNOVO	Design rules for Novel Organic photoVoltaics from natural phOtosystems through computational modelling	various	general	MSCA	172750,08	2025	2027
101084124	DIAMOND	Ultra-stable, highly efficient, low-cost perovskite photovoltaics with minimised environmental impact	perovskites	general	R&I	5,115,876.00	2022	2025
727529	DISC	Double side contacted cells with innovative carrier-selective contacts	Silicon	general	R&I	4,743,519	2016	2019
101065785	ECLIPSE	Ecological impacts of floating photovoltaics in lake ecosystems	various	integrated applications	MSCA	264693,6	2022	2025
101118127	ECOLOOP	ECOLOOP	various	integrated applications	Coordination	7325300	2023	2027
101150783	ECOPV	Green solvent recycling for sustainable, eco-friendly perovskite photovoltaics	perovskites	recycling	MSCA	222727,68	2024	2026
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	2015	2018
101068387	EFESO	Exploiting Flexible pErovskites Solar technOlogies	perovskites	general	MSCA	288112,44	2023	2026
101119780	EIFFEL	EffIcient Fullerene-Free organic solar cELls	OPV	general	MSCA	2642112	2024	2028
701104	ELSi	Industrial scale recovery and reuse of all materials from end of life silicon-based photovoltaic modules	Silicon	recycling	IA	2,529,607	2016	2018
101162648	ENFORCE	ENhancing the power conversion eFficiency of mOnocRystalline nitrogen-doped silicon solar CElls	silicon	general	MSCA	177251,52	2024	2026
955413	ENGIMMONIA	Sustainable technologies for future long distance shipping towards complete decarbonisation	N/A	integrated applications	CSA	€9,500,000.00	2021	2025
767180	Envision	ENergy harVesting by Invisible Solar IntegratiON in building skins	various	buildings	IA	4,900,313	2017	2022
657270	EpiSil-IBC	Epitaxial silicon foil solar cells with interdigitated back contacts	Silicon	general	MSCA	160,800	2015	2017
878182	ESMOS	Efficient, Safe and Multi-Functional Operation of Solar-Roads	Silicon	integrated applications	SME	50,000	2019	2020
764047	ESPResSo	Efficient Structures and Processes for Reliable Perovskite Solar Modules	perovskites	general	R&I	5,412,658	2018	2021
881226	ETC Solarshade	Invisible metal contacts for solar cells – boosting power output while cutting costs	various	general	SME	2,032,343	2019	2021
727272	ETIP PV - SEC	Support to all stakeholders from the Photovoltaic sector and related sectors to contribute to the SET-Plan	N/A	general	RIA	€596,812.50	2016	2018
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	Coordination	922,875	2018	2022
101075398	ETIP PV Secretariat	Support to all stakeholders from the Photovoltaic sector and related sectors to contribute to the SET-Plan	various	general	Coordination	946,500.00	2022	2025
764805	EU HEROES	EU routes for High pEnentration of solaR PV into lOcal nEtworkS	N/A	system integration	Coordination	1,230,558	2017	2020

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
101036457	EU-SCORES	European Scalable Complementary Offshore Renewable Energy Sources	N/A	integrated applications	Coordination	€34,831,483.81	2021	2025
101122208	EVERPV	Highly efficient delamination technologies to recover and reuse metals, glass, polymers from end-of-life photovoltaic panels	various	recycling	R&I	5,367,184.00	2023	2026
101113332	EVOLUTE	Evolution of Advanced Luminescent Technology Software	LSC	general	ERC	150000	2023	2025
101151994	EXPLEIN	Electron Transport Experimental Investigation of Perovskites using Light and Electron Injection at the Nanoscale	perovskites	general	MSCA	187624,32	2024	2026
101092339	Exploit4InnoMat	An Open Innovation Ecosystem for exploitation of materials for building envelopes towards zero energy buildings	various	buildings	IA	11340890,38	2023	2026
101152684	EXT-PIMMCH	Extending the perovskite-inspired mixed-metal chalcohalide alloy space for solar cells	various	general	MSCA	199694,4	2024	2026
747331	FALCO	Financing Ambitious Local Climate Objectives	N/A	general	Coordination	€1,172,451.25	2017	2022
797546	FASTEST	Fully Air-Processable and Air-Stable Perovskite Solar Cells Based on Inorganic Metal Halide Perovskite Nanocrystals	perovskites	general	MSCA	180,277	2018	2020
101065174	FaWB ChaLT	Fabrication of Wide Bandgap Chalcopyrite Photovoltaics at Low Temperatures for Prospective Tandem Solar Cells	CIGS	general	MSCA	217309,2	2022	2024
101096803	Flex2Energy	Automated Manufacturing Production Line for Integrated Printed Organic Photovoltaics	OPV	general	IA	15,702,550.00	2023	2026
646428	Flex4Grid	Prosumer Flexibility Services for Smart Grid Management	N/A	system integration	RIA	€2,680,253.00	2015	2018
101043783	FOCUS	Fluorescent Optical Concentration of Uncollimated Sunlight	LSC	general	ERC	2998125	2022	2027
101138503	FORESi	FOstering a Recycled European Silicon supply	silicon	recycling	IA	6999848,75	2024	2026
101080029	FORTESIE	CBDC powered Smart PerFORrmance contracTs for Efficiency, Sustainable, Inclusive, Energy use	various	buildings	IA	7367150	2022	2025
101084261	FreeHydroCells	Freestanding energy-to-Hydrogen fuel by water splitting using Earth-abundant materials in a novel, eco-friendly, sustainable and scalable photoelectrochemical Cell system	various	general	IA	3748300	2022	2026
804519	FREENERGY	Lead-free halide perovskites for the highest efficient solar energy conversion	perovskites	general	ERC	1,500,000	2019	2024
966334	FREENERGY	Lead-free halide perovskites for the highest efficient solar energy conversion	perovskites	general	ERC	150,000	2021	2022
101106492	Full-Fission	Singlet fission in fullerene-based single-material organic solar cells	opv	general	MSCA	181152,96	2024	2026
101156968	GEN2HU	GENERON 2.0 Integrated Solar Roof Tile	various	Buildings	IF	2,220,000.00	2024	
101070721	GH2	GreenH2 production from water and bioalcohols by full solar spectrum in a flow reactor	various	system integration	ERC	2201654,72	2022	2025

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
792059	GOPV	Global Optimization of integrated PhotoVoltaics system for low electricity cost	N/A	system integration	Innovation	9,403,873.42	2018	2022
687008	GOTSolar	New technological advances for the third generation of Solar cells	perovskites	general	RIA	2,993,404	2016	2018
101151408	GPSpace	Graphene-based flexible perovskite solar cells for space applications	perovskites	space	MSCA	181152,96	2025	2027
701254	GreenChalcoCell	Green and sustainable chalcopyrite and kesterite nanocrystals for inorganic solar cells	various	general	MSCA	171,461	2016	2018
101153827	GreenPeroInk	Scalable processing of highly stable, flexible multi-junction perovskite solar cells from green inks	perovskites	O&M	MSCA	173847,36	2025	2027
727362	GRIDSOL	SMART RENEWABLE HUBS FOR FLEXIBLE GENERATION: SOLAR GRID STABILITY	N/A	system integration	R&I	€3,421,447.50	2016	2019
101059015	HaloCell	Harnessing Halogen Bond in Perovskite Solar Cells	perovskites/OPV	buildings	MSCA	235737,6	2023	2025
101152917	HEAT-PV	HEAT-PV: High Efficiency Antimony Selenide (Sb2Se3) based Photovoltaic Devices	CIGS	general	MSCA	156778,56	2025	2026
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	2,486,865	2017	2022
101122345	HEPAFLEX	High-Efficiency Perovskites on Flexible Substrates for Sustainable Applications	perovskites	general	R&I	4,308,772.50	2023	2027
101108639	HESOZA	All-in-one solar rechargeable Zinc-air battery enabling direct storage of solar energy	various	system integration	MSCA	189687,36	2024	2026
839136	HES-PSC-FCTL	High efficiency and stability perovskite solar cells based on the functionalized charge transport layers	perovskites	general	MSCA	224,934	2019	2021
101122203	Hi-BITS	High efficiency bifacial thin film chalcogenide solar cells	CIGS	integrated applications	R&I	4,962,618.54	2023	2026
190146412	HighLine	Fine Line Dispensing Process to apply Narrow Metal Contacts onto Solar Cells	HJT	general	IA	2500000	2023	2025
857793	HighLite	High-performance low-cost modules with excellent environmental profiles for a competitive EU PV manufacturing industry	Silicon	buildings	Coordination	12,870,478	2019	2022
857775	HIPERION	Hydrid photovoltaics for efficiecny record using optical technology	III-V	CPV	Coordination	10,590,511	2019	2023
655272	HISTORIC	High efficiency GaInP/GaAs Tandem wafer bonded solar cell on silicon	III-V	general	MSCA	159,461	2015	2017
101117858	HOLOFAST	Holographic nanoscale imaging via femtosecond structured illumination	OPV	general	ERC	1499838	2024	2029
101159263	Honkisaarenneva PV solar park	Honkisaarenneva PV solar park	various	integrated applications		4,131,273.00	2024	2041
101132875	HOPE	High-efficient Onshore PV module production in Europe	HJT	general	IF	200,000,000.00	2024	2032
101104491	HOPES	High-throughput Optimization for Indoor Organic Photovoltaic Energy Systems	OPV	general	MSCA	181152,96	2024	2026

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
850275	HORIZON	Redefining solar technology with retractable soalr power folding roofs. Unlocking photovoltaics for waste water treatment plants towards self-sufficient plants.	Silicon	integrated applications	SME	2,488,125	2019	2021
795716	HYBRICYL	Organic-Inorganic Hybrid Heterojunctions in Extremely Thin Absorber Solar Cells Based on Arrays of Parallel Cylindrical Nanochannels	perovskites	general	MSCA	159,461	2018	2020
101061809	HyPerGreen	Revealing pathways towards efficient and stable eco-friendly tin perovskite solar cells by photo-Hall and surface photo-voltage measurements	perovskites	general	MSCA	189687,36	2023	2025
756962	HYPERION	HYbrid PERovskites for Next GeneratION Solar Cells and Lighting	perovskites	general	ERC	1,759,733	2017	2022
674502	HySolarKit	Converting conventional cars into hybrid and solar vehicles	Silicon	integrated applications	SME	50,000	2015	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	159,461	2017	2019
717956	HyTile	Sensitive integrated Solar Hybrid Roofing for historical buildings.	Silicon	buildings	SME	50,000	2016	2016
101084259	IBC4EU	Piloting novel cost-competitive bifacial IBC technology for vertical integrated European GW scale PV production value chain	IBC	general	R&I	13,490,668.75	2022	2025
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	Coordination	2,706,940	2017	2020
101040153	IDOL	Inverse Design of Optoelectronic Phosphosulfides	various	general	ERC	2263750	2023	2027
101077766	illicitLABOUR	Illicit labour: Unveiling the dark sides of the global photovoltaic industry	various	general	ERC	1500000	2024	2029
826013	IMPRESSIVE	ground-breakIng tandeM of transPaRent dyE SenSitIsed and peroVskite solar cEIls	perovskites	general	Coordination	2,929,050	2019	2022
101136112	Increase	effectIve advaNCements towaRds uptakE of PV integrAted in buildingS & infrastructurE	various	integrated applications	IA	8,008,853.37	2023	2028
777968	INFINITE-CELL	International cooperation for the development of cost-efficient kesterite/c-Si thin film next generation tandem solar cells	Kesterites	general	MSCA	1,318,500	2017	2022
101152448	INFRALIGHT	Collecting Plasmonic Near-Infrared Photons through a Schottky junction	various	general	MSCA	172750,08	2024	2026
101077006	INPERSPACE	Ultra-efficient and stable perovskite tandem solar cells for extreme conditions in space	perovskites	space	ERC	2500000	2024	2029
101107885	INT-PVK-PRINT	An intelligent perovskite solution printing line	perovskites	general	MSCA	188590,08	2023	2025
101066273	IONMIGRATIONPSC	Study of Ion Migration in Perovskite Solar Cells via X-ray Photoemission Spectroscopy Imaging and Photoluminescence Microscopy	perovskites	general	MSCA	173847,36	2022	2024
101098900	IPROP	Ionic Propulsion in Atmosphere	various	space	IA	2999993,75	2023	2027

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
101109355	ISDT	Design and implementation of a frequency domain online diagnostic tool for PV modules	various	O&M	MSCA	188590,08	2024	2026
190190195	iSPLASH	Industrial Selective PLAting for Solar Heterojunction	HJT	general	IA	2449440	2022	2024
101158748	Koirivaara Solar Park Finland	Koirivaara Solar Park Finland	various	general		5,196,396.82	2024	2041
101158420	Kuortane Solar	Kuortane Solar	various	general		9,979,244.00	2024	2041
101087673	LAMI-PERO	Laminated Perovskite Photovoltaics: Enabling large area processing of durable and high efficiency perovskite semiconductor thin films.	perovskites	general	ERC	2349755	2023	2028
101147311	LAPERITIVO	Large-Area Perovskite Solar Module Manufacturing with High Efficiency, Long-Term Stability and Low Environmental Impact	perovskites	general	Coordination	6,952,728.98	2024	2028
190132742	LAYER®	Development of an organic photovoltaic module that generates energy from ambient light	various	system integration	IA	1622881	2022	2024
101151487	LEKPV	Revolutionizing Indoor Energy: The Emergence of Low-Cost Eco-Friendly, High-Efficiency Kesterite Solar Cells	kesterites	integrated applications	MSCA	165312,96	2024	2026
876320	LightCatcher	Scalable energy efficiency modules integrating both energy recovery and passive cooling systems for the solar photovoltaic industry	Silicon	PVT	SME	50,000	2019	2020
101041809	LOCAL-HEAT	Controlled Local Heating to Crystallize Solution-based Semiconductors for Next-Generation Solar Cells and Optoelectronics	perovskites	general	ERC	1500000	2022	2027
101158646	Loukkaanaro solar park	Loukkaanaro solar park	various	general		2,353,563.18	2024	2040
841265	LOVETandemSolar	Local Optoelectronic Visualisation for Enhancing Tandem Perovskite/Silicon Solar Cells	perovskites	general	MSCA	212,934	2019	2022
856071	LUMIDUCT	Transparent PV that regulates indoor climate	III-V	buildings	SME	50,000	2019	2019
101147653	LUMINOSITY	Large area uniform industry compatible perovskite solar cell technology	perovskites	general	Coordination	6,996,063.13	2024	2028
101105123	MaDLED	Mastering Electronic Doping in Tin-Halide Perovskites to Develop Near Infrared Light Emitting Diodes	perovskites	general	MSCA	188590,08	2024	2025
764787	MAESTRO	MAking pErovskiteS TRuly explOitable	perovskites	general	MSCA	3,829,217	2017	2022
101146874	MAPLE	Multidimensional generAtion of bulk Photovoltaic currents by vectorial Light Engineering	various	general	MSCA	172750,08	2025	2027
101135299	MASS-IPV	Enabling Massive Integration of PV into Buildings and Infrastructure	various	integrated applications	IA	7,190,188.74	2023	2027
707168	MatchForSolar	Mechanochemical Approach to Inorganic-Organic Hybrid Materials for Perovskite Solar Cells	perovskites	general	MSCA	131,565	2016	2018
101096139	MC2.0	Mass customization 2.0 for Integrated PV	various	integrated applications	IA	7,592,626.00	2023	2026
101091915	MEloDIZER	SUSTAINABLE MEMBRANE DISTILLATION FOR INDUSTRIAL WATER REUSE AND DECENTRALISED	various	system integration	IA	7007470,74	2022	2026

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
		DESALINATION APPROACHING ZERO WASTE						
101083409	Micro-Bio-CHP	Development of a novel highly efficient energy supply system for energy autonomous multi-family buildings based on biomass gasification coupled with an SOFC and a PV system	various	system integration	IA	3924195	2022	2025
101087086	MIRACLE	Quantum-engineered lattice-matched III-V-on-Si multijunction solar cells	III-V	general	ERC	2808686	2025	2029
101130860	MISTiCal	Semi-Transparent Micro-Striped Chalcopyrite Cu(In,Ga)Se2 solar cells for window applications	CIGS	buildings	MSCA	195973,2	2023	2026
795206	MolDesign	Molecule design for next generation solar cells using machine learning approaches trained on large scale screening databases	various	general	MSCA	208,964	2018	2022
726360	MOLEMAT	Molecularly Engineered Materials and process for Perovskite solar cell technology	perovskites	general	ERC	1,878,085	2017	2023
101153019	MOLMAPS	MOLecular Materials for Passivation in large Area Perovskite Solar modules	perovskites	general	MSCA	191760	2024	2026
653184	MPerS	Sustainable Mixed-ion Layered Perovskite Solar Cells	perovskites	general	MSCA	195,455	2015	2017
656658	NanoCuI	Nano-Copper Iodide: A New Material for High Performance P-Type Dye-Sensitized Solar Cells	OPV/DSSC	general	MSCA	195,455	2015	2017
696519	NanoSol	Accelerating Commercialization of Nanowire Solar Cell Technologies	III-V	general	SME	1,740,375	2016	2019
655039	NANOSOLAR	HYBRID QUANTUM-DOT/TWO-DIMENSIONAL MATERIALS PHOTOVOLTAIC CELLS	various	general	MSCA	158,122	2015	2017
641023	Nano-Tandem	Nanowire based Tandem Solar Cells	III-V	general	RIA	3,561,842	2015	2019
101084348	NATURSEA-PV	NOVEL ECO-CEMENTITIOUS MATERIALS AND COMPONENTS FOR DURABLE, COMPETITIVE, AND BIO-INSPIRED OFFSHORE FLOATING PV SUBSTRUCTURES	various	integrated applications	R&I	3,621,694.10	2022	2026
101135639	Nautical SUNRISE	Survivability assessment, cost redUction pathways and eNvironmental evaluation of offshoRe Installed floating Solar energy farms	various	integrated applications	IA	6,803,003.95	2023	2027
101146980	NEBULAE	Eco-friendly ytterbium-doped perovskite nanocrystals embedded in glasses for solar cells	various	general	MSCA	199694,4	2025	2027
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	195,455	2015	2017
727523	NextBase	Next-generation interdigitated back-contacted silicon heterojunction solar cells and modules by design and process innovations	Silicon	general	R&I	3,800,421	2016	2019
656208	NEXTNANOCELLS	Next generation nanowire solar cells	III-V	general	MSCA	173,857	2015	2018
101075330	NEXUS	NEXt generation of sUstainable perovskite-Silicon tandem cells	perovskites	general	Coordination	3,978,201.25	2022	2025
101158719	Niittyneva Solar Park	Niittyneva Solar Park	various	general		837,039.00	2024	2040

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
101154100	OFFSET	Perovskite Ferroelectric Materials For Sustainable Energy Technologies	perovskites	general	MSCA	261380,64	2024	2027
101158777	Ohrasuo Solar Park funding application	Ohrasuo Solar Park funding application	various	general		990,500.00	2024	2041
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	2018	2022
686116	OptiNanoPro	Processing and control of novel nanomaterials in packaging, automotive and solar panel processing lines	various	O&M	IA	5,516,910	2015	2018
101120262	OPVStability	Understanding, Predicting and Enhancing the Stability of Organic Photovoltaics	opv	general	MSCA	2700619,2	2023	2027
101067838	P4SPACE	Development of Perovskite Photovoltaics for Space Environment	perovskites	space	MSCA	207609,6	2023	2025
774717	PanePowerSW	Transparent Solar Panel Technology for Energy Autonomous Greenhouses and Glass Buildings	OPV/DSSC	buildings	SME	50,000	2017	2017
804554	PanePowerSW	Transparent Solar Panel Technology for Energy Autonomous Greenhouses and Glass Buildings	OPV/DSSC	buildings	SME	1,491,783	2018	2021
101086805	PARACRYST	The Semi-paracrystalline Organization in Polymers: Towards Stable Organic Solar Cells	opv	general	ERC	1999000	2024	2028
101122283	PEARL	FLEXIBLE PEROVSKITE SOLAR CELLS WITH CARBON ELECTRODES	perovskites	general	R&I	4,498,458.00	2023	2026
639760	PEDAL	Plasmonic Enhancement and Directionality of Emission for Advanced Luminescent Solar Devices	LSC	buildings	ERC	1,447,410	2015	2021
101084251	PEPPERONI	Pilot line for European Production of PEROvskite-Silicon taNdem modules on Industrial scale	perovskites	general	R&I	12,950,825.00	2022	2026
850937	PERCISTAND	Development of all thin-film PERovskite on CIS TANDem photovoltaics	perovskites	general	Coordination	4,997,437	2020	2023
101087679	PEROVAP	Engineering metal halide PEROvskites by VAPour deposition	perovskites	general	ERC	1999843,75	2024	2029
659237	PerovskiteHTM	New Hole-Transport Materials to Enhance Perovskite Solar Cells	perovskites	general	MSCA	195,455	2016	2018
841005	PerSiSTanCe	Low-cost and Large-Area Perovskite-Silicon Solar Tandem Cells	perovskites	general	MSCA	203,149	2019	2021
101098168	PERSTACK	Perovskite triple and quadruple junction solar cells	perovskites	general	ERC	2999926	2024	2028
763977	PERTPV	Perovskite Thin-film Photovoltaics (PERTPV)	Perovskites	general	R&I	4,996,041.25	2018	2021
101125948	PHASE	Photonic metasurfaces for resource-efficient ultrathin high efficiency tandem solar cells	various	general	ERC	2676875	2024	2029
101111407	PHOMOTRIPP	PHOtoactivated Metal Oxide TRansport layers for Indoor Perovskite Photovoltaics	perovskites	integrated applications	MSCA	188590,08	2024	2026
101069357	Photo2Fuel	Artificial PHOTOsynthesis to produce FUELs and chemicals: hybrid systems with microorganisms for improved light harvesting and CO2 reduction	various	system integration	IA	2493171	2022	2025

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
745776	PHOTOPEROVSKITES	Photoexcitation Dynamics and Direct Monitoring of Photovoltaic Processes of Solid-State Hybrid Organic-Inorganic Perovskite Solar Cells	perovskites	general	MSCA	195,455	2017	2020
101118129	PHOTOSINT	PHOTOelectrocatalytic systems for Solar fuels energy INTegration into the industry with local resources	various	system integration	Coordination	4993752,5	2023	2027
795079	PhotSol	Towards the Photonic Solar Cell - In-Situ Defect Characterization in Metal-Halide Perovskites	various	general	MSCA	159,461	2019	2021
737447	PHYSIC	Photovoltaic with superior crack resistance	Silicon	O&M	ERC	149,500	2017	2018
101084046	PILATUS	Digitalised pilot lines for silicon heterojunction tunnel interdigitated back contact solar cells and modules	HJT	general	R&I	10,158,731.15	2022	2025
889405	PIPER	Printing of Ultra-Thin, Flexible Perovskite Solar Cells and its Commercial Application	perovskites	buildings	SME	50,000	2019	2020
832606	PISCO	Photochromic Solar Cells: Towards Photovoltaic Devices with Variable and Self-Adaptable Optical Transmission	various	general	ERC	2,497,742	2019	2024
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	158,122	2016	2017
101058459	Platform-ZERO	Customizable AI-based in-line process monitoring platform for achieving zero-defect manufacturing in the PV industry	various	general	IA	9131043	2023	2026
762726	PLATIO	Innovative outdoor solar and kinetic energy harvesting pavement system	silicon	integrated applications	SME	50,000	2017	2017
651970	POLYSOLAR	A light weight, recyclable, tracking support system, for solar photovoltaic modules based on inflatable polymer membranes	various	O&M	SME	50,000	2014	2015
747221	POSITS	High Performance Wide Bandgap and Stable Perovskite-on-Silicon Tandem Solar Cells	perovskites	general	MSCA	175,420	2017	2019
101033940	POWER UP	SOCIAL ENERGY MARKET PLAYERS TO TACKLE ENERGY POVERTY	N/A	general	Coordination	€1,962,832.50	2021	2025
101158421	Poytya Solar	Poytya Solar	various	general		4,011,984.00	2024	2041
727722	PRINTSolar	Printable Perovskite Solar Cells with High Efficiency and Stable Performance	perovskites	general	ERC	150,000	2016	2018
101079469	PROMISE	Photovoltaics Reliability Operations and Maintenance Innovative Solutions for Energy Alliance	various	recycling	Coordination	1500000	2022	2025
715354	p-TYPE	Transparent p-type semiconductors for efficient solar energy capture, conversion and storage.	OPV/DSSC	general	ERC	1,499,840	2017	2022
646554	PV FINANCING	PV FINANCING	N/A	system integration	RIA	2,050,939	2015	2017
842547	PV Impact	Actual execution of the Implementation Plan for Photovoltaics and monitoring the Implementation Plan's delivery	N/A	general	Coordination	1,094,565	2019	2022
101096409	PV4Plants	AgriPV system with climate, water and light spectrum control for safe,	various	integrated applications	IA	4,079,701.00	2023	2026

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
		healthier and improved crops production						
818342	PVadapt	Prefabrication, Recyclability and Modularity for cost reductions in Smart buildings systems	Silicon	buildings	Coordination	8,978,434	2018	2022
657359	PVFIFTY	TOWARDS A 50% EFFICIENT CONCENTRATOR SOLAR CELL AND A 40% EFFICIENT SPACE SOLAR CELL	III-V	space	MSCA	183,455	2015	2017
684528	PVFINAL	Photo Voltaic Fully Integrated and Automated Line	Silicon	general	SME	50,000	2015	2015
101147000	PVOP	Digitalising the PV sector for the era of Terawatts	various	O&M	Coordination	4,856,743.63	2024	2027
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	Coordination	2,501,739	2017	2020
691768	PVSITES	Building-integrated photovoltaic technologies and systems for large-scale market deployment	various	buildings	RIA	5,467,612	2016	2020
101122298	QUASAR	70%plus eco-efficiency gains in the PV EOL supply chain by closed loop systems with enhanced recycling rates, systematic collection and management utilising digital twins	various	recycling	R&I	6,815,473.39	2023	2027
101105718	QuBics	Understanding the Working Mechanisms of Quaternary Blend Organic Photovoltaics (OPVs)	opv	general	MSCA	222727,68	2023	2025
655852	Quokka Maturation	A mature Quokka for everyone – advancing the capabilities and accessibility of numerical solar cell simulations	various	general	MSCA	171,461	2016	2018
702629	R2R-3G	Towards Roll-to-Roll Production of Third Generation Solar Cells	III-V	general	MSCA	187,420	2016	2018
776362	RadHard	Ultra High Efficiency Radiation Hard Space Solar Cells on Large Area Substrates	III-V	space	RIA	3,072,973	2018	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	50,000	2015	2015
101137773	REALIZE	RENEWABLE ENERGY ACTIONS LEVERAGING INNOVATION TOWARDS ZERO EMISSIONS IN EUROPE	various	general	IA	997383,58	2024	2026
101096056	REGACE	Crop Responsive Greenhouse Agrivoltaics System with CO2 Enrichment for Higher Yields	various	integrated applications	IA	5,330,750.00	2023	2026
101103450	RENplusHOMES	Renewable ENergy-based Positive Homes	various	system integration	IA	5999983	2023	2026
683928	REPHLECT	Recovering Europe´s PHotovoltaics LEadership through high Concentration Technology	III-V	CPV	SME	1,633,601	2015	2018
101096250	RePower	Improving Renewables Penetration Through Plug and Play Microgrids	various	system integration	IA	9,988,745.87	2023	2027
649767	RESCOOP MECISE	RESCOOPs Mobilizing European Citizens to Invest in Sustainable Energy	N/A	general	CSA	€2,185,000.00	2015	2019

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
101058583	RESILEX	Resilient Enhancement for the Silicon Industry Leveraging the European matriX	silicon	recycling	IA	10577055	2022	2026
101082355	RESPONDENT	Renewable Energy Sources Power FOrecasting and SyNchronisation for Smart GriD NEtworks MaNagemenT	various	O&M	IA	2147112,5	2022	2025
101122332	Retrieve	Reintegration of photovoltaic panel waste back into manufacturing as high value products	various	recycling	R&I	6,943,801.55	2023	2027
862474	RoLA-FLEX	Roll-2-Roll and Photolithography post-processed with LAser digital technology for FLEXible photovoltaics and wearable displays	OPV/DSSC	general	RIA	4,705,038.38	2020	2023
101154277	S3EM	A Semantic 3D Energy Model for Prosumer With Integrated Photovoltaics Systems	various	buildings	MSCA	214934,4	2025	2027
101153098	SAMper	Boosting Efficiency and Stability of Tin-Lead Perovskite Photovoltaics with Chemically Smart Device Architectures	perovskites	general	MSCA	181152,96	2024	2026
101033676	SCCALE 203050	Sustainable Collective Citizen Action for a Local Europe 20-30-50	N/A	general	Coordination	€1,999,166.25	2021	2024
101096126	SEAMLESS-PV	Development of advanced manufacturing equipment and processes aimed at the seamless integration of multifunctional PV solutions, enabling the deployment of IPV sectors	silicon	integrated applications	IA	12,582,309.31	2023	2026
886287	SecureTracker	New-generation bifacial solar tracker with integrated wind protection system for large scale photovoltaic arrays	Silicon	O&M	SME	50,000	2019	2020
953016	SERENDI-PV	Smooth, REliable aNd Dispatchable Integration of PV in EU Grids	N/A	system integration	Coordination	9,779,145.88	2020	2024
641004	Sharc25	Super high efficiency Cu(In,Ga)Se2 thin-film solar cells approaching 25%	CIGS	general	RIA	4,563,123	2015	2018
101065298	SHERPA	Self-healing screen-printed perovskite photovoltaics beyond Shockley–Queisser Limit	perovskites	general	MSCA	188590,08	2022	2024
101147275	SiLEAN	Silicon solar cells with Low Environmental footprint and Advanced interfaces	HJT	general	Coordination	2,996,153.75	2024	2027
101075626	SITA	Stable Inorganic TAndem solar cell with superior device efficiency and increased durability	HJT	general	Coordination	4,987,479.50	2022	2025
727497	SITASOL	Application relevant validation of c-Si based tandem solar cell processes with 30 % efficiency target	III-V	general	R&I	4,298,201	2017	2021
101114653	SmartHyMat	Smart Hybrid Materials for Opto(electro)ionics	perovskites	general	ERC	2123241	2024	2029
101122327	SMARTLINE-PV	Fast plasma-assisted perovskite crystallization for high efficiency lead-free perovskite thin film photovoltaics	perovskites	general	R&I	4,994,686.25	2024	2027
844655	SMOLAC	Theoretical design of non-fullerene small molecule acceptors for organic solar cells with improved efficiency.	OPV/DSSC	general	MSCA	174,806	2019	2022
736217	SOcool	SunOyster cooling (SOcool)	III-V	PVT	SME	50,000	2016	2017
778106	SOcool	SunOyster cooling (SOcool)	III-V	PVT	SME	1,398,478	2017	2021

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
683876	SoHo3X	Introducing a novel concept of solar photovoltaic module in the market	Silicon	CPV	SME	50,000	2015	2015
647281	SOLACYLIN	A preparative approach to geometric effects in innovative solar cell types based on a nanocylindrical structure	various	general	ERC	1,938,655	2015	2020
952879	SolAqua	Accessible, reliable and affordable solar irrigation for Europe and beyond	N/A	system integration	Coordination	1,757,211	2020	2023
101114041	SOLAR BABYSITTER	Solar BabySitter'- technology to change solar world	various	O&M	Coordination	75000	2023	2024
815019	Solar Bank	Virtual Energy Trading IT System to couple photovoltaic production and electric vehicles charging.	N/A	system integration	SME	50,000	2018	2018
649997	Solar Bankability	Improving the Financeability and Attractiveness of Sustainable Energy Investments in Photovolatics: Quantifying and Managing the Technical Risk for Current and New Business Models	N/A	system integration	CSA	1,355,106	2015	2017
786483	Solar Cofund 2	SOLAR-ERA.NET Cofund 2	N/A	general	Coordination	6,333,425	2018	2023
101099284	SolarCO2Value	Lab-to-tech transition of the current best low temperature electrolyser technology for CO2 reduction to CO using solar energy	various	system integration	IA	2373125	2022	2025
718003	SolardeSaLt	A Renewable Approach for Industrial Water Desalination by using Hybrid Photovolt	Silicon	integrated applications	SME	50,000	2016	2016
791411	SolarGaps	SolarGaps - Energy generating solar smart window blinds	N/A	buildings	SME	50,000	2017	2018
101103762	SolarHyValue	Simultaneous solar hydrogen and value-added product generation by inexpensive photoelectrodes	perovskites	system integration	MSCA	157622,4	2024	2026
760311	SolarSharc	SOLARSHARC - a durable self-clean costing for solar panels to improve PV energy generation efficiency	various	O&M	IA	2,267,636	2017	2019
721452	SOLAR-TRAIN	Photovoltaic module life time forecast and evaluation	various	O&M	MSCA	3,576,248	2016	2020
101046297	SOLARUP	Advanced Strategies for Development of Sustainable Semiconductors for Scalable Solar Cell Applications	various	general	IA	2930127,5	2022	2026
101148726	SolarWay	Solar syngas streamed from photonic-enhanced perovskite photovoltaics: paving the way for market deployment	perovskites	system integration	MSCA	156778,56	2024	2026
870004	Solar-Win	Next generation transparent solar windows based on customised integrated photovoltaics	CIGS	buildings	IA	2,419,594	2019	2021
101041554	SOLBATT	Storage of Electrons into Chemical Bonds: Towards Molecular Solar Electrical Batteries	opv	general	ERC	1449034	2022	2027
101063676	SOLIDUPCONVERSION	Active Triplet-Mediator Matrices for Efficient Solid-State Triplet-Triplet Annihilation Photon Upconversion Devices	various	general	MSCA	206887,68	2022	2024
101136148	SOLINDARITY	SOLar-driven INDustrial power And heat upgRaded with hIgh-temperature heaT pumps for enhanced integrated process efficiencY	various	integrated applications	IA	6,998,055.00	2024	2027

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
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	50,000	2019	2020
101122288	SolMates	Scaleable High-Power Output and Low Cost Made-to-Measure Tandem Solar Modules Enabling Specialised PV Applications	CIGS/perovskites	general	R&I	4,998,579.50	2023	2026
647311	Sol-Pro	Solution Processed Next Generation Photovoltaics	Various	general	ERC	1,840,940	2015	2020
684019	Soltile	A roof integrated solar tile system to develop cost-effective distributed solar power generation.	Silicon	buildings	SME	50,000	2015	2015
726703	SolTile	A roof integrated solar tile system to develop cost-effective distributed solar power generation	Silicon	buildings	SME	1,542,733	2016	2019
101150737	SolVa	Solar To Value	perovskites	general	MSCA	191760	2024	2026
101064961	SpaceTimeFerro	Space-time visualization of photo-excited carrier dynamics in ferroelectric solar-energy converters by ultrafast electron microscopy	perovskites	general	MSCA	189687,36	2023	2024
101149132	SPARKLES	Femtosecond laser processing for micro- and nanopatterning of metal halide perovskite thin films for enhanced light management in solar cells	perovskites	general	MSCA	175920	2024	2026
818762	SPECTRACON	Materials Engineering of Integrated Hybrid Spectral Converters for Next Generation Luminescent Solar Devices	LSC	buildings	ERC	2,124,593	2019	2024
101136094	SPHINX	Sustainable Photovoltaics Integration in buildings and Infrastructure for multiple applications	various	integrated applications	IA	5,247,990.98	2023	2026
101068936	SPIKE	Engineering Water Repellent Coatings by Functional Nano-Sponges: a Springboard to Stable Perovskite Devices (SPIKE)	perovskites	general	ERC	150000	2023	2024
101105363	SpinBioAnode	Nature's spin-flipping machine: design of the semiconductor-free biophotoanode	various	general	MSCA	189687,36	2023	2025
101063375	SpinSC	Spin-mediated spectral conversion for efficient photovoltaics	various	general	MSCA	188590,08	2023	2025
743419	SpinSolar	Characterisation method for spin-dependent processes in solar energy technology	various	general	MSCA	159,461	2017	2019
101113313	SPRINT	Sputtering Halide Perovskites for Integration in Monolithic Tandem Solar Cells	perovskites	general	ERC	150000	2023	2024
720907	STARCELL	Advanced strategies for substitution of critical raw materials in photovoltaics	Kesterites	general	RIA	4,832,185	2017	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	191,149	2019	2021
101108851	STED	Real Space-Time imaging and control of Electron Dynamics	various	general	MSCA	181152,96	2023	2025
737884	STILORMADE	Highly efficient non-standard solar modules manufactured through an automated, reconfigurable mass production	Silicon	buildings	IA	2,836,035	2017	2019

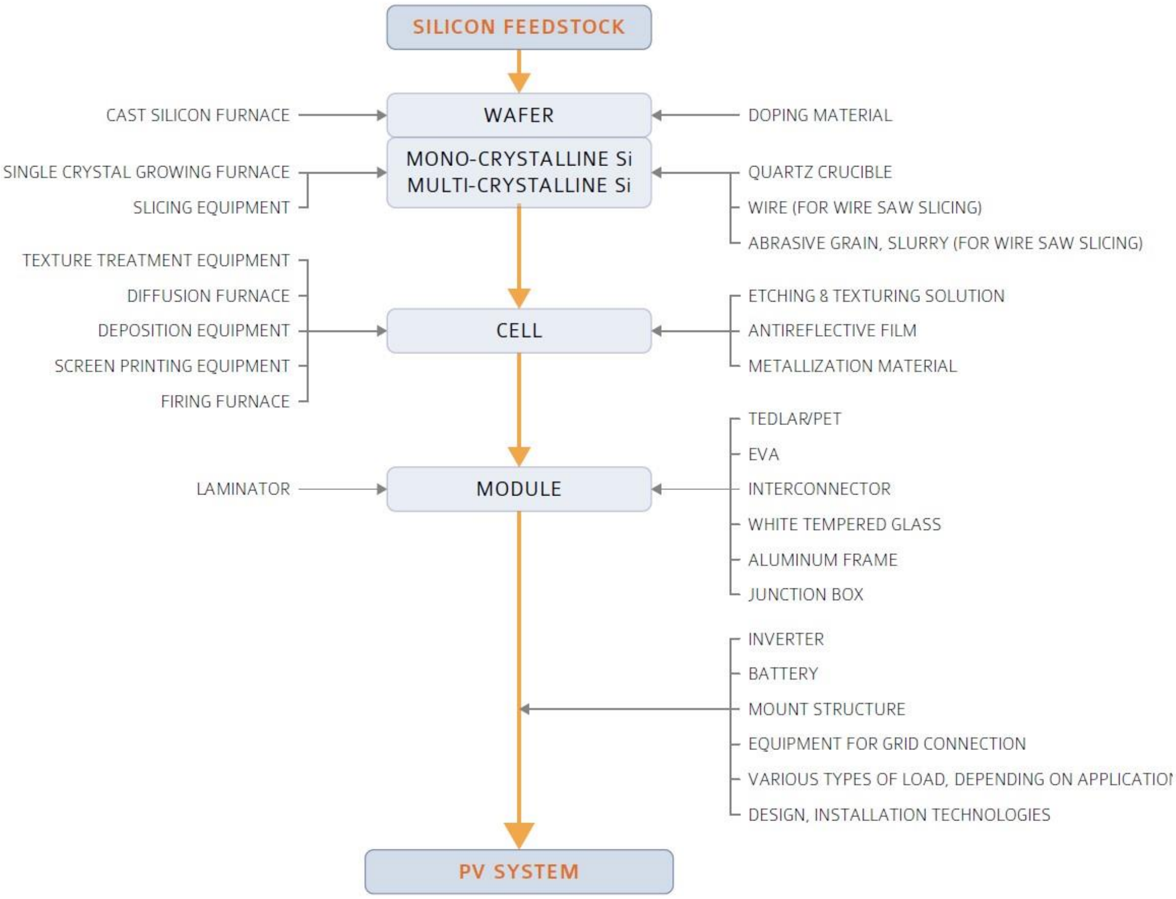
Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
		processes delivering 30% reduction in costs						
101138070	STORE-LIGHT	Photoelectrodes that STORE LIGHT energy	various	system integration	ERC	150000	2024	2025
101032239	Sun4All	Eurosolar for all: energy communities for a fair energy transition in Europe (Sun4All)	N/A	general	Coordination	€1,660,264.87	2021	2024
101156750	SUNAGRI Carbon Farm	Dynamic Agrivoltaic for Farm decarbonization and agriculture sustainability	various	integrated applications	IF	4,268,378.00	2024	2031
101058481	SUNER-C	SUNER-C: SUNERGY Community and eco-system for accelerating the development of solar fuels and chemicals.	various	integrated applications	IA	3997646	2022	2025
738842	SUNINBOX	Portable SolUtioN for dIstributed geNeration in a BOX	N/A	system integration	SME	1,407,542.50	2017	2019
101084422	SUNREY	Boosting SUstaiNability, Reliability and EfficiencY of perovskite PV through novel materials and process engineering.	perovskites	general	R&I	4,249,978.00	2022	2025
792245	SUPER PV	CoSt redUction and enhanced PERformance of PV systems	various	O&M	Innovation	9,907,793	2018	2022
101146883	SUPERNOVA	OPERATION AND MAINTENANCE AND GRID FRIENDLY TOOLS AND SOLUTIONS FOR SOLAR DATA FUSION AND INSIGHT EXPLOSION FOR RELIABLE, BANKABLE, CIRCULAR PV PLANTS	various	O&M	Coordination	4,906,167.00	2024	2027
101075605	SuPerTandem	Sustainable materials and manufacturing processes for the development of high efficiency, flexible, all-Perovskite Tandem photovoltaic modules with low CO2 footprint	perovskites	general	Coordination	4,930,196.25	2022	2025
101135567	SuRE	Sustainable, Reliable, and Efficient Floating PV Power Plants	various	integrated applications	IA	7,162,648.99	2024	2027
101083342	SUREWAVE	STRUCTURAL RELIABLE OFFSHORE FLOATING PV SOLUTION INTEGRATING CIRCULAR CONCRETE FLOATING BREAKWATER	various	integrated applications	IA	3515097,5	2022	2025
640868	SWInG	Development of thin film Solar cells based on WIde band Gap kesterite absorbers	Kesterites	general	RIA	3,254,755	2015	2018
101096352	Symbiosyst	Create a Symbiosis where PV and agriculture can have a mutually beneficial relationship	various	integrated applications	IA	4,827,668.00	2023	2026
101119744	TALOS	roboTics and Artificial intelligence Living labs improving Operations in PV Scenarios	various	integrated applications	IA	8769661,5	2023	2026
826002	Tech4Win	Disruptive sustainable TECHnologies FOR next generation pvWINdows	various	buildings	Coordination	2,877,045	2019	2022
101147545	TERASUN	Towards Terawatt Production of c-Si Solar Photovoltaics	HJT	general	Coordination	2,997,076.75	2024	2027
101079488	TESTARE	Twinning for excellence in TEsting new generation PV: Long-term STAbility and field REliability	perovskites	general	Coordination	1499996,25	2023	2026
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	2016	2018

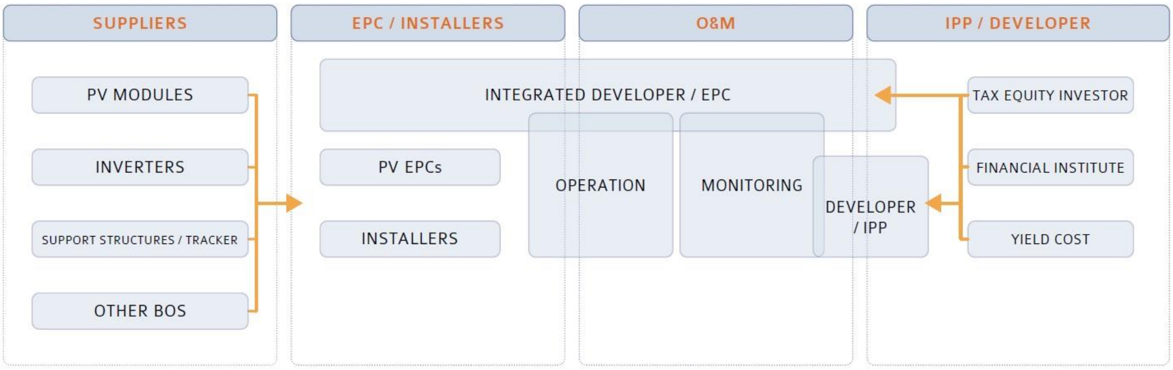
Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
828485	THE SOLAR URBAN HUB	A SOLAR URBAN HUB with integrated lighting and information system for optimal Smart Cities efficiency	N/A	integrated applications	SME	50,000	2018	2019
751375	TinPSC	Towards Stable and Highly Efficient Tin-based Perovskite Solar Cells	perovskites	general	MSCA	185,857	2018	2020
706094	TONSOPS	Titanium Oxide Nanocomposites for Scalable Optimized Perovskite Solar cells	perovskites	general	MSCA	170,122	2016	2018
785005	TRAINEE	TowaRd market-based skills for sustAINable Energy Efficient construction	N/A	general	Coordination	€877,006.25	2018	2020
793424	TRIBOSC	Towards Radically Innovative Materials for Better and Sustainable Organic Solar Cells	OPV/DSSC	general	MSCA	183,455	2018	2020
101075725	TRIUMPH	Triple junction solar modules based on perovskites and silicon for high performance, low-cost and small environmental footprint	perovskites	general	Coordination	5,131,150.00	2022	2026
952957	TRUST-PV	Increase Friendly Integration of Reliable PV plants considering different market segments	N/A	system integration	Coordination	9,969,043.63	2020	2024
101076447	TwInSolar	Improving research and innovation to achieve a massive integration of solar renewables	various	general	Coordination	1488249,75	2022	2025
101159827	TWINSOLARSURF	TWINNING FOR SOLAR ENERGY-DRIVEN SURFACE ENGINEERING OF METALLIC PARTS	various	general	Coordination	1420042,44	2024	2027
101106654	ULTRA-2DPK	Ultrafast physics in 2D halide perovskites for applications in optoelectronic devices	perovskites	general	MSCA	211754,88	2023	2025
101039110	UNIFY	Unification of the best piezoelectric and photovoltaic properties in a single photoferroelectric material	various	general	ERC	1496023	2022	2027
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	1,986,125	2017	2022
101082176	VALHALLA	Perovskite solar cells with enhanced stability and applicability	perovskites	recycling	R&I	3,877,396.50	2023	2025
101039746	WEPOF	Watching Excitons in Photoactive Organic Frameworks	various	integrated applications	ERC	1499375	2022	2027
843872	WONDER	Low-Bandgap Fused Ring Electron Acceptors towards High-Efficiency Organic Solar Cells	OPV/DSSC	general	MSCA	203,852	2019	2021
825142	ZeroR	Resistance-free charge spreading for LEDs and solar cells	various	general	ERC	150,000	2019	2020
101147547		Printed Perovskite Solar Cells for Large Area User Applications	perovskites	general	Coordination	6,704,170.02	2024	2027
101128521		Ceo allIance Cross-border European green hydROgeN valuE chain - Green Ammonia infrastructure study	various	general		3,377,473.00	2023	2024
863724		Floating Solar Energy mooRing: Innovative mooring solutions for floating solar energy	various	integrated applications		709,409.00	2019	2022
97201830		Preparing the port of Karlshamn for the next generation of large Ro-Pax vessels and provision of onshore power supply	various	system integration		3,000,000.00	2019	2022

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
101079550		Bilbao Port Net-Zero Green Onshore Power System for Comprehensive Support & Core TEN-T Cold Ironing Capabilities Expansion in the Atlantic Corridor	various	system integration		14,253,975.90	2022	2026
101101650		Southern European EV fast-charging network (Italy, France, Spain)	various	system integration		19,040,000.00	2022	2025
101101652		Southern European EV fast-charging network (Portugal)	various	system integration		3,660,000.00	2022	2025
101119113		Electricity supply infrastructure development for the transition to environmentally sustainable ground operations at Tallinn airport	various	system integration		1,032,486.00	2023	2025
101119368		Establishment of Electricity Supply and Charging Infrastructure in the Baltic States' Airports in North Sea-Baltic CNC / TEN-T Corridor for the Transition to Environmentally Friendly Operations	various	system integration		3,649,010.00	2022	2025
101119381		Accelerate the Central and East European Ultra-Fast Charging	various	system integration		15,180,000.00	2022	2025
101137163		Accelerating on-the-go EV ultra-fast charging network in Italy, France, Spain and Portugal	various	system integration		49,980,000.00	2023	2026
101103027		The Brouchy Agrivoltaic Canopy - An acceleration toward energy transition	various	integrated applications	IF	2,756,167.00	2022	2026
101038976		Airborne wind hybrid renewable microgrid with RedOX Flow battery to provide flat renewable energy to an industrial site	various	integrated applications	IF	2,024,737.00	2022	2026
101038836		CO2-Free Agriculture for the Mediterranean region	various	system integration	IF	4,356,000.00	2022	2027
101133214		200MW Production of thin-film solar by Sweden	CIGS	general	IF	32,265,535.00	2023	2030
101038908		Development and operation of a GREEN energy community in the port of MOTRIL	various	general	IF	4,347,980.00	2022	2029
101038919		Demonstrating manufacturing for innovative BIPV roof components	Silicon	Buildings	IF	3,733,140.00	2021	2027
101103011		Demonstrating a novel Energy-as-a-Service solution for industrial sector energy consumers	various	integrated applications	IF	2,614,114.00	2023	2027
101038964		airPort sustaInability secONd lifE battEry stoRage	various	integrated applications	IF	3,102,623.00	2022	2027
101156515		Solar HEliup Energy for Flat roofTop	various	integrated applications	IF	3,224,824.71	2023	2027
101133050		NorSun AS: Resource efficient and highly innovative n-type mono-Silicon wafers for Europe.	various	general	IF	53,600,000.00	2023	2030
101051356		ITaliAN PV Giga factOry	HJT	general	IF	117,675,100.00	2021	2033
101103370		Initiating the Production of Green Hydrogen for Transport and Other Applications in the Czech Republic	various	general	IF	4,470,000.00	2023	2030
4724		Demonstration of an innovative Building Integrated PhotoVoltaic system toward net-zero-energy buildings	various	Buildings		2,622,654.00	2017	2023

Id	Acronym	Title	PV Technology	Application	Action	EU Contribution [EUR]	Start	End
4894		SUNALGAE - Innovative process of enhancing the efficiency of solar panels through the use of algae	various	general		1,633,670.00	2018	2023
101074260		Demonstration of a disruptive solar energy (OPV) technology reducing battery waste and enabling renewable power for IoT applications	OPV	general		2,431,502.00	2022	2026
101113574		LIFE Adaptation with Photovoltaics	various	integrated applications		3,499,854.35	2023	2027
101113580		Land use efficient, agriculturally sound large scale photovoltaics	various	integrated applications		3,007,113.59	2023	2027
101114040		Demonstration at pre-commercial level of an innovative cable-suspended bifacial PV system on artificial water bodies, deployable on unexploited lands and industrial sites	various	integrated applications		1,813,284.06	2023	2026
101076395		Joining Actors for LOcal development of New large-scale regional energy communities	various	integrated applications		1,747,388.89	2022	2026
101077514		Collaboration between cities/regions and energy cooperatives as vehicles to accelerate the energy transition	various	general		1,749,177.91	2022	2025
101120960		New Skills for Nearly Zero Energy Buildings	various	integrated applications		932,346.00	2023	2026

Annex 5 Upstream c-Si technology sector and downstream utility-scale installation sector





Source: (IEA-PVPS, 2023)

Annex 6 Sustainability Assessment Framework

The detailed explanation of Sustainability Assessment Framework (SAF) is available in the report "Proposal for a Sustainability Assessment Framework for energy technologies" (European Commission, 2023e), developed to support the Clean Energy Technology Observatory (CETO) in the sustainability assessment of energy technologies. In the SAF, sustainability aspects based on the Driver-Pressure-State-Impact-Response framework are captured and, in the following table, some relevant information is reported for photovoltaics.

Sustainability aspect	Method/approach	Indicators	Assessment of photovoltaics	Additional insights
Market trend	No specific guidance is available in the context of sustainability assessment. Assessment based on energy statistics and literature review for insights on forecasts	- Energy demand - Price of PV modules	At global level, the quantity of energy required by consumers and industries can increase due to population and economic growth. For the EU, urbanization, increasing levels of industrialization and changing comfort preferences can be drivers of increased energy demand. More extreme climate conditions might also play a role, as they can result in increasing/decreasing energy demand, for heating and cooling. The reduction in PV module prices has been remarkable. In the past 43 years, there is a 24.4 % decrease in module prices following each doubling of cumulative PV module production (Fraunhofer ISE, 2024). According to projections, the global median price of modules will decrease from USD 0.32/W_p in 2022 to USD 0.18/W_p in 2032 (VDMA, 2023). The price of modules decreased significantly in 2023 and is expected to stay at low level especially considering the continued overcapacities in manufacturing (VDMA, 2024). As far as inverters are concerned, no significant cost reductions are expected in the next ten years impacting the total capital cost of the PV systems. Capital cost reductions will be in the range of 35 % and will effectively be a result of module price and soft costs reductions. Projections for worldwide average utility-scale system costs suggested USD 504/kW_{DC} in 2034 (VDMA, 2024).	
Trade and trade balance		- Trade balance	The EU maintained its presence amongst the top ten global exporters and importers. The intra-EU imports remained at the same level (32 % in 2020-2022).	

Sustainability aspect	Method/approach	Indicators	Assessment of photovoltaics	Additional insights
			The EU presence as an importing partner in the global market is intensifying as, in 2022, imports almost doubled, and exports more than halved compared to the previous year, resulting in a trade deficit of almost EUR 22 billion. Extra-EU exports are almost stable, since LED were 25 % and semiconductors 40 % of the importing streams (COMEXT data, see section 4.2)	
Cost of energy	No specific guidance is available in the context of sustainability assessment. Assessment based on energy statistics and literature review for insights on forecasts.	CAPEX, OPEX, LCoE	Increasing energy demand and limited resource availability can result in higher cost, which can threat the affordable access to energy. Increasing cost of energy can also be driven by changes in the supply side, due to a variety of events, e.g. natural disasters impacting energy infrastructures or conflicts and geopolitical controversies where resources are used as political weapons, as in the case of the Russian invasion of Ukraine. Between 2010 and 2020, the cost of residential, commercial rooftop and utility-scale PV systems decreased by 64 %, 69 % and 82 % respectively (Feldman *et al.*, 2021). **CAPEX**: In 2022, the PV modules and the mounting /structural BoS (including labour and equipment) make up for 65 % of the total cost while the soft costs account for the remaining 36 %. (VDMA, 2023). In the past 43 years, there is a 24.4 % decrease in module prices following each doubling of cumulative PV module production (Fraunhofer ISE, 2024). In December 2023, the average cost of c-Si modules sold in Europe was 93 % lower compared to 2009, while the global cumulative installed capacity grew 35-fold between 2010 and 2023, reaching 1.6 TW_p (IRENA, 2024). **OPEX**: The O&M benchmark costs in the US in 2020 are reported to be USD 18.7/kW_{AC}/year for commercial ground-mounted installations, USD 18.6/kW_{AC}/year for commercial	

Sustainability aspect	Method/approach	Indicators	Assessment of photovoltaics	Additional insights
			roof-mounted installations, USD 28.9/kW_{AC}/year for residential installations, USD 16.3/kW_{AC}/year for fixed utility-scale installations and USD 17.5/kW_{AC}/year for 1- axis tracking utility-scale installations (IRENA, 2020b). **LCoE**: After the increase of the global benchmark LCoE (levelised cost of electricity) for electricity produced by PV systems at the end of 2021 and in 2022, it continued to decrease for non-tracking systems to a record low of USD2022 41/MWh at the end of 2023 (Jäger-Waldau, 2024). The main reason for this was the lower module prices due to the oversupply along the value chain. The full range of LCoE for non-tracking PV systems varied between USD 34 and 174/MWh. On the other hand, the global cost benchmark for tracking PV systems increased by about 9% in 2023 to USD2022 48/MWh. This was due mainly to higher costs for labour, balance of systems and financing in the USA. After freight costs peaked in Q3 2021 (six fold increase compared to H1 2020), they were in the same range as 2020 for most of 2023 with a tendency to fall towards the end (Jäger-Waldau, 2024).	
Critical Raw Materials (CRMs)	The periodical EC list of CRMs should be use as a reference to describe the potential supply chain bottlenecks.	The EC method includes various indicators concerning import reliance, governance, supply concentration, etc.	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 (European Commission, 2022d).	
Technology-specific permitting requirements	No specific guidance is available in the context of sustainability assessment.			

Sustainability aspect	Method/approach	Indicators	Assessment of photovoltaics	Additional insights
Skills and technology development	Skill development concerns four categories: 1. Skills gap, the distance between the skill level in society and the skills required for the technology development and deployment; 2. Skill obsolescence, the loss of skills due to the lack of use, or the risk the skills become irrelevant; 3. Skill shortages, when there are jobs, but no qualified staff in the community; 4. Over and under skilling, when people have skills above or below the requirements. Technology transfer and development is the process for converting research into economic development, or for using technology, expertise or know-how for a purpose not originally intended by the developing organization. It is fundamental for the improvement of social conditions and to prevent further environmental damage related to old technology use.	Not available	Reskilling and upskilling workers is fundamental for the PV sector, as many workers are shortly going into retirement. At the same time, the needs for workers will continue to grow along with the planned manufacturing expansions as well as the planned installations in the next years.	
Resilience	Resilience is the ability to reduce and withstand the			

Sustainability aspect	Method/approach	Indicators	Assessment of photovoltaics	Additional insights
	magnitude and duration of disruptive events, which include the capability to anticipate, adsorb adapt to and/or rapidly recover from such an event. This aspect can be qualitatively assessed taking into account the following aspects: diversity in the market, suppliers and technologies; risk reduction; adaptive capacity (Zamagni 2019).			
Resource efficiency and recycling	Circular economy indicators	Material recovery rates	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 (European Commission, 2022c).	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[30] is currently working to improve the recycling of Photovoltaic (PV) panels and

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

Sustainability aspect	Method/approach	Indicators	Assessment of photovoltaics	Additional insights
				recovery of Raw Materials (RM). This project is implemented by a consortium of 13 organisations in the period 2021-2024.
Energy balance	Quantitative indicators	Energy Pay Back Time (EPBT) Energy Return on Energy Invested (EROI)	In the past 24 years, the Energy Payback Time (EPBT) of PV has experienced a decrease of 12.8 %. Depending on the location and the technology used for the PV system, its EPBT can be as low as 0.9 years (South Europe), while in the Northern European countries it slightly exceeds the one year (Fraunhofer ISE, 2024). According to the IEA PVPS Task 12, the Non Renewable Energy Payback Time (NREPBT)[31] 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). The highest EROI is observed for the CdTe technology in the United States, whereas the lowest for CIGS PV systems in Japan (Fthenakis and Leccisi, 2022).	
Climate change	LCA / Product Environmental Footprint (PEF)	Global warming potential (GWP100)	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)[32]. PV modules In terms of technologies, thin-film modules have the lowest	

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[31] 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.

[32] 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 %.

Sustainability aspect	Method/approach	Indicators	Assessment of photovoltaics	Additional insights
			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). Based on assumptions for different parameters (silicon content, yield over time and energy mix of the manufacturing phase), mono c-Si emit between 11[33] and 48[34] gCO_{2eq}/kWh and poly c-Si between 18[35] and 49[36] gCO_{2eq}/kWh (Polverini *et al.*, 2023). 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 180μ in 2010 to approximately 170μ in 2021 and a notable silicon usage reduction from 7 g/W_p in 2010 to 2.5 g/W_p in 2021, contributed to a lower carbon footprint (Fraunhofer ISE, 2022). New approaches indicate that the carbon footprint of crystalline technology may be notably lower and between 13 and 30 gCO_{2eq}/kWh (Müller *et al.*, 2021).	
Ozone depletion	LCA / Product Environmental Footprint (PEF)	Ozone Depletion Potential (ODP)		
Particulate matter/Respiratory inorganics	LCA / Product Environmental Footprint (PEF)	Human health effects associated with exposure to PM2.5		There are materials used in the manufacturing procedure covered by dispositions under the REACH regulation (lead in c-Si and perovskites, cadmium in CdTe,

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[33] Assumptions: hydropower (best) scenario, high yield (6 730 kWh/m^2), 588 g Si content.
[34] Assumptions: hard coal (worst) scenario, low yield (5 540 kWh/m^2), 1 080 g Si content.
[35] Assumptions: hydropower (best) scenario, high yield (5 920 kWh/m^2), 646 g Si content.
[36] Assumptions: hard coal (worst) scenario, low yield (5 120 kWh/m^2), 833 g Si content.

Sustainability aspect	Method/approach	Indicators	Assessment of photovoltaics	Additional insights
				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) (Latunussa et al., 2016; Ardente, Latunussa and Blengini, 2019). 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 vapours that may potentially put in danger the health of humans and the air

Sustainability aspect	Method/approach	Indicators	Assessment of photovoltaics	Additional insights
				quality (Tchognia Nkuissi *et al.*, 2019).
Ionising radiation, human health	LCA / Product Environmental Footprint (PEF)	Human exposure to ^{235}U		
Photochemical ozone formation	LCA / Product Environmental Footprint (PEF)	Tropospheric ozone concentration increase		
Acidification	LCA / Product Environmental Footprint (PEF)	Accumulated Exceedance (AE)		
Eutrophication, terrestrial	LCA / Product Environmental Footprint (PEF)	Accumulated Exceedance (AE)		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).
Eutrophication, aquatic freshwater	LCA / Product Environmental Footprint (PEF)	Fraction of nutrients reaching freshwater end compartment (P)		
Eutrophication, aquatic marine	LCA / Product Environmental Footprint (PEF)	Fraction of nutrients reaching marine end compartment (N)		
Land use	LCA / Product Environmental Footprint (PEF)	Soil quality index[37] aggregating: Biotic production, Erosion resistance, Mechanical filtration and Groundwater replenishment	1.9 hectares/MW (IRENA, 2020b). 1-2 hectares/MW_p (IFC, 2015).	
Water use	LCA / Product Environmental Footprint (PEF)	User deprivation potential (deprivation weighted water consumption)	PV modules The available reported water consumption of PV module technologies in studies is considered outdated due to the rapid technological advancements of PV. Results for the impact	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

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[37] Average residential system

<table>
<tr><th>Sustainability aspect</th><th>Method/approach</th><th>Indicators</th><th>Assessment of photovoltaics</th><th>Additional insights</th></tr>
<tr><td></td><td></td><td></td><td>category water use are available also in the PEFCR for PV panels (European Commission, 2019).
<table>
<tr><th>PV technologies</th><th>Life cycle excl. use stage Water use (l world_{eq}/kWh)</th><th>Use stage Water use (l world_{eq}/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>
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><td>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).[38]
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).</td></tr>
<tr><td>**Resource use, minerals and metals**</td><td>LCA / Product Environmental Footprint (PEF)</td><td>Abiotic resource depletion (ADP ultimate reserves)</td><td>No information</td><td></td></tr>
</table>

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[38] Average residential system

Sustainability aspect	Method/approach	Indicators	Assessment of photovoltaics	Additional insights
Resource use, energy carriers	LCA / Product Environmental Footprint (PEF)	Abiotic resource depletion - fossil fuels (ADP-fossil)	Not available	
Biodiversity	Descriptive, based on current EU legislation			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 (European Commission, 2020a).
Child labour	The assessment of this aspect can be performed looking at the main suppliers and countries involved in the production of raw materials, intermediate products and components used in PV	Percentage of working children under the legal age or 15 years old (total, male and female) – country level	No information	
Forced labour	The assessment of this aspect can be performed looking at the main suppliers and countries involved in the production of raw materials,	Frequency of forced labour (estimated prevalence of population in modern slavery, victims per 1,000 population) - country level	Concerns have risen over the years regarding forced labour particularly in the Uyghur Region in China, which now accounts for approximately 35 % of the world's polysilicon (down from 45 %) and as much as 32 % of global metallurgical grade silicon production. The vast majority of modules produced	

Sustainability aspect	Method/approach	Indicators	Assessment of photovoltaics	Additional insights
	intermediate products and components used in PV		globally continues to have exposure to the Uyghur Region (Crawford and Murphy, 2023).	
Equal opportunities / discrimination	Reference scale	Gender wage gap (%) - country level Women in the labour force (ratio) – country/sector level	One third of the total jobs in renewable energies is in the PV sector (IEA PVPS, 2024b). Women represent 40 % of the total employees in the PV sector, the highest share in all renewable energies and oil and gas sector. Most women in the PV sector are employed in administrative positions (58 %), followed by non-STEM (science, technology, engineering and mathematics) technical positions. The share of women in STEM jobs is 32 % (the global average is 35 % (IRENA and ILO, 2023).	
Freedom of association and collective bargaining	Reference scale	Right to strike / Right to association / Right of collective bargaining (point in scale) Trade union density (%)	No information	
Working hours	Reference scale	Hours of work per employee and week (hours)	No information	
Fair salary		Sector average wage, per month Living wage, per month Minimum wage, per month (Eur/month) country/sector level	No information	
Health and safety		Rate of fatal and non-fatal accidents at workplace (# per 100,000 employees) - country/sector level		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 vapours that

Sustainability aspect	Method/approach	Indicators	Assessment of photovoltaics	Additional insights
				may potentially put in danger the health of humans and the air quality (Tchognia Nkuissi *et al.*, 2019).
Responsible materials sourcing	Descriptive, should look at severe risks in technologies value chains and can be based on due diligence guidance for minerals supply chain (OECD, 2016).	The OECD Guidance indicates areas of risks to be taken into account in a due diligence process, through a qualitative assessment.	No information	
Competition for material resources (incl. water, land, food) and indigenous rights	Descriptive, based on narratives and literature review.	Insights from the Environmental justice Atlas		
Contribution to economic development (including employment)	GVA + Employment	% of GDP (positive impact)	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. EU's GVA in PV exhibited a CAGR of 24 % between 2016 and 2022 (from EUR 4.6 to EUR 17 billion). Germany is again the leading EU market (EUR 5.8 billion), followed by Spain (EUR 1.7 billion) in 2022 (EurObserv'ER, 2024a). Employment data differ significantly based on the data source. Therefore, caution is advised when evaluating the data. EU PV jobs in 2022 vary between 500 000 and 826 000, depending on the source and the methodology behind the analysis. IRENA and SolarPower Europe report 719 000 and 826 000 PV jobs in 2023. The IEA-PVPS reports 500 000 and 7 200 000 PV jobs in the EU and in the world respectively for the same year. EU's share is therefore 7 % of the global jobs in the PV sector. Most of the jobs (84 %) is in deployment of PV. In the manufacturing sector, 73 % of the jobs are related to inverter production. The EU countries with the highest	It has to be noted that the level of automation is constantly increasing. Regarding the deployment sector, jobs may be less stable than in the manufacturing sector but can benefit local communities and economies.

Sustainability aspect	Method/approach	Indicators	Assessment of photovoltaics	Additional insights
			number of employees in the PV sector are Germany and Poland, accounting for 19 % and 14 % of the EU's PV employees, respectively. China remains the country with the highest number of employees in PV with 65 % share of the global PV employment (SolarPower Europe, 2021a, 2022, 2023b, 2024a; IEA-PVPS, 2021, 2022, 2023; IRENA and ILO, 2021, 2022, 2023, 2024; EurObserv'ER, 2022, 2024a; IEA PVPS, 2024b).	
Affordable energy access	Several indicators/methods exist, but no specific guidance is available in the context of sustainability assessment.			
Public acceptance	Descriptive, based on narratives and literature review	Insights from the Environmental justice Atlas	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 agrivoltaics and floating photovoltaics (competition to agricultural use of land and fishing, biodiversity and environmental impact concerns).	
Rural development	While specific guidance in the context of sustainability assessment is not available, relevant indicators can be selected from the FAO Guidelines on defining rural areas and compiling indicators for development policy (2018), adapting them to capture the impact of Energy technologies on rural development.	Example of indicators from the FAO report, based on SDGs: -Proportion of population below the international poverty line -Prevalence of moderate or severe food insecurity in the population - Proportion of population with access to electricity - Proportion of population with primary reliance on clean fuels and technology	Agrivoltaics can significantly boost EU's rural development and economy.	

Annex 7 List of EU companies for polysilicon, ingot, wafer, cell and module production equipment and for module components, tracking systems and inverters

Segment	Company (Country)
Polysilicon production equipment	ECM Technologies (FR)
Ingot production equipment	Arnold Group (DE)
Wafer production equipment	R2D Automation (FR)
	Siemens (DE)
	Jonas & Redmann (DE)
	Schmid-Group (DE)
	ZS Handling (DE)
	Decker (DE)
	Hennecke Systems (DE)
	Von Ardenne (DE)
	PSS/Lapmaster Wolters (DE)
Cell production equipment	ECM GREENTECH S.A.S. (FR)
	Singulus (DE)
	Siemens (DE)
	Centrotherm (DE)
	Schmid-Group (DE)
	Jonas & Redmann (DE)
	RENA (DE)
Module production equipment	Mondragon Assembly (ES)
	Solean (FR)
	Ecoprogetti (IT)
	Teknisolar (IT)
	Eurotron (NL)
	SM-InnoTech (DE)
	PVA Tepla (DE)

Segment	Company (Country)
	J.v.G. Technology GmbH (DE)
	Siemens (DE)
	M10 Solar equipment (DE)
	Team Technik (DE)
	Schmid-Group (DE)
	Burkle (DE)
	Schiller-automation (DE)
	Manz (DE)
Module components	Viasolis (LT)
	Sunified (NL)
	Interfloat (DE)
	Dunmore (DE)
	Satinal (IT)
	Coveme (IT)
Tracking systems	Mounting Systems GmbH (DE)
	DEGER ENERGIE GMBH & CO. KG (DE)
	Ideematec Deutschland GmbH (DE)
	Schletter Solar GmbH (DE)
	Soltigua S.r.l (IT)
	Comal (IT)
	Convert Italia (IT)
	Optimum Tracker (FR)
	Nexans Solar Technologies (FR)
	Arcellor Mittal Exosun (FR)
	Deger Iberica (ES)
	Stansol Energy (ES)
	STI Norland S.L. (ES)

Segment	Company (Country)
	PVH PV Hardware Solutions S.L. (ES)
	Axial Structural Solutions (ES)
	Soltec Energías Renovables S.L. (ES)
	Deger Iberica (ES)
Inverters	Fimer (IT)
	Fronius (AT)
	Ingeteam (ES)
	Power Electronics (ES)
	Kostal (DE)
	SMA (DE)
	Kaco (DE)
	Refu (DE)
	Steca (DE)
	Sungrow – Repair centre (DE)

Source: SolarPower Europe

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