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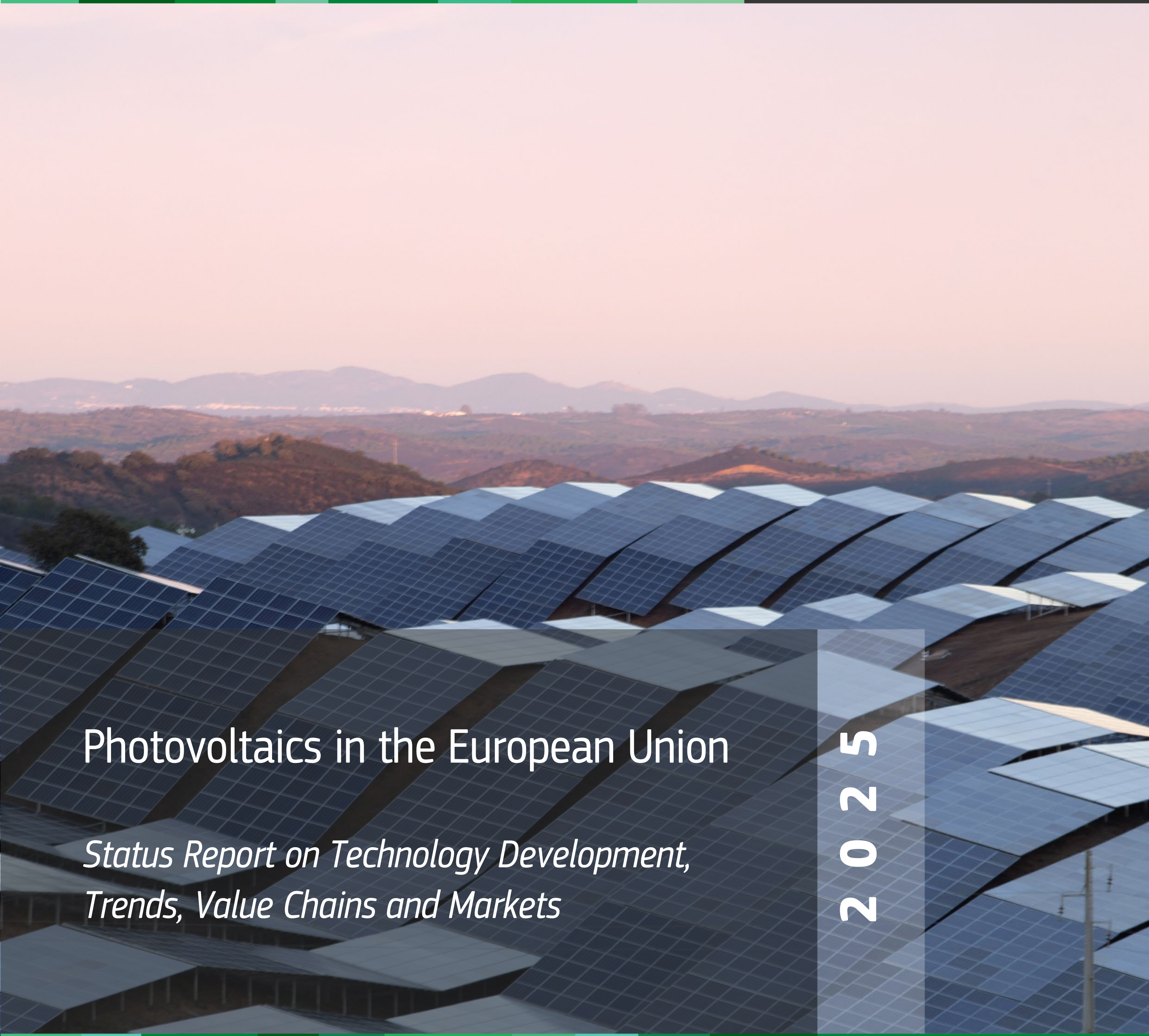

Photovoltaics in the European Union

Status Report on Technology Development, Trends, Value Chains and Markets

2025

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Contents

Abstract

Global Photovoltaic (PV) capacity doubled from 1TW$_p$ in 2022 to over 2TW$_p$ in 2024, with 3TW$_p$ expected by the end of 2025 - confirming PV as the fastest - growing renewable technology. At the same time, PV module efficiencies increased from 9% in 1980 to 22.6% in 2024, while cutting-edge technologies like perovskites and silicon-based tandems now exceed 30% efficiency in laboratory settings. Costs have plummeted, with the global utility-scale Levelised Cost of Electricity (LCoE) falling 87% since 2010 to just USD 43/MWh, and rooftop PV in Europe achieving energy payback in about a year. Although the EU leads in PV innovation and hosts one-quarter of global PV innovators, its manufacturing base is struggling to compete with low-cost Chinese imports, causing bankruptcies and risking technology sovereignty. To close this gap and meet growing demand, urgent and coordinated policy action is needed to strengthen the EU's supply chain, meet NZIA targets, and restore competitiveness - especially in upstream production of wafers, cells, and modules. Stable, harmonised policies are essential to unlock the full potential of PV, boost resilience, and achieve the European Union's climate and energy independence goals.

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, recognizing 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 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

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Executive summary

EU objectives and challenges / policy context

Photovoltaics (PV) have been the fastest-growing renewable electricity generation technology over the past decade - and continues to lead. The EU's installed PV capacity is projected to reach, and even exceed, the 700GW$_p$ target set by the EU Solar Energy Strategy for 2030.

Despite the remarkable progress, PV in the EU is facing challenges. One of the main obstacles is the lengthy permitting procedures and administrative delays, both for manufacturing facilities and project deployment. Additionally, the lack of grid capacity, feed-in flexibility, and robustness as well as insufficient roll out of energy storage solutions poses a significant barrier to the further development of PV systems. The EU PV manufacturing industry is facing a highly competitive environment in which it cannot match very low prices offered by others. Supply chain disruptions and shortage of skilled workforce are two other barriers. The lack of public awareness and insufficient public acceptance in addition to land use competition may pose additional barriers. Another key challenge is to address the remaining technological barriers to achieving higher efficiency, greater reliability, improved sustainability, longer lifetimes, enhanced recyclability, and better system integration. Finally, policy and regulatory uncertainty can severely hamper the future of PV.

While EU energy policies set ambitious targets and frameworks, they often fall short on enforcement, harmonization, grid readiness, financing, social inclusion, and innovation support, which are crucial for fully meeting the energy transition goals.

Technology status

Silicon-based PV technology is the predominant technology. As a possible future alternative to silicon, perovskite technology has developed rapidly and potentially might achieve comparable costs. Two of the most promising technologies in terms of efficiency are silicon-based tandems with either a III-V layer or perovskite as top material. Further research and improvements are required to realise higher efficiencies, combined with less material consumption, scaling up and long-term durability at lower production costs.

The global cumulative PV installed capacity exceeded 2.2TW$_p$ in 2024. The EU alone reached a cumulative installed PV capacity of 347GW$_p$ at the end of 2024 and a cumulative electricity generation of 308TWh from PV systems. According to model projections from the Joint Research Centre (JRC) and SolarPower Europe, the EU capacity will increase to at least 700-750GW$_p$ in 2030 and 2.3TW$_p$ in 2050, whereas according to IEA, the projected global installed capacity is predicted to increase to 5-7TW$_p$ in 2030 and 16-22TW$_p$ in 2050.

The Levelised Cost of Electricity (LCoE) from PV and electricity storage decreased by 87% between 2010 and 2024 from USD$_{2024}$ 417/MWh to USD$_{2024}$ 43/MWh (global weighted-average LCoE for utility-scale projects). This remarkable decrease is mainly (91%) attributed to a decrease of total installation costs, with module prices impacting the most (46%). Projections for the EU indicate that the LCoE will further decrease by 15% in 2030 and by 40% in 2050.

The EU, as a whole, hosts almost one-fourth of the global innovators in the field of PV and is leading in high-value patents and produces highly-cited publications.

Investment and funding

In 2023, Germany and France together accounted for more than 50% of the global public RD&I investments in PV (with the caveat that data for China are not available and for the United States are limited). Germany, France, Belgium, Austria and Sweden are the top five EU countries with the highest public investment in PV. Regarding private RD&I investments in PV, the EU accounts for 15% of the global investments and Germany is the EU leader with an average share of 64% of the EU's total private investments since 2010.

Even though in 2024, EU venture capital investment dropped back down to pre-2021 levels to EUR 277 million (82% decrease compared to 2023), they captured 24% of the total global Venture Capital investment, leading ahead the United States and China.

From 2014, a total of approximately EUR 1.4 billion has been invested in three hundred and eighty-nine PV-related projects through EU funding programmes. Almost half of the EU funding is directed to projects dealing with performance enhancement and cost reduction, while one fifth is awarded to projects related to diversified applications and integration. In terms of technology, one fourth of the total budget was given to silicon heterojunction projects and 10 % to projects related to perovskite technology.

Value chain

EU's PV estimated turnover increased from EUR 9 billion in 2015 to EUR 66 billion in 2023 (28% of Compound Annual Growth Rate (CAGR)) and the top five Member States (Germany, Spain, Italy, the Netherlands and France) accounted for 72% of the EU's turnover in 2023.

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. Jobs in 2028 are expected to more than double in the manufacturing sector compared to current levels. Finding the needed workforce will be challenging and the appropriate actions must be taken at an early phase (skilling, re-skilling, up-skilling, etc.).

China is the main manufacturer of PV hardware as well as the largest market in terms of installations. The country exhibits only a limited dependence on the EU on manufacturing. In 2024 and based on data for the top 10 PV OEMs, China accounted for 96% of the polysilicon, 97% of the wafer, 92% of the cell and 86% of the module global production. The respective shares for the EU in 2024 were less than 2%. On the contrary and despite the reduction of its respective share to global manufacturing, EU's position for inverters and trackers manufacturing demonstrates a positive trend thanks to its advanced technology, innovation, and strong industrial capacity in these segments.

Sustainability

The Energy Payback Time (EPBT) of a rooftop PV system in Southern Europe is one year, whereas in Northern Europe less than a year and a half.

PV has a very low CO_2 footprint (based on a full life cycle analysis). PV systems using crystalline silicon modules have a CO2 footprint of between 35.8 and 43.6gCO_{2eq}/kWh, whereas PV systems using thin-film modules are lower, ranging from 25 to 35.5gCO_{2eq}/kWh. Several sustainability aspects are being addressed in the proposed Ecodesign framework that considers the full life cycle of PV modules, including the end-of-life phase, and which forms the basis for the market requirements and 'ecological profile' of products.

EU positioning and global competitiveness

Regarding trade, a persistent EU trade deficit in value for PV modules, with a declining trend, is observed. In 2024, extra-EU imports fell by 43%, while exports dropped by 21% compared to 2023, reducing the trade deficit by 44% at EUR 10.4 billion. In inverters, in 2024, the EU shifted from a EUR 6.1 billion deficit to a EUR 0.7 billion surplus.

With the currently operational manufacturing capacity, the EU accomplishes both NZIA targets (at least 40% of the Union's annual deployment with domestically manufactured components and 15% share of global manufacturing) only for PV inverters and PV trackers and their mounting structures. In the case of ingots, wafers, cells and modules, the EU falls considerably behind. Some additional efforts are needed for polysilicon to boost domestic production.

SWOT analysis

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

Strengths	**Weaknesses**
– The EU is a technology leader in polysilicon, PV inverters, PV trackers and mounting structures 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. – Development of measures for the revitalisation of the EU PV industry under the NZIA, CID, etc.	– The economic availability of critical raw materials used in current module designs may be a limitation. – The concentration of major segments of the supply chain in a single country poses a risk to supply security and industry resilience. – More direct and targeted support schemes for manufacturing are being applied in the US (IRA) and India (PLI).

Source: JRC 2025

1. Introduction

1.1 Scope and context

This report on photovoltaics (PV) is part of the annual series of reports from the Clean Energy Technology Observatory (CETO). It builds on EU studies in this field and updates the previous CETO report. It provides an overview of the current state of PV, including the technology's maturity status, development and trends, value chain analysis, and global market and EU positioning.

PV play a crucial role in achieving the objectives of the European Green Deal (EGD) and the REPowerEU, the Net Zero Industry Act (NZIA), the Renewable Energy Directive (RED III), the Energy Performance of Buildings Directive (EPBD) and the Clean Industrial Deal (CID). The EU has set ambitious targets for the renewable energy share in electricity generation and carbon neutrality, and PV are expected to contribute significantly to these efforts.

The report is organized into five main chapters. **Chapter 2** examines the state of the art and future developments of PV, focusing on advancements in technology readiness, energy capacity, costs, and research funding. **Chapter 3** focuses on the value chain analysis, covering economic contributions, sustainability, and the role of EU companies in the market. **Chapter 4** provides an overview of the EU's global position and competitiveness in the PV industry, analysing market status, trade dynamics, and resource efficiency. **Chapter 5** concludes the report by synthesizing key findings and highlighting strategic opportunities and challenges.

1.1. Methodology and data sources

The present report follows the general structure of all CETO technology reports and is divided into four 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 report uses the following information sources:

- Eurostat data;
- 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 overview

The average PV module efficiency has increased from 9% in 1980 to 22.6% in 2024 (Table 2) (VDMA, 2025). This chapter includes a presentation of the main PV technologies that are currently commercially available, as well as of those not yet commercialised but particularly interesting for their high efficiencies.

Table 2. Yearly average module efficiencies for the period 2014-2024[1].

Year	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Aver. module efficiency [%]	16.3	17.0	17.5	17.7	18.4	19.2	20.0	20.9	21.2	21.8	22.6

Source: (VDMA, 2025)

Crystalline silicon

The crystalline silicon technology accounts for 98% of global PV module production (VDMA, 2025). 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, 2025). The record efficiency of c-Si cells is 26.1% (ISFH, p-type TBC) (Green et al., 2025), whereas the efficiency of the modules is 26% (LONGI HBC) (Green et al., 2025). The efficiency of average commercial wafer-based silicon modules increased from 16% to over 22% over the last 10 years (Fraunhofer ISE, 2025). 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., 2025).

Bifacial modules[2][3] than p-type Passivated Emitter and Rear Contact (PERC). Bifacial technology is already dominating the market with 64% and expected to further increase its market share to 81% in the next ten years (VDMA, 2025).

Rear contact modules represent another major advancement (Wilson et al., 2020). With PERC modules being near their upper-efficiency limit (currently 21.7% efficiency with projections reaching their limit, 22% in 2029), the industry is investing in n-type technology with major manufacturers switching to TOPCon (currently 23.2% efficiency with projections reaching 24.7% in 2035) and HJT technologies (currently 23.6% efficiency with projections reaching 25% in 2035) (VDMA, 2025).

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[1] 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) in combination with a standardised module size of about 1.64m^2 with 60 cells. Average module efficiencies for PERC modules in 2020 are assumed to 20 % based on the ITRPV 12th edition and in 2021 to 20.9 % in the 13th edition, 21.2 % in the 14th edition, and 21.8 % in the 15th edition respectively.

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

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

Thin-film

Thin-film technologies account for only about 3% of global PV module production, corresponding to roughly 15GW$_p$. Most of the thin-film PV technologies are cadmium telluride (CdTe), while copper indium gallium selenide (CIGS) and amorphous silicon account for only a minor share (Fraunhofer ISE, 2025). The record cell efficiencies of CdTe and CIGS are 23.1% (First Solar) and 23.6% (Evolar/Uppsala) respectively. For the modules, CdTe modules exhibit an efficiency of 19.9 % (First Solar) and CIGS 19.2% (Solar Frontier (70 cells)) (Green et al., 2025). The CdTe module efficiency has increased from 9% to 19% in the last 10 years (Fraunhofer ISE, 2025).

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 27.3 ± 0.6% (Soochow/UNSW/BaimaLake) in 2024 whereas the perovskite module record efficiency is 19.2% (SolaEon) (Green et al., 2025). It is expected that module efficiencies will be comparable to current existing PV technologies within the next 5 years.

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., 2025).

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 34.85% (LONGI, 2-terminal), while the record efficiency for modules is 30.6% (Trina) (Green et al., 2025).(VDMA, 2025)(Wilson et al., 2020)(VDMA, 2025).

Silicon based tandem modules will enter into mass production after 2027 (26.9% efficiency) and their expected efficiency will reach 30.5% in 2035 (VDMA, 2025). The n-type TOPCon manufacturing capacity increased considerably in past few years, becoming already dominant in 2024 with projections suggesting a market share of 42-45% by 2035 (VDMA, 2025). HJT technology (current market share of 7%) will increase its market share to 20% in 2034. Silicon based tandem will appear in the market after 2025 and reach a market share of 10% in 2035, while PERC technology with a market share of 35% in 2024, will disappear from the market by 2029 (VDMA, 2025).

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. 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 (VDMA, 2025).

2.2. Technology readiness level

The European Strategic Research and Innovation Agenda for PV (SRIA) (ETIP PV, 2024) identifies 5 challenges for the PV sector. These are related to performance enhancement and cost reduction through advanced PV technologies and manufacturing (Challenge 1), lifetime, reliability and sustainability enhancements (Challenge 2), new applications through integration of PV (Challenge 3), smart energy system integration of PV (Challenge 4) and socio-economic aspects of the transition to high PV contribution (Challenge 5). According to SRIA, the main objectives for Challenge 1 are PV modules with higher efficiencies and lower costs per kWh, system design for lower LCoE of various applications and digitalization of PV.

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.

The efficiencies of commercial CIGS and CdTe modules need to increase and reach those 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.).

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 PV applications in infrastructure, buildings, vehicles, etc.

Research and innovation regarding performance, integration and sustainability are still essential 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).

The technology targets and research priorities for the main PV technologies as they are identified in SRIA are presented in Table 3.

Table 3. Technology Readiness Level (TRL) of crystalline silicon, thin-film, perovskite and multi-junction PV technologies.

<table>
<tr><th></th><th colspan="9">TRL (Technology Readiness Level)</th></tr>
<tr><th>Sub-Technology</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th></tr>
<tr><td rowspan="7">Crystalline silicon</td><td></td><td colspan="2">Nanophotonic structures to allow thinner cells</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="2">Boost efficiency by advanced technologies (up/down conversion, direct bandgap films, etc.)</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="3">Low-cost crystal pulling of ingots for G12 and beyond</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="3">Module development (3D, aesthetics, circularity, etc.)</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="3">Process/equipment for epi wafers/alternatives</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="3">Sustainable module technology for higher performance: Pb-free, F-free, longer lifetimes, etc.</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Pilot lines for advanced ingot pulling and for epi wafers</td><td></td></tr>
</table>

							Establish European pilot lines for advanced homo and hetero cell/module		
Thin-film		Screening of novel TF-absorber materials for single- and multi-junctions							
			Development of TF for specific integrated PV applications						
			Module design for improved sustainability						
					Large-area module production with reduced lab-to-fab losses				
					Production processes for "Mass Customisation" for integrated PV applications				
							Next generation production equipment for larger size modules		
							Pilot lines for "Mass Customisation"		
Perovskite		Pb-free TF PV absorbers							
		Low-cost highly performant transparent electrodes							
		Recycling strategies for Pk							
			Module manufacturing						
					Demonstrate at pilot level Pk modules on glass and on foils for various applications				
							Establish EU pilot lines for Pk modules on glass and on foils		
Multi-junction			Stable high-quality recombination layers and charge-selective layers						
			Improved module concepts for 3T and 4T						
					High throughput processing up to module level				
					Bifacial multi-junction devices				
							Establish European pilot lines for various tandem technologies and applications		

Source: (ETIP PV, 2024).

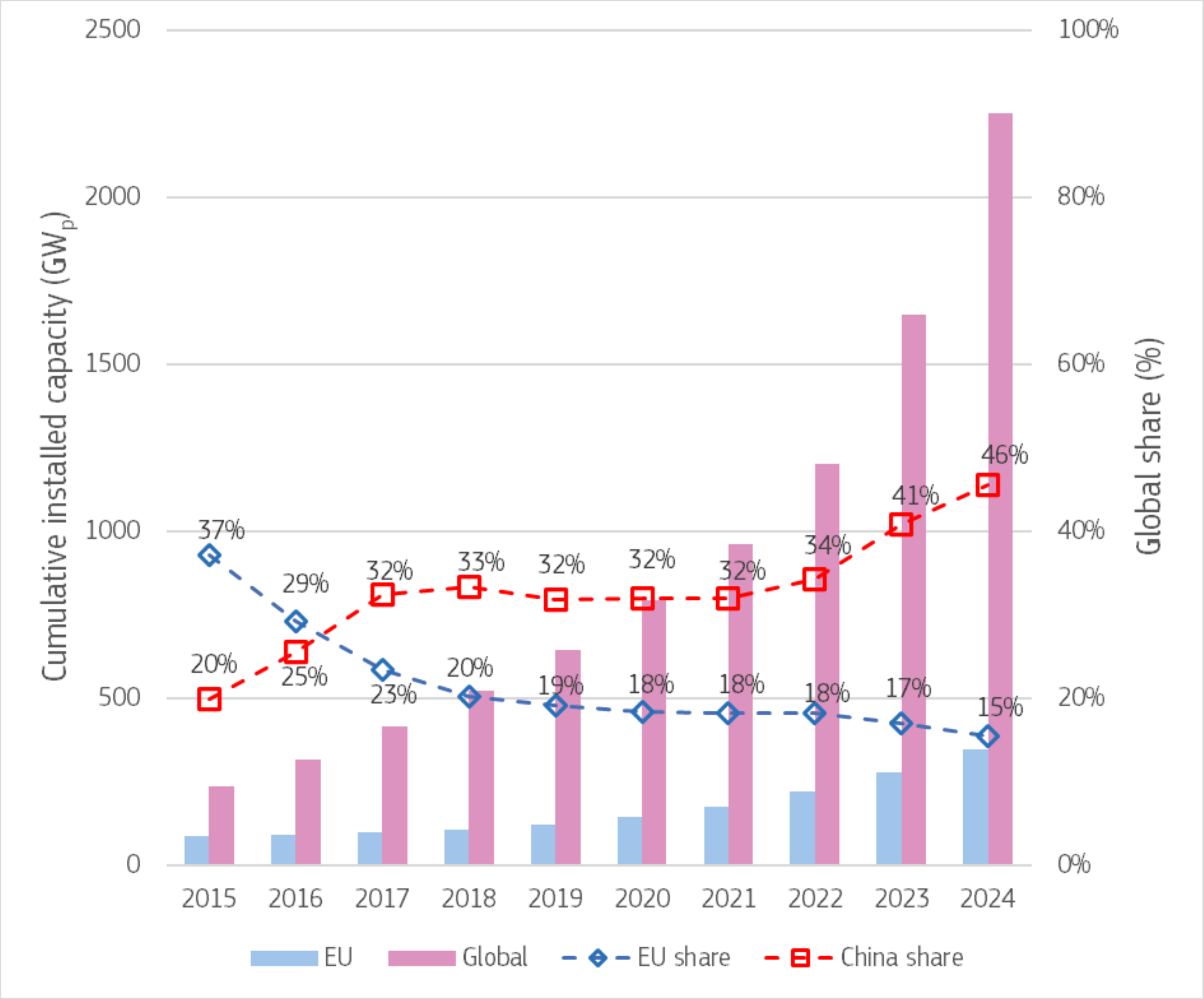
2.3. Installed energy capacity and production/generation

Proper and straightforward comparisons between countries are not possible as there are several factors (IEA-PVPS, 2024, 2025; Jäger-Waldau, 2024) impacting these statistics. For more information, check Annex 2.

The cumulative installed PV capacity in the EU reached 347GW$_p$ in 2024 from 279GW$_p$ in 2023, thus a 24% increase. The global installed PV capacity increased by 37% in the same period reaching

2 251GW$_p$ in 2024. At the same time, China exhibited a remarkable increase in PV installed capacity of 53% (1 026GW$_p$). As depicted in Figure 1, between 2015 and 2024, the situation has reversed, and the EU has gradually decreased its global share by 60%, while China on the contrary increased its share by 130%, accounting for 46% of the global PV installed capacity in 2024.

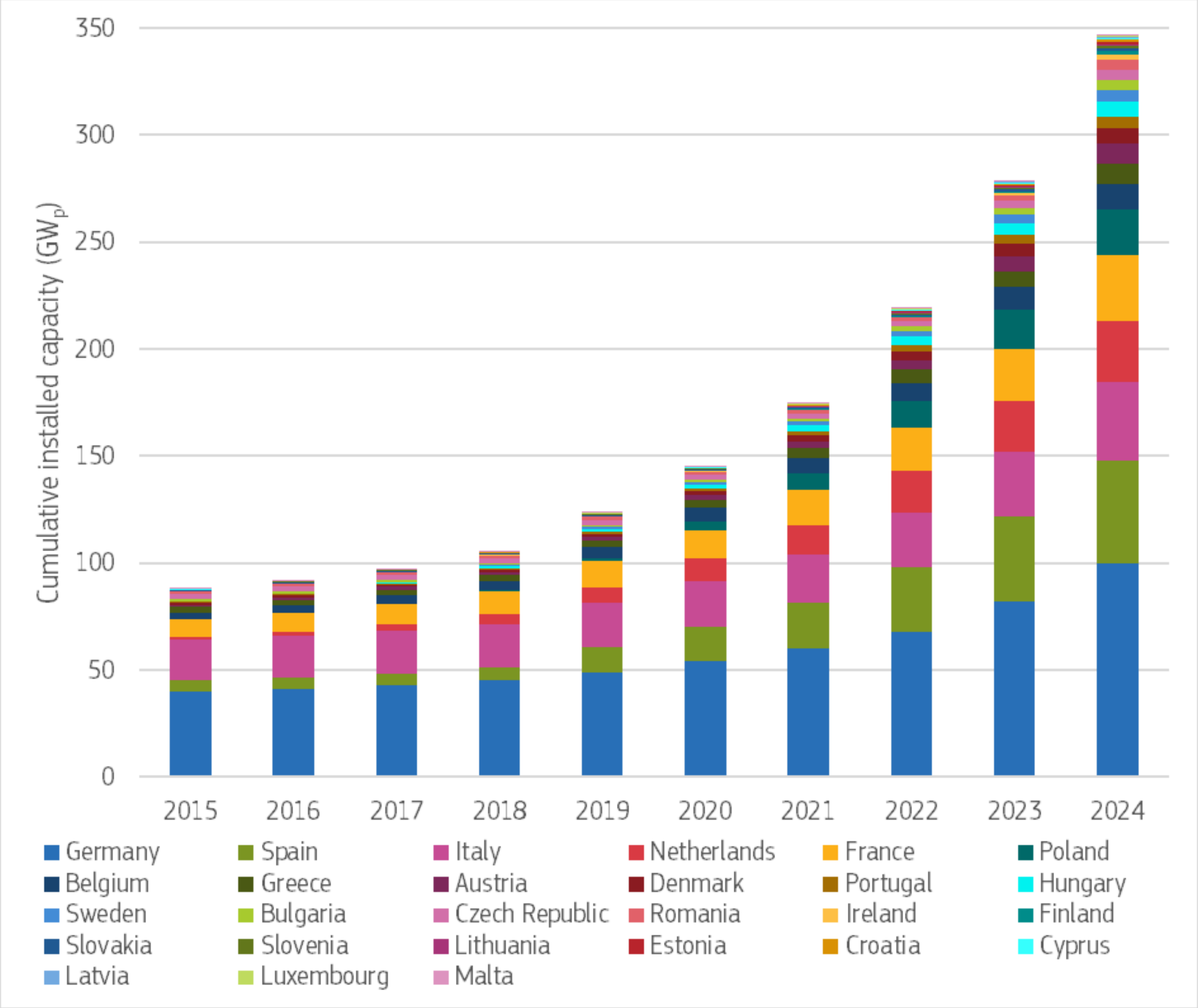
Figure 1. Cumulative global and EU PV installed capacity with EU and China shares for the period from 2015 to 2024.



Source: (IEA-PVPS, 2025; Jäger-Waldau, 2025)

At EU level, Germany, Spain, Italy, the Netherlands and France account for 70% of the EU's PV installed capacity in 2024 (Figure 2). The same countries accounted for 84% of the EU's PV installed capacity in 2015 and between 2023 and 2024 increased their capacity by 20-25%. The countries with the highest CAGR between 2015 and 2024 are Estonia, Poland and Ireland, while those with the lowest are Italy, Czech Republic and Slovakia.

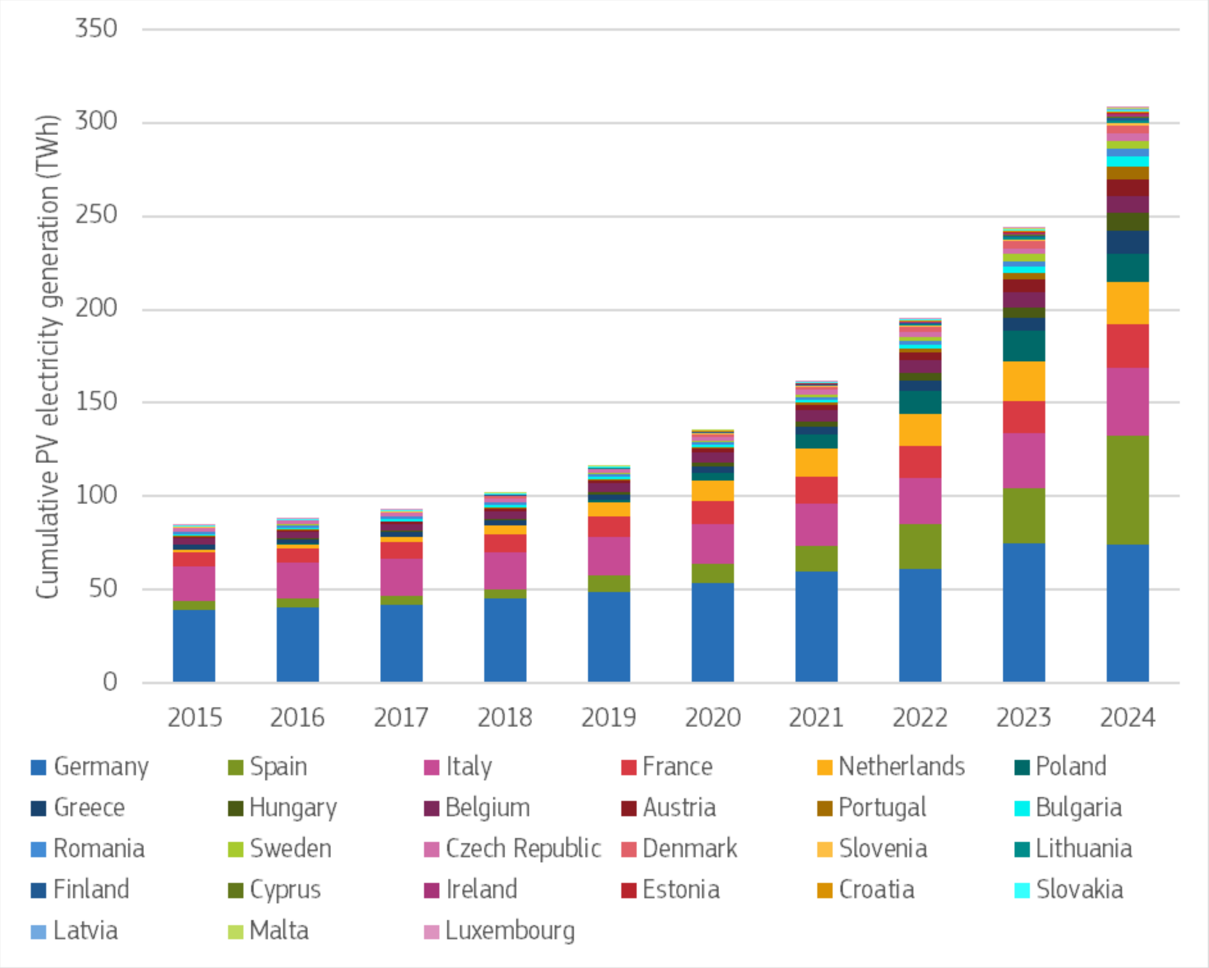
Figure 2. Cumulative installed PV capacity in the EU from 2015 to 2024.



Source: (IEA-PVPS, 2025; Jäger-Waldau, 2025)

The share of solar electricity generation in the EU's electricity mix increased from 2.9% in 2013 to 9.2% in 2023 and 11% in 2024 (Graham et al., 2024). The respective percentage for the world increased from 0.6% to 5.4% and 6.9% (Graham et al., 2024). The EU generated 308TWh from PV, which is 14% of the global generation (2 129TWh). Germany, Spain, Italy, the Netherlands and France, as the top five PV installers in the EU, generated also the biggest part of the EU's PV electricity, accounting for 70% (Figure 3). Ireland, Poland, Finland, Hungary and Sweden exhibited CAGRs of over 50% between 2015 and 2024. The EU's global share of PV generated electricity decreased from 41% in 2015 to 14% in 2024, while China's global share increased from 12% in 2015 to 39% in 2024. The EU's and China's CAGRs between 2015 and 2024 were 14% and 43% respectively.

Figure 3. Cumulative electricity generation from PV in the EU from 2015 to 2024.



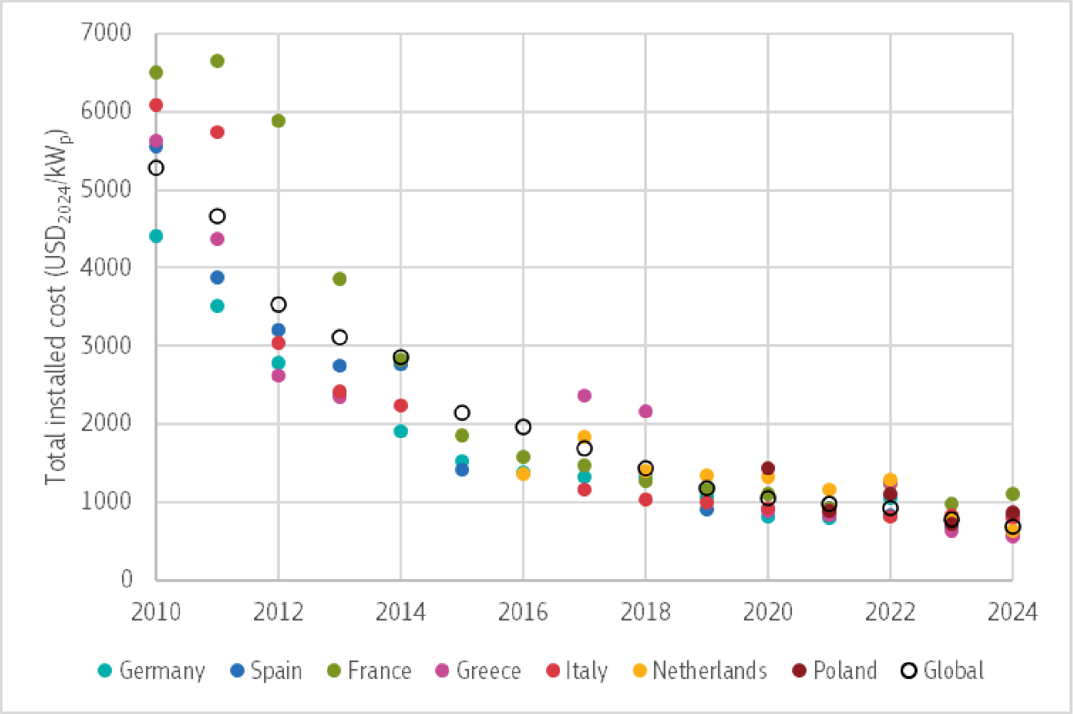
Source: Based on (EMBER, 2025; Eurostat, 2025).

2.4. Technology costs

The global weighted average utility-scale PV total cost decreased from 5 283 USD_{2024}/kW_p in 2010 to 691 USD_{2024}/kW_p in 2024. This 87% decrease is attributed to module price decrease (50%), to installation/EPC/development decreases (15%) and to other soft costs decreases (15%). Inverters and racking and mounting price reductions contributed with 10% and 7% respectively (IRENA, 2025). Figure 4 depicts the evolution of total cost reduction for the period 2010-2024 for some of the biggest PV markets in the EU.

In the EU in 2010, only utility-scale projects in Germany exhibited a lower total installed cost than the global average value, while in France and Italy the costs were significantly higher. In 2024, total installed costs for utility-scale PV were lower than the global value in Germany, Greece and Netherlands. France still has a total installed cost higher than the global average.

Figure 4. EU countries and global weight average total installed cost evolution.

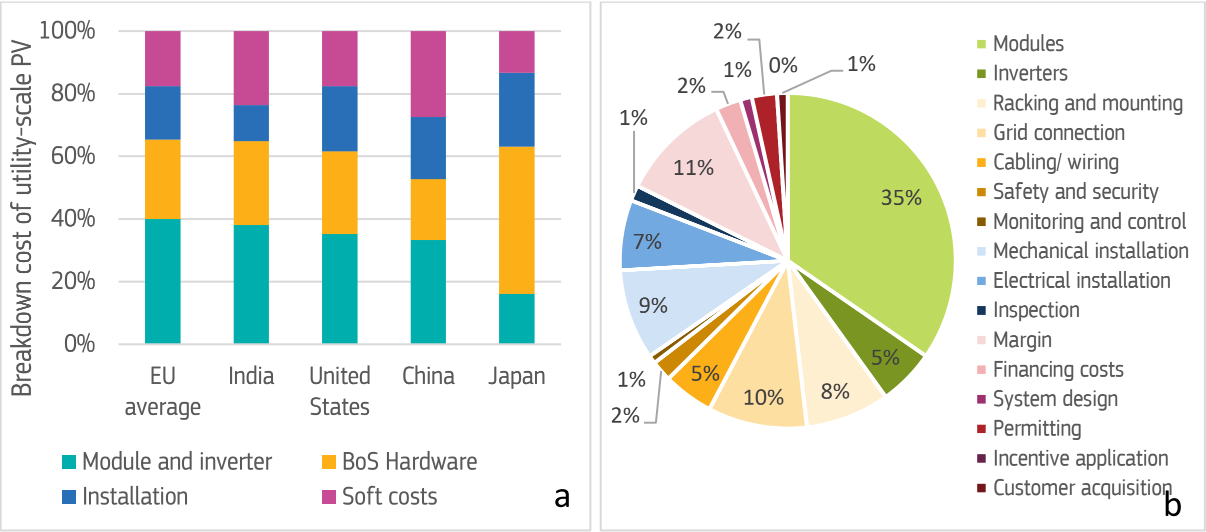


Source: JRC based on (IRENA, 2025).

CAPEX & OPEX

The breakdown of the CAPEX in 2024 for the major PV markets is presented in Figure 5a and b. There are no major discrepancies between the EU countries and therefore an average value for the EU is presented. Module and inverters contribute the most for the total cost in the EU (40%), India (35%) and China (33%), whereas in Japan, BoS hardware accounts for the 47% of the total cost. Soft costs in China account for 27% and installation costs contribute the least in India (12%) (IRENA, 2025).

Figure 5. (a) Breakdown cost for utility-scale PV in different countries/regions in 2024 and (b) analytical breakdown cost for utility-scale in the EU in 2024.

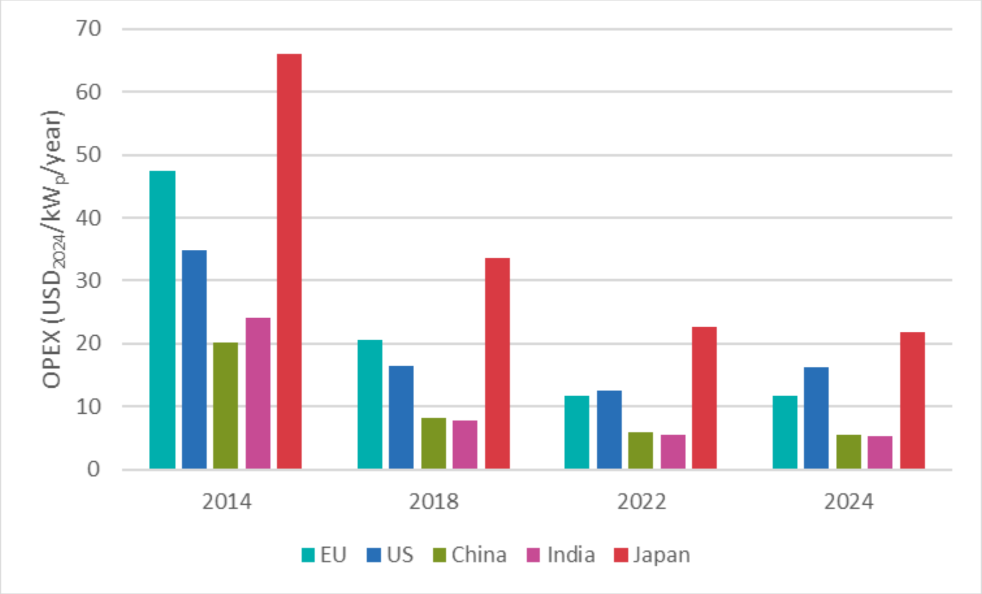


Source: JRC based on (IRENA, 2025).

A more detailed view of the cost breakdown in the EU, shows a 35% contribution of modules to the total costs, opposed to only 5% of inverters. As far as the BoS hardware component is concerned, the main contributor with 10% is grid connection, followed by racking and mounting (8%). Installation and soft costs account for a bit over one third of the total cost in the EU and are attributed mostly to mechanical and electrical installation and margin in terms of soft costs (IRENA, 2025).

The average EU operational expenditure (OPEX) is reported to be 11.6 USD_{2024}/kW_p/year in 2024 from 47.5 USD_{2024}/kW_p/year in 2014, a 76% decrease in ten years (Figure 6). These values are in accordance with an average value between 6.8 and 14.8 EUR/kW_p/year (low range value for fixed systems, high range value for 2-axis tracking system), reported in the previous CETO reports (Chatzipanagi et al., 2024). A similar decrease in OPEX is observed for India (-78%) and China (-73%) and to a lesser extent in the United States (- 54%) and Japan (-67%).

Figure 6. OPEX evolution in different countries/regions.

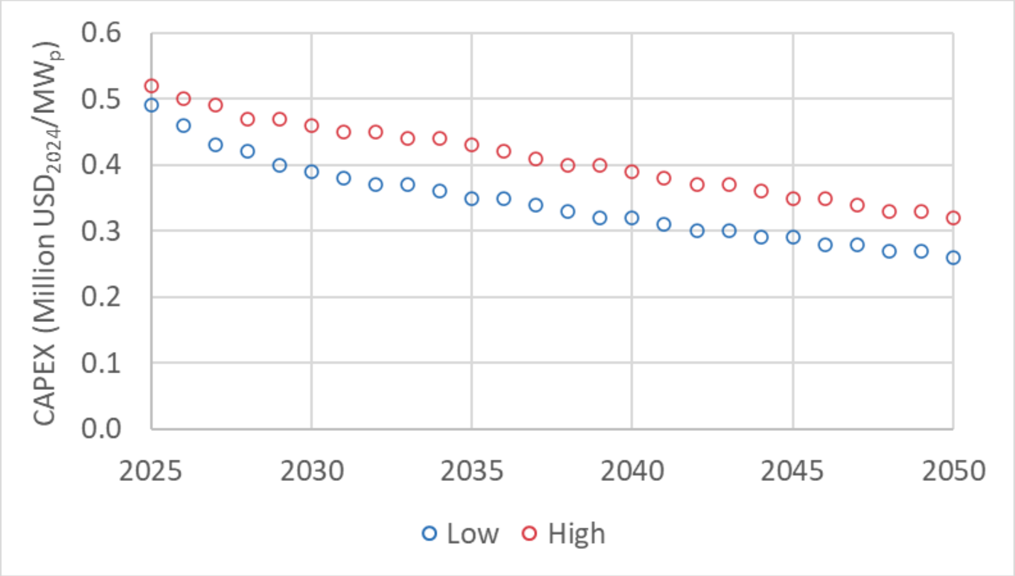


Source: JRC based on (Bloomberg New Energy Finance, 2025b).

Figure 7 and Figure 8 present the projections for CAPEX and OPEX in the EU until 2050 respectively. CAPEX could decrease from the 0.56 in 2024 to 0.26-0.32 million USD_{2024}/MW_p according to the projections. This corresponds to a total decrease of 43-54% between 2024 and 2050. Regarding other major PV markets, the highest potential for CAPEX reduction until 2050 is projected for the United States (67%), followed by Japan (53%) and China (46%). India is expected to experience CAPEX reduction of only 26% between 2024 and 2050 (Bloomberg New Energy Finance, 2025b).

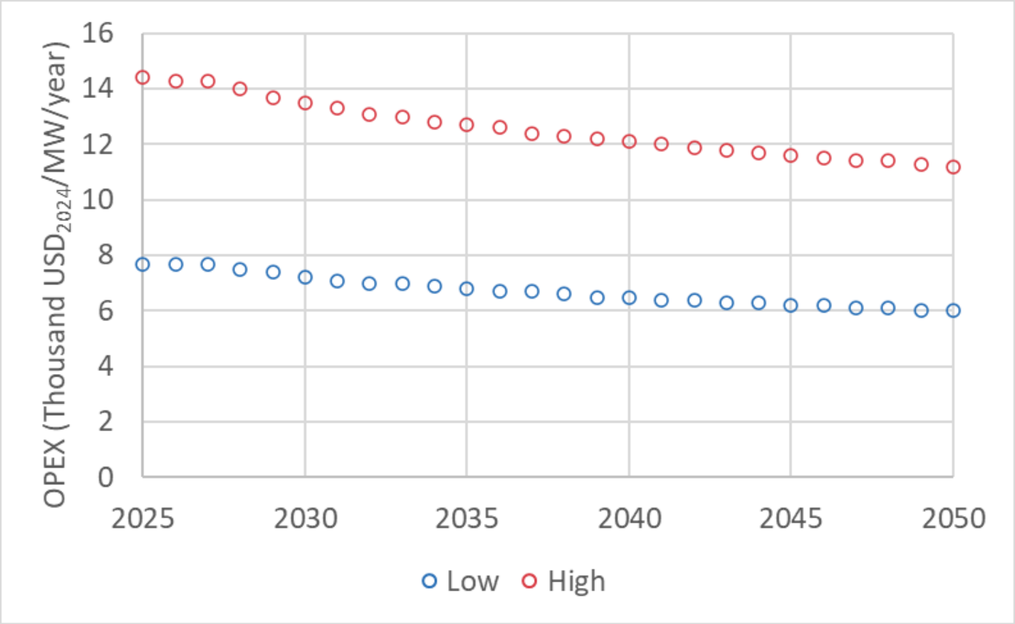
As far as OPEX is concerned, it is projected to reach an average value of 8.6 thousand USD_{2024}/MW_p/year (range: 6-11.2 thousand USD_{2024}/MW_p/year as shown in Figure 8) in 2050, thus exhibiting a 24% decrease in the next 25 years. Only India and China are expected to have lower OPEX in 2050 because of the lower labour costs, with respective values of 5.4 and 4.0 thousand USD_{2024}/MW_p/year, respectively. The United States will stand at 12.0 thousand USD_{2024}/MW_p/year and Japan at 16.4 thousand USD_{2024}/MW_p/year in 2050 (Bloomberg New Energy Finance, 2025b).

Figure 7. Projection of CAPEX (range) for the EU until 2050.



Source: JRC based on (Bloomberg New Energy Finance, 2025b).

Figure 8. Projection of OPEX (range) for the EU until 2050.



Source: JRC based on (Bloomberg New Energy Finance, 2025b).

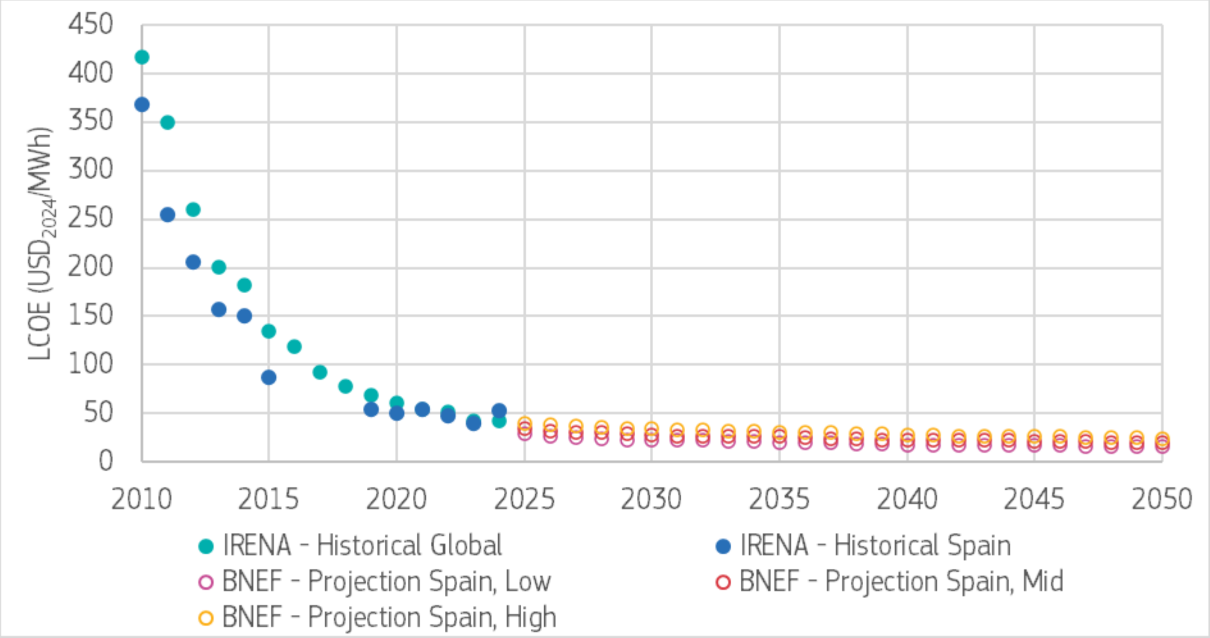
LCoE

The global weighted average utility-scale PV LCoE decreased from 417 USD_{2024}/MWh in 2010 to 43 USD_{2024}/MWh in 2024. This remarkable decrease is mainly (91%) due to a decrease of total installation costs, with module prices impacting the most (46%). Cost reduction of inverters contributed with 9%, racking and mounting with 6%, other BoS hardware with 2% and installation/EPC/development with 14%. A 14% share contribution to the LCoE reduction is attributed to soft costs reduction. The utility-scale capacity factor evolution increase from 15% in 2010 to 17.4% in 2024, is responsible for a 3% reduction of LCoE, as is the OPEX (IRENA, 2025).

The above LCoE benchmark costs show a general trend. LCoE is heavily affected and therefore varies significantly by financing and labour costs, regulatory requirements, import duties and taxes and the actual local generation costs that are location dependent. Other parameters influencing LCoE are related to the available solar irradiation, tracking or no-tracking system choices, inverter configuration (string or central), OPEX and connection costs, total financing cost or Weighted Average Cost of Capital (WACC) (Jäger-Waldau, 2025).

Figure 9 presents the historical LCoE values for the globe and for Spain between 2010 and 2024 (IRENA, 2025), as well as the projections for Spain until 2050 (Bloomberg New Energy Finance, 2025b). Spain is used as the country possesses a high number of utility-scale PV. The projections for Spain assume a 16.5% capacity factor for the low projection and 18.5% for the high projection. From 53 USD_{2024}/MWh in 2024, the country is projected to exhibit a decrease between 55% and 70% in LCoE by 2050, reaching 16 USD_{2024}/MWh according to the projection low and 24 USD_{2024}/MWh according to the projection high.

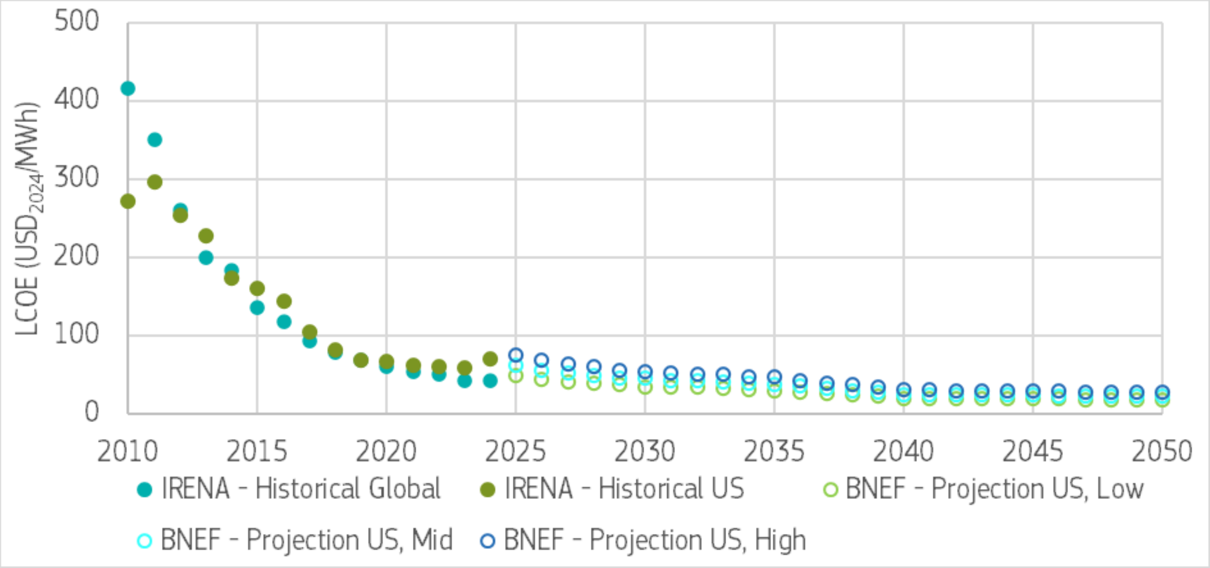
Figure 9. Historical weighted average global utility-scale, historical and projected (low, mid and high) fixed-axis LCoE estimates for Spain.



Source: JRC based on (Bloomberg New Energy Finance, 2025b; IRENA, 2025)

In the case of the United States (Figure 10), the reduction of LCoE according to the projection low is 74%, from 70 USD_{2024}/MWh in 2024 to 18 USD_{2024}/MWh in 2050, whereas in the case of the projection high the LCoE in 2050 will be 27 USD_{2024}/MWh (-61%). The assumed capacity factor for the United States is 14.2% and 21.8% for the “low” and “high” projections, respectively.

Figure 10. Historical weighted average global utility-scale, historical and projected (low, mid and high) fixed-axis LCoE estimates for the United States.



Source: JRC based on (Bloomberg New Energy Finance, 2025b; IRENA, 2025)

2.5. Public RD&I funding

The public investments in solar energy and PV (treated as a sub-category) at EU and global level from 2014 until 2023 are illustrated in Figure 11 and Figure 12a and b. The data included in this analysis are for IEA members and several major countries may be excluded[4].

Over the past decade, RD&I investments in solar energy increased but in PV slightly decreased. In 2014, global public RD&I investments in PV, with EUR 385 million, accounted for 51% of the total RD&I investments in solar energy (EUR 752 million), whereas in 2023 this share decreased to 32% (EUR 291 million for PV of EUR 909 million for solar energy). Over the total period between 2014 and 2023, PV accounted for 34% of the total investments in solar energy in general.

At EU level, RD&I investments in PV have remained rather stable in the past decade. In 2014, EUR 191 million of the continent's public RD&I investments were directed to PV. These investments correspond to 25% of the total investments in solar energy (EUR 241 million). This share decreased to 19% in 2023 (EUR 171million for PV of EUR 241 million for solar energy).

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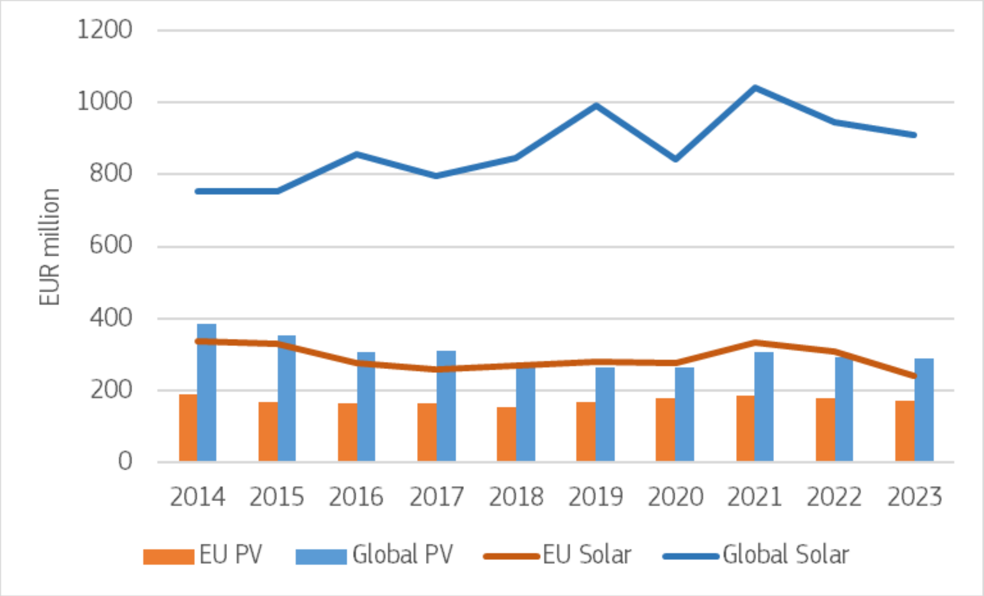
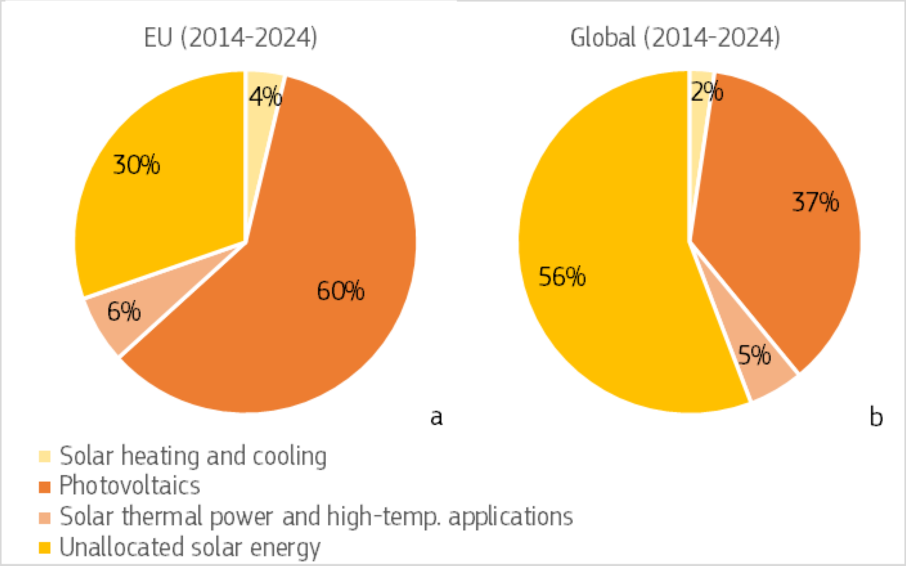
[4] It must be noted that data for 2023 are provisional and that for the same year funding from Italy is not reported. Furthermore, in 2021 Spain has changed the methodology for collecting data, resulting in a break in the time series between 2020 and 2021 and in the same year, France has revised the data transmitted by the CNRS from 2002 to improve the coverage.

Figure 11. EU and global public investments in solar and PV R&D.



Source: JRC based on IEA, 2025.

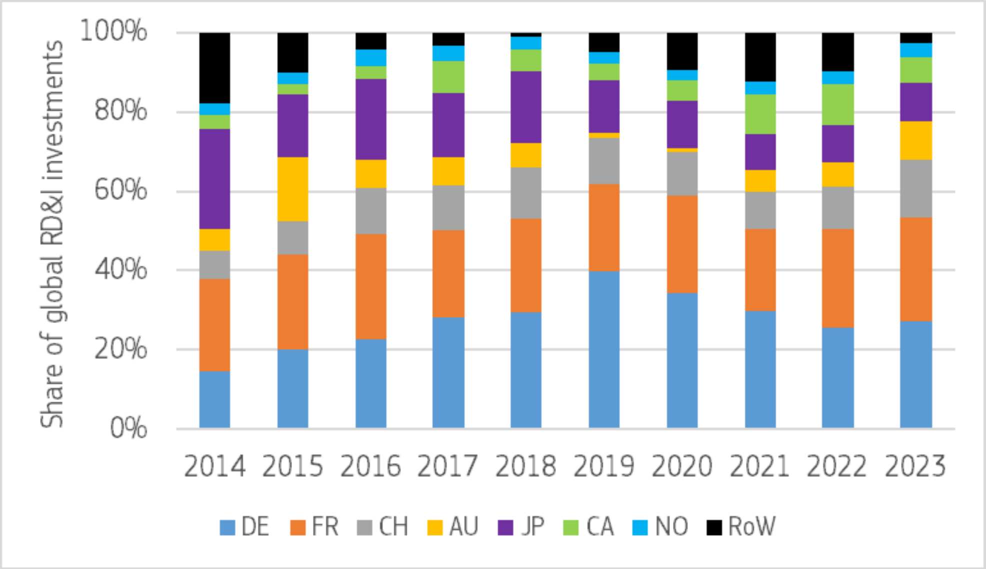
Figure 12. (a) EU and (b) global allocation of solar energy technologies for the period 2014 to 2023.



Source: JRC based on IEA, 2025.

Taking a global glance, Germany accounted for 25% of the global RD&I investments in 2023, followed by France with 24%. However, whereas France demonstrates a stable share in RD&I over the past decade, Germany has increased its own from 13% in 2014. The third country with the highest share in 2023 is Switzerland (14%) and Australia and Japan follow with 9% each. It must be noted that data for China are not available and for the United States are limited (Figure 13).

Figure 13. Share of public RD&I investments in photovoltaics for the period 2014 to 2023.

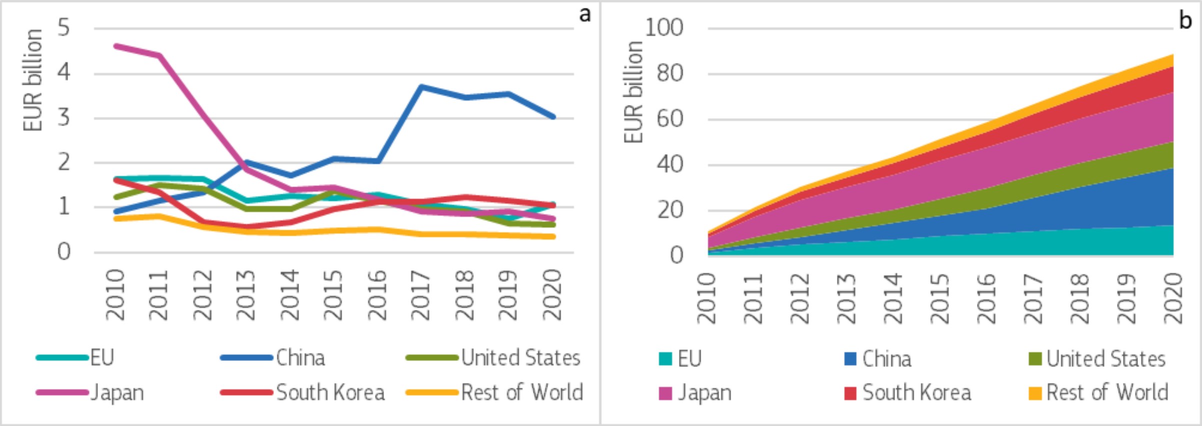


Source: JRC based on IEA, 2025.

2.6. 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), approximately two-thirds of the R&D funding comes from the private sector and the remaining one-third from the public sector.

Figure 14. (a) Annual and (b) cumulative EU and global private RD&I investment in PV for the period 2010 to 2020.



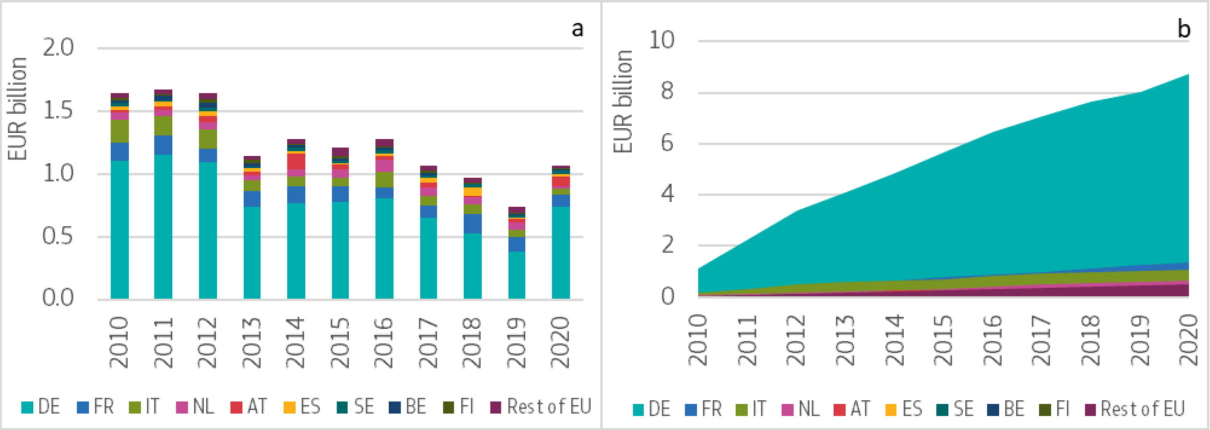
Source: JRC (Fiorini et al., 2017; Pasimeni et al., 2019) based on PATSTAT data

The following tentative analysis is based on the use of patenting output as a proxy for private funding (Fiorini et al., 2017; Pasimeni et al., 2019) and the results should be interpreted with caution (especially for China). Unlike public investments, the analysis is performed from 2010 until 2020 (with near complete data), since 2021 data is incomplete.

On average, from 2010 until 2020, the EU accounted for 15% of the global cumulative private RD&I investments, with a peak share of 20% in 2014. According to Figure 14a, China has increased considerably (80%) its annual private R&D investments between 2016 and 2017, while Japan experienced the same level of decrease in its annual private investments in the period 2011-2014. During 2010-2019, the EU has cut-off almost half of its annual private R&D investments.

At global level, in 2010, the EU and South Korea accounted for 15% of the global cumulative private R&D investments in the field of PV each, whereas the leading economy was Japan with a share of 43%. In the next ten years (2020), the EU retained its 15% global share, while Japan reduced it to 24% and China became the leader in cumulative private R&D investments with 28% share (Figure 14b).

Figure 15. (a) Annual and (b) cumulative EU private RD&I investment per MS in PV for the period 2010 to 2020.



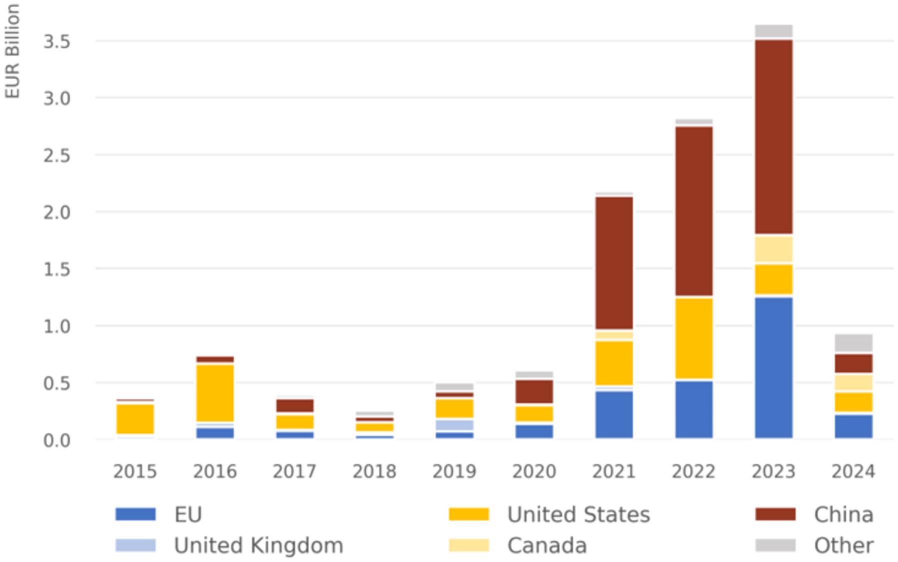
Source: JRC (Fiorini et al., 2017; Pasimeni et al., 2019) based on PATSTAT data

At EU level (Figure 15a and b), Germany is the country with the highest private investments in R&D throughout the period from 2010 to 2020, accounting for 64% of the EU's cumulative private investments for this particular period. France and Italy are following with considerably lower shares of 10% and 8% respectively.

2.6.1. Venture capital and early and later-stage investments

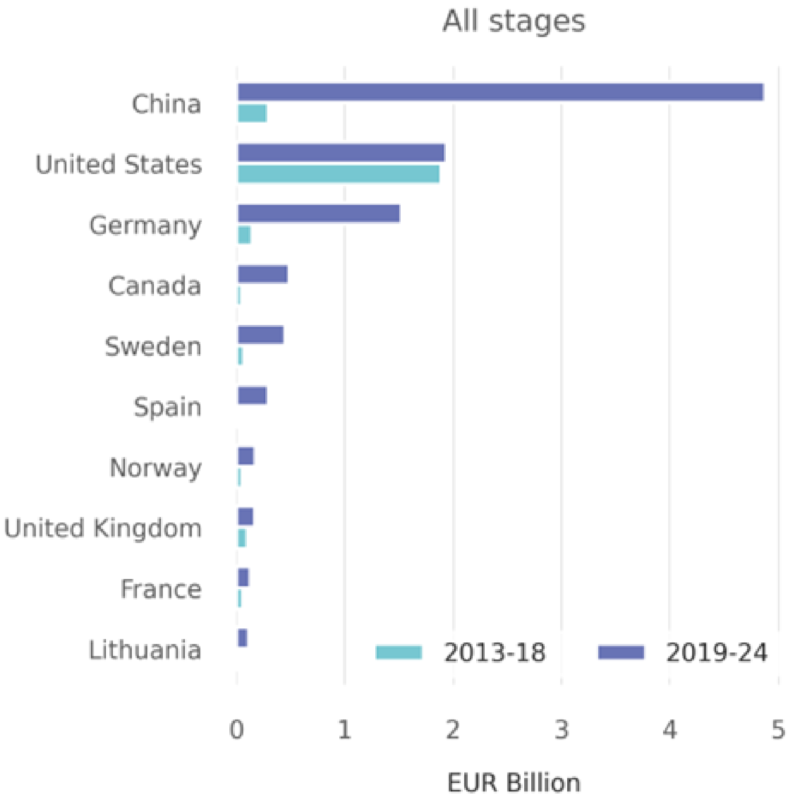
With only 65 deals recorded in 2024 (compared to 105 in 2023), global VC investment has plummeted in 2024 down to EUR 934 million (74% drop compared to 2023) but still remain higher than the total realised in 2020 (+ 54% compared to 2020) (Figure 16). This marks the end of a wave of very large deals seen between 2021 and 2023 in China in particular, driven by companies such as Gokin Solar, HuaSun Energy and Astroenergy. Between the period of 2013-2018 and 2019-2024, only the United States have maintained the same VC/PE investment in PV. For the rest of the top 10 countries, including Germany, Spain, Sweden, France and Lithuania, VC/PE investment in PV has increased significantly in the second period (2019-2024) (Figure 17).

Figure 16. Global VC/PE EU investment in the photovoltaic sector, by region for all deals.



Source: JRC based on Pitchbook.

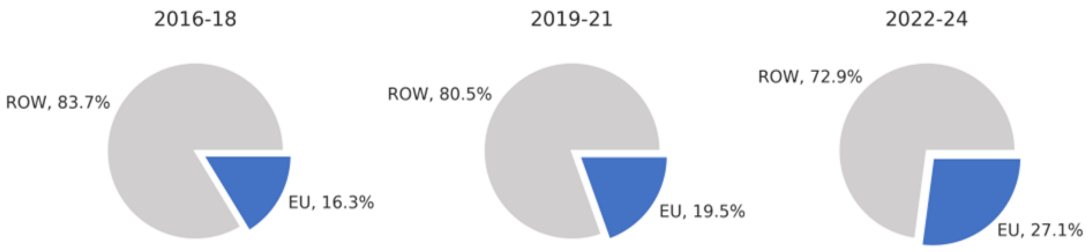
Figure 17. VC/PE investment in photovoltaics top 10 beneficiary countries, by period for all deals.



Source: JRC based on Pitchbook.

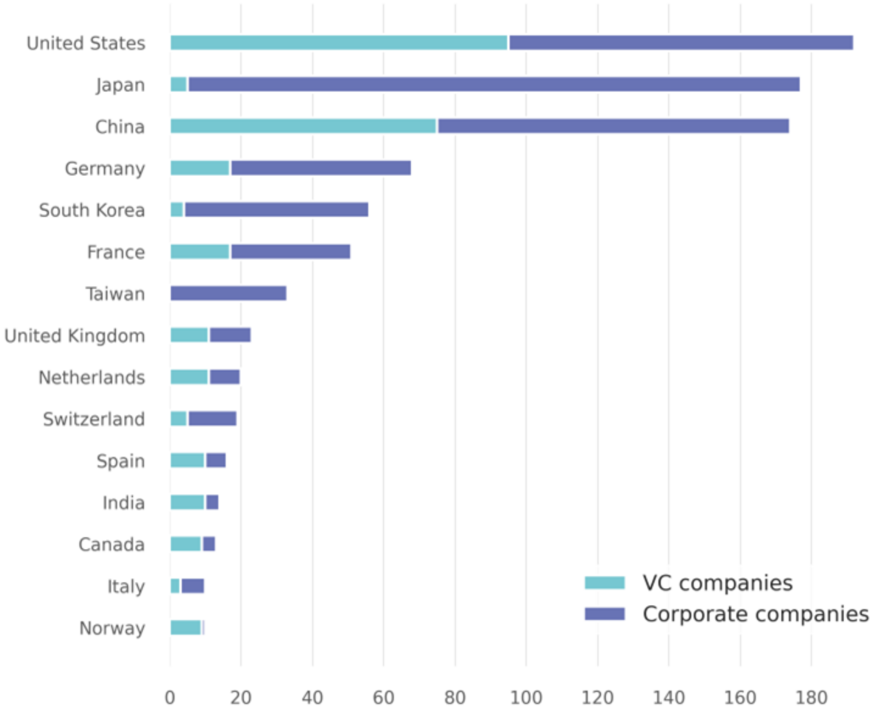
Between 2021 and 2023, EU captured 26% of global VC investment (far behind China, which accounted for 51% of the total). Larger deals in EU based ventures include AE Solar (German solar panel manufacturer, EUR 250 million in 2023) and Svea Solar (Sweden solar panel manufacturer, two deals of EUR 100 million in 2022). Those fundraising successes are finally channelling equity funding towards the development of domestic manufacturing capacities and not only towards integrators such as Enpal (Germany, EUR 227 million in 2023).

Figure 18. VC/PE investment in photovoltaics in the EU and in the Rest of World (RoW) for all deals over the 9 years, by period of 3 years.



Source: JRC based on Pitchbook.

Figure 19. Number of active innovating companies by type over a 6-year period, ranking of top 15 countries in photovoltaics[5].



Source: JRC based on Pitchbook and PATSTAT data.

In 2024, EU investment also dropped back down to pre-2021 levels and reached EUR 277 million (82% decrease compared to 2023). In 2024, the EU however captured 24% of the VC investment

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[5] VC companies count over 2019-24. Count of corporate companies over 2017-2022.

total, leading ahead the US and China. This performance is mainly due to a successful fundraising by company NexWafe (Germany, monocrystalline solar wafer, EUR 150 million)[6].

When looking into the period 2016-2024, split in 3 sub-periods (Figure 18), the EU has increased its share of global VC/PE investment in PV from 16.3% (2016-2018) to more than one forth (2022-2024).

According to Figure 19, corporate companies monopolise the innovative companies domain in Japan, South Korea and Taiwan between 2019 and 2024, while in The United States and China, corporate companies and VC companies are equal in number. Germany and France, among the top 15 countries with the highest number of active innovative companies in PV (4th and 6th place respectively), have corporate companies exceeding VC companies over the same period.

2.7. 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 must be noted though that data for 2022 is not complete.

As depicted in Figure 20, China has the largest number of patents with almost 22 700 inventions, followed by South Korea (approx. 3 700 inventions) and Japan (approx. 1 300 inventions). The EU is in 4th position with 680 inventions in total between 2020 and 2022.

However, when only the share of high-value inventions[7] is taken into consideration, the EU moves 1st with 63% of its total inventions being high-value ones and China results into the last position, thus suggesting that the EU, unlike China, is generally filing to more than one patent office[8]. The same trend is evident also as far as international inventions[9] 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. However, the EU is surpassed by Japan and the United States regarding the international inventions. While Figure 20 shows the high-value inventions as a percentage of the total number of inventions, Figure 21a presents the number of high-value inventions in absolute

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[6] Note: VC investment reported in this edition for the EU in 2022 and 2023 differ from the one reported in previous edition. This variation is due for half of it to an update of deal sizes or dates as previously recorded by PitchBook. The other half is due to the inclusion of new companies such as AE Solar (DE) and Svea Solar (SE) that were not previously identified as Venture capital companies by PitchBook but have raised Venture Capital or Private Equity Growth funding since.

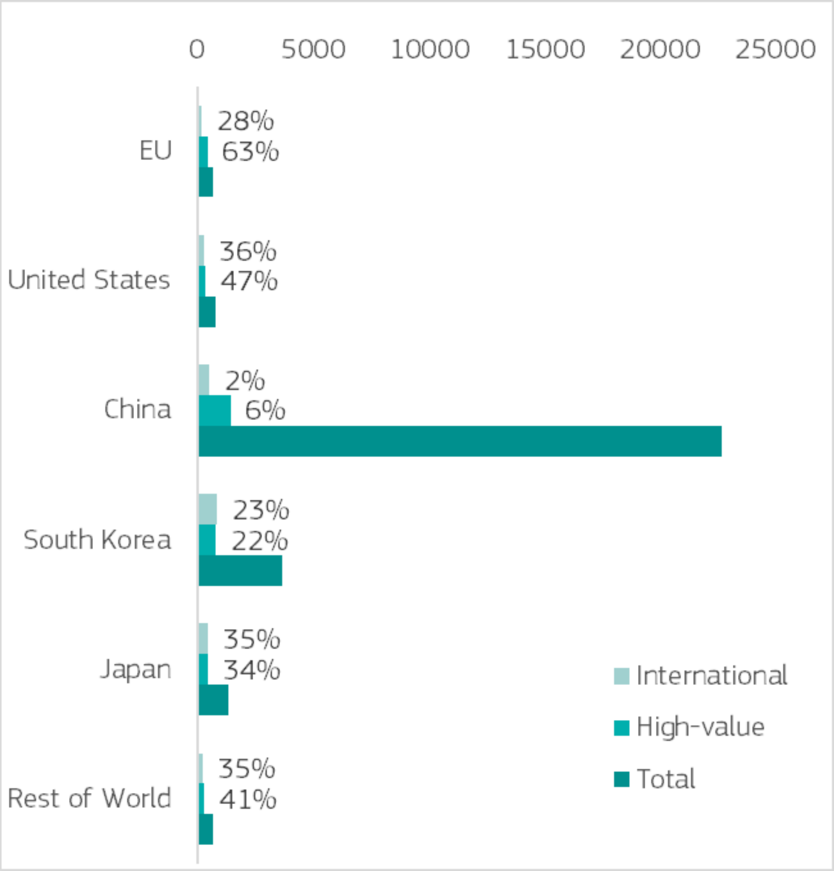
[7] High-value inventions (or high-value patent families) refer to patent families that include patent applications filed in more than one patent office. International inventions include patent applications protected in a country different to the residence of the applicant. High-value considers EU countries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

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

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

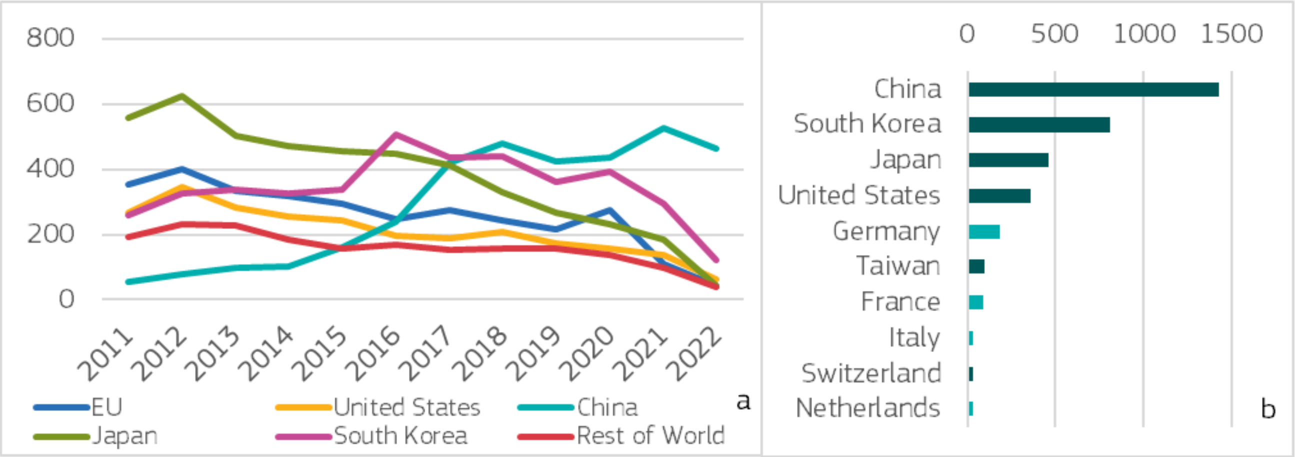
numbers for each year from 2011 until 2022. Germany, France, the Netherlands and Italy (last year Spain) are among the top ten countries with the highest number of high-value inventions between 2020 and 2022 (Figure 21).

Figure 20. Number of inventions and share of high-value and international activity in PV from 2020 to 2022.



Source: JRC (Fiorini et al., 2017; Pasimeni, 2019; Pasimeni et al., 2019, 2021; Pasimeni & Georgakaki, 2020) based on PATSTAT data

Figure 21. (a) Number of high-value Inventions between 2011 and 2022 and (b) Top ten countries with high-value inventions for the period 2020-2022.



Source: JRC (Fiorini et al., 2017; Pasimeni, 2019; Pasimeni et al., 2019, 2021; Pasimeni & Georgakaki, 2020) based on PATSTAT data

Table 4 presents the top ten global entities filing the highest number of inventions in PV between 2020 and 2022.

In the top ten, global entities with high-value inventions are mostly based (five out of ten) in South Korea and China (three). The EU with Germany and United States conclude the ranking with one entity each. Merck Patent Gmbh (Germany), the only EU entity in this top ten (Table 4).

Table 4. Global top ten entities with high-value inventions in PV for the period 2020-2022.

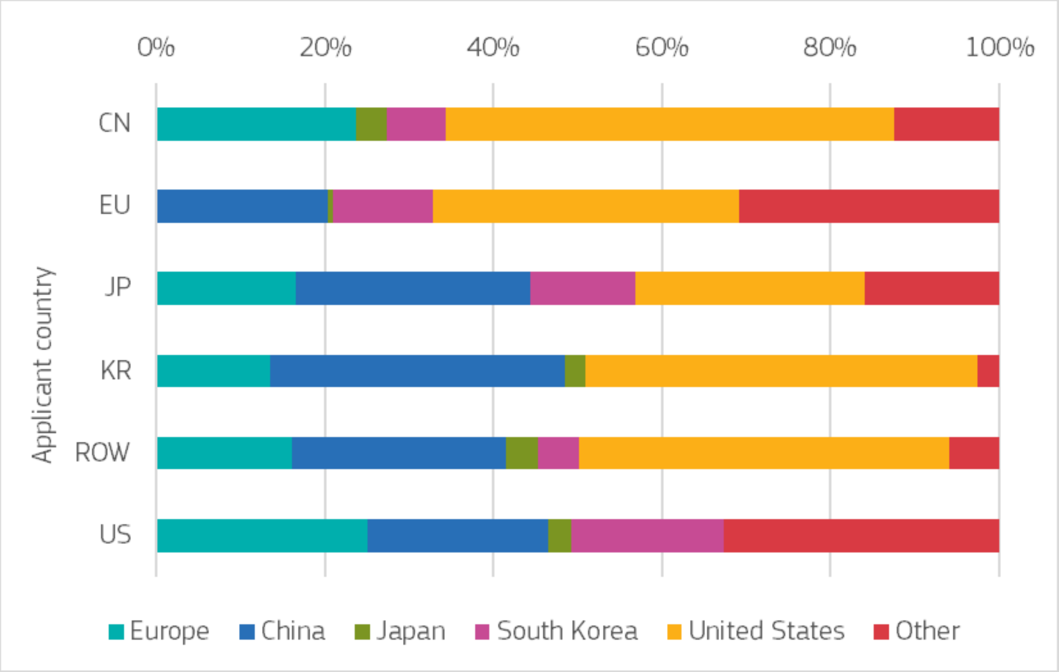
Position	Company	Number of high-value inventions	Country
1	Samsung Display Co Ltd	293	South Korea
2	Boe Technology Group Co Ltd	111	China
3	Wuhan China Star Optoelectronics Semi-conductor Display Technology Co Ltd	100	China
4	Universal Display Corp	52	United States
5	Lg Chem Ltd	50	South Korea
6	Samsung Electronics Co Ltd	44	South Korea
7	Samsung Sdi Co Ltd	42	South Korea
8	Merck Patent Gmbh	40	Germany
9	Beijing Summer Sprout Technology Co Ltd	40	China
10	Duk San Neolux Co Ltd	35	South Korea

Source: JRC (Fiorini et al., 2017; Pasimeni, 2019; Pasimeni et al., 2019, 2021; Pasimeni & Georgakaki, 2020) based on PATSTAT data

Figure 22 presents the countries in which patents for high-value inventions were submitted, and subsequently enjoyed patent protection, between 2020 and 2022. Chinese applicants have mainly chosen to patent their inventions in the US (53%). The number of Chinese patent applications in the EU is around 25% and in other countries small. US inventors have split their patent applications more evenly between China, Europe and other geographical areas. The same applies also for EU inventors, where patent applications are split evenly between the United States and others and to a lesser extent but still significant (20%) in China. Applicants from South Korea are mainly applying in the United States (46%) and China (35%) and to a lesser extent in Europe (13%). In conclusion, the US is receiving the largest number of high-value invention applications. Europe is 3rd position, behind China.

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 2010 onwards 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 until 2019 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 2021 and started decreasing thereafter, with South Korea and China being the leaders. Japan is leading in the field of dye-sensitised, mono c-Si and a-Si PV cell patents with a considerable decrease in the more recent years. 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 surpassing it after 2021.

Figure 22. International flows of high-value inventions between major economies (2020-2022).



Source: JRC (Fiorini et al., 2017; Pasimeni, 2019; Pasimeni et al., 2019, 2021; Pasimeni & Georgakaki, 2020) based on PATSTAT data

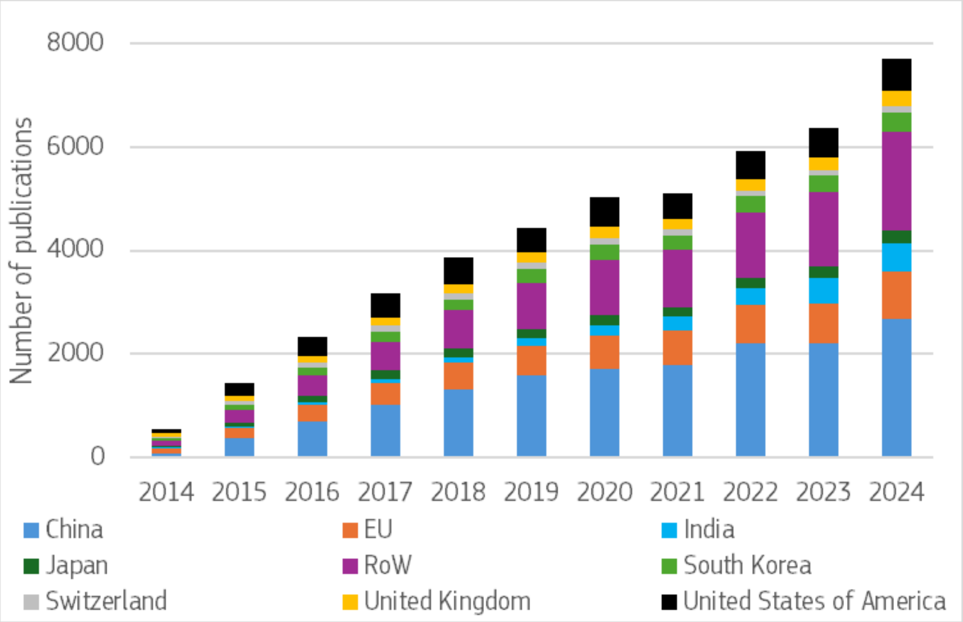
2.8. Scientific publication trends

Most of the global publications on PV technologies are in the field of perovskites (75%), followed by kesterites and CIS/CIGS with each accounting for 6%. Figure 23 presents the evolution of global publications on perovskites between 2014 and 2024. Publications related to this promising PV technology note a remarkable increase (from 546 in 2014 to 7 693 in 2024, Figure 23), whereas publications on kesterites and CIS/CIGS remain rather constant in total number throughout the ultimate 10 years. Of the total global number of publications on perovskites, China accounted for 34% on average over the period 2014-2024, starting with 16% in 2014, whereas the EU started with 17% of the global publications on perovskites in 2014 to decrease its share by 5% in 2024. The United States follow with 12%.

Half of the EU's scientific publications on perovskites are attributed to Germany (26%), Spain (12%) and Italy (11%). France, Sweden and Netherlands contribute with 9%, 7% and 7% respectively each.

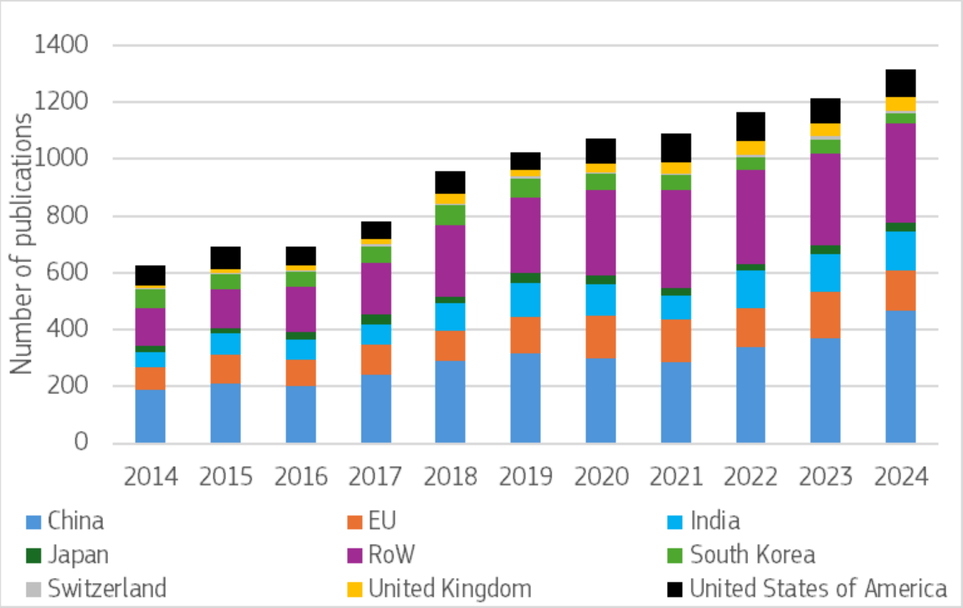
Regarding PV system-related publications, research on inverters attracts most interest with 92% of the global publications on PV systems (Figure 24). After 2019, publications on tracking system have gained attention as they doubled between 2019 and 2024. China held its high share of inverter-related publications with an average of 30% between 2014 and 2024, followed by the EU with 13% and India with 10%. Germany and Spain, having several companies manufacturing inverters, account (almost equally) for 30% of the EU's publications on the topic, while Denmark, Italy, France and Sweden conclude the top six EU countries that account for 70% of the EU's publications on inverters.

Figure 23. Global publications on perovskites for the period 2014-2024.



Source: JRC, 2025.

Figure 24. Global publications on inverters for the period 2014-2024.

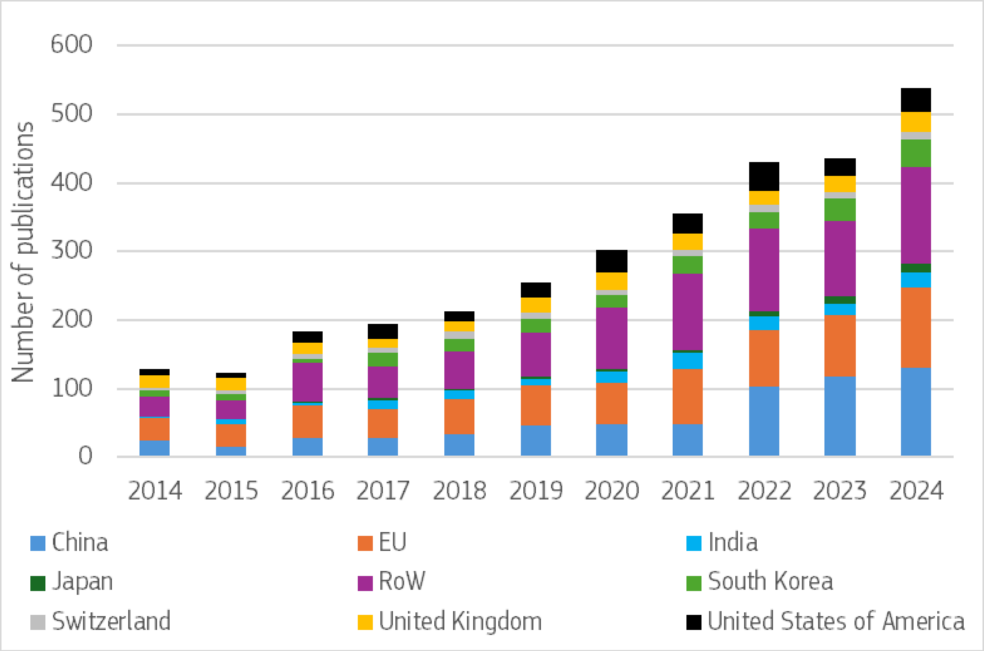


Source: JRC, 2025.

When evaluating publications on PV applications, Building Integrated PV remains the most popular area, accounting for 67% of the global publications (Figure 25). Publications on floating PV and agrivoltaics follow with 16% and 14% respectively. Noteworthy is the interest in agrivoltaics as global publications have increased by 1 400% between 2020 and 2024. In comparison, for the same period, Building Integrated PV and floating PV global publications experienced a 78% and 402% increase, respectively. Publications on Building Integrated PV originating from China have increased from 19% in 2014 to 24% in 2024 and decreased from 26% (2014) to 22% (2024) for the EU. The most noteworthy decrease in publications dealing with the application is for the United Kingdom that dropped from 15% of the global publications in 2014 to 5% in 2024. In the EU, 50% of the publications on Building Integrated PV originates from Italy (22%), Spain (14%) and Germany (11%). Alongside come also Netherlands, France and Poland that account for an average share of 7% each.

In the field of agrivoltaics, the EU is leading the scientific publications with an average share of 28% between 2014 and 2024, followed by the United States with an average share of 18% for the same period. The EU is also leader in scientific publications on floating PV, accounting for an average of 21% of the global publications between 2014 and 2024.

Figure 25. Global publications on Building Integrated PV for the period 2014-2024.

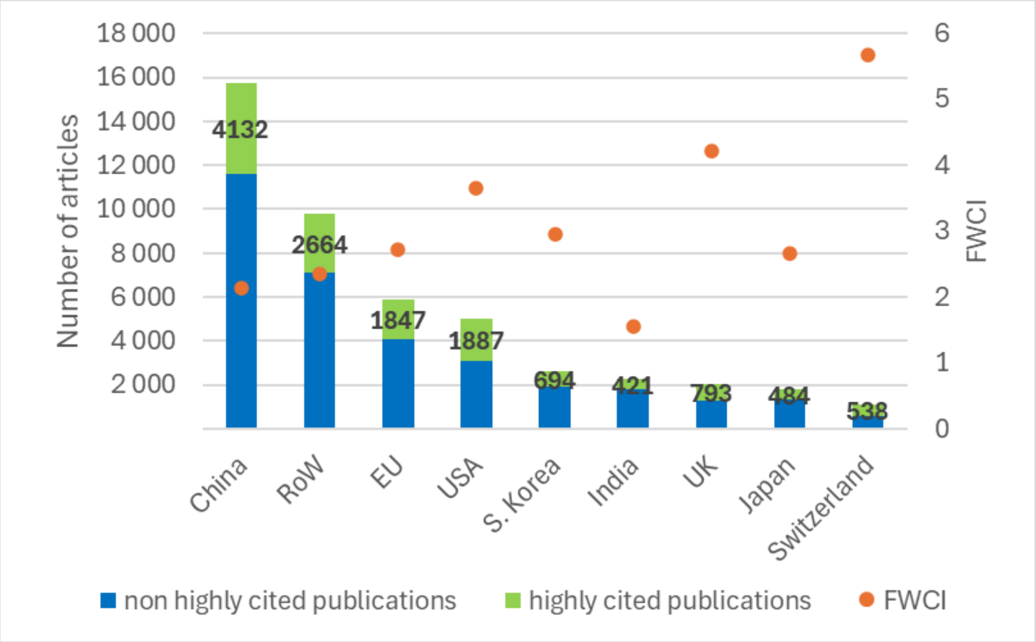


Source: JRC, 2025.

However, apart from the total number of publications, an analysis of the quality of publications is required. As depicted in Figure 26, the EU has 2.7 times less publications on perovskites than China but the EU's highly cited publications are slightly more numerous than China's ones (31% of total against 26% of total). The best performing country is Switzerland, for which 48% of its total number of publications is also highly cited. The United States and the United Kingdom follow with approx. 40%. In terms of Field Weighted Citation Impact (FWCI), China's FWCI is lower (2.1) than the EU's (2.9), meaning less frequent citations despite the large number of papers as a total. Almost half of the total number of publications on perovskites in Switzerland are highly cited publications and the country's FWCI is 5.7, denoting the high quality and frequent citation of the relevant papers.

China has the greatest number of publications on inverters, followed by the EU, India and the United States but only 17% of China's publications are highly cited, whereas the United States' portion of highly cited publications is 21%. Compared to last year's report (REF: CETO PV report 2024), the EU has decreased significantly the number of highly cited publications. For the period 2013-2023, 25% of the total publications where highly cited, whereas for the period 2014-2024, the percentage has decreased to 16%. China's FWCI is 1.6 against 1.4 for the EU and 2.3 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.

Figure 26. Global highly cited publications on perovskites and EU position for the period 2014-2024.



Source: JRC, 2025.

Even though the EU has the highest number of papers on Building Integrated PV, the highly cited ones represent only 15% of the total for the period 2014-2024. By comparison, China's highly cited papers on Building Integrated PV represent 21% of its total publications on the topic. China has a higher FWCI than the EU (1.6 against 1.4). The United Kingdom's and Japan's highly cited publications are 23% and 22% of their total publications on Building Integrated PV respectively and the countries have FWCIs of 1.8 and 1.7 respectively.

In terms of collaborations in scientific publications on perovskites, researchers from China collaborate with researchers from the United States, whereas EU researchers publish with colleagues from India, Switzerland and the United Kingdom. South Korea and Japan constitute a separate collaboration node for publications on perovskites. At EU level, there is a close collaboration between Germany, Italy, Sweden and Finland. Country proximity plays a strong role as two other collaboration nodes identified are: Belgium-the Netherlands-Denmark and Poland-Czech Republic-Slovakia. In the field of inverter publications there is a strong collaboration between China and the EU and India-United States-South Korea-Japan. At EU level, Spain, Italy, Poland and Denmark publish together likewise France, Greece and Cyprus. Building Integrated PV was identified as the most interesting topic for publications in the PV applications field and there is a close collaboration between China-South Korea and the United States. On the other side, the EU publishes mostly with Switzerland and India. In the EU, an established cluster is between France, Spain, Denmark and Austria.

2.9. Assessment of R&I project developments

The 2023 revised PV Implementation Plan (Table 5) adopts the challenges and corresponding targets and R&I topics from ETIP-PV SRIA (ETIP PV, 2021), (updated in August 2024, (ETIP PV, 2024)). 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, 2023).

Table 5. 2023 PV Implementation Plan activities.

2023 Implementation Plan (adopted from the 2024 ETIP PV SRIA)	
Priority 1	Performance enhancement and cost reduction
Priority 2	Enhancing lifetime, reliability and sustainability
Priority 3	Diversified application and integration
Priority 4	Smart energy system integration
Priority 5	Socio-economic aspects of the transition

Source: (IWG PV, 2023)

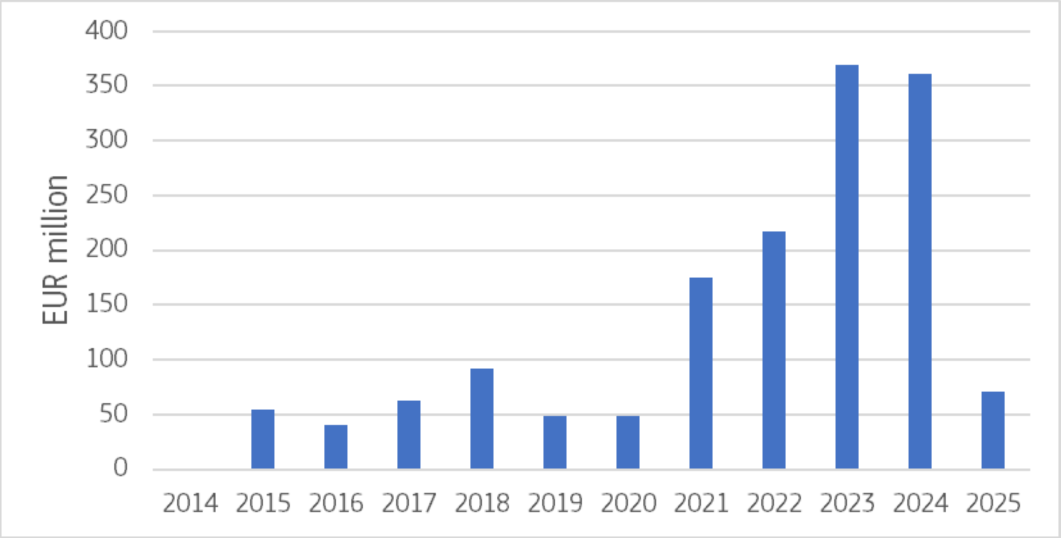
The assessment of the R&I developments covers the 2014 to 2025 period and includes projects from Horizon 2020, Horizon Europe, LIFE, LIFE2027, Innovation Fund (IF), Connecting Europe Facility (CEF), Connecting Europe Facility 2027 (CEF2027), Renewable Energy Financing Mechanism (RENEWFM), European Maritime and Fisheries Fund/European Maritime, Fisheries and Aquaculture Fund (EMFF/EMFAF) and European Research Council (ERC).

From 2014, a total of approximately EUR 1.54 billion has been invested in three hundred and seventy-seven PV-related projects. Of this amount, EUR 366 million were granted to projects that were concluded by 2024 and the remaining EUR 1 175 million concern ongoing projects that will be concluded after 2025 (and up to 2041). Of the overall EU funded projects, almost 30% are Marie Skłodowska-Curie programmes receiving however only 3% of the EU total funding. Coordination actions, Innovation Actions and projects under the ERC account 13% of the total awarded projects each but only Coordination actions and Innovation Actions receive considerable EU funding (16% and 18% respectively). Even though only 4% of the projects is funded under the Innovation Fund (IF), the corresponding EU funding received by these projects accounts for 29% of the total EU budget. Under the 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 27, came from the IF and were dedicated to TANGO project.

Small projects receive below EUR 1 million in funding whereas large projects receive funding over EUR 1 million. There have been 235 large projects identified which received approximately EUR 1 509 million in funding, corresponding to 98% of the total EU financial contribution and 142 small projects which received around EUR 31 million, corresponding to the remaining 2% of the total EU financial contribution to projects.

Funding in 2014 was only EUR 50 000 and is not visible in Figure 27. The year with the highest EU financial contribution was 2023 when EUR 369 million were granted to PV-related projects. In 2024 the EU financial support to projects amounted to EUR 361 million, of which 57% (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), 67% of the EUR 175 million presented in Figure 27, came from the IF and were dedicated to TANGO project.

Figure 27. EU funding contribution for the period 2014-2025.



Source: JRC analysis based on data compilation

Almost half of the EU funding is directed to projects dealing with priority 1: Performance enhancement and cost reduction, while one fifth is awarded to projects related to priority 3: Diversified application and integration. Projects under priority 2: Enhancing lifetime, reliability and sustainability and priority 4: Smart energy system integration account for 12% and 14% respectively, leaving projects related to priority 5: Socio-economic aspects of the transition with around EUR 54 million funding. There are 13 projects that deal with both priority 1 and 2 and receive EUR 45 million.

The majority of the funded projects deals with various PV technologies, while a lot of attention, and therefore funding, is being attracted to perovskite PV technology. As far as applications are concerned, the projects entering the category “general” account for most of the funding (TANGO and HOPE projects included in this category), followed by system integration and integrated applications with 12% share of the total EU funding each. Building applications account for 10%, whereas recycling and O&M for 4%.

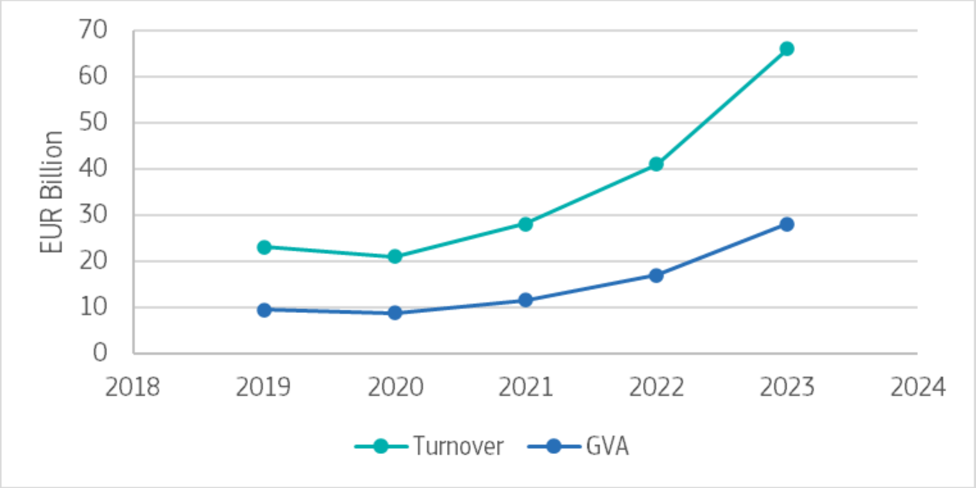
The breakdown to country level finds Germany being the country participating in most H2020 and Horizon Europe projects (participation in 45% of the total number of projects) from 2014 until 2025, followed by Spain, Italy and France with 37%, 34% and 29% respectively.

3. Value chain analysis

3.1. Turnover and Gross Value Added

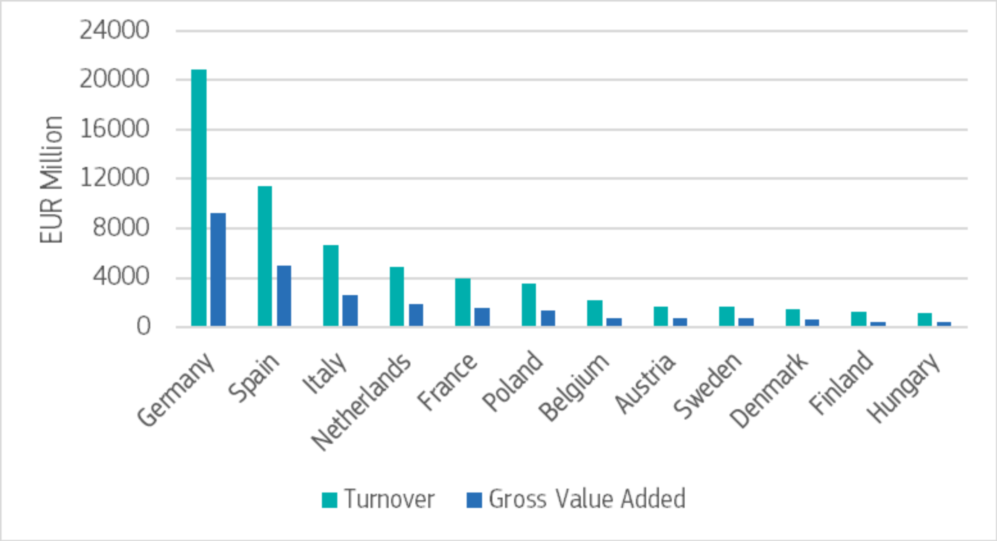
The EU PV turnover in 2023 was approximately EUR 66 billion, growing from EUR 41 billion in 2022. The slight decrease in turnover between 2019 and 2020, as depicted in Figure 28 was the result of a price effect rather than a volume effect, as the installed capacity between 2019 and 2020 actually increased. 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 23% between 2019 and 2023. The EU's GVA in the PV sector saw a CAGR of 24% between 2019 and 2023, from EUR 9.5 billion to EUR 28 billion (Figure 28).

Figure 28. Turnover and gross value added of the EU PV sector in the period 2019-2023.



Source: JRC based on (EurObserv'ER, 2025).

Figure 29. Turnover and gross value added of the PV sector in EU Member States in 2023 for countries with more than EUR 1 000 million turnover.



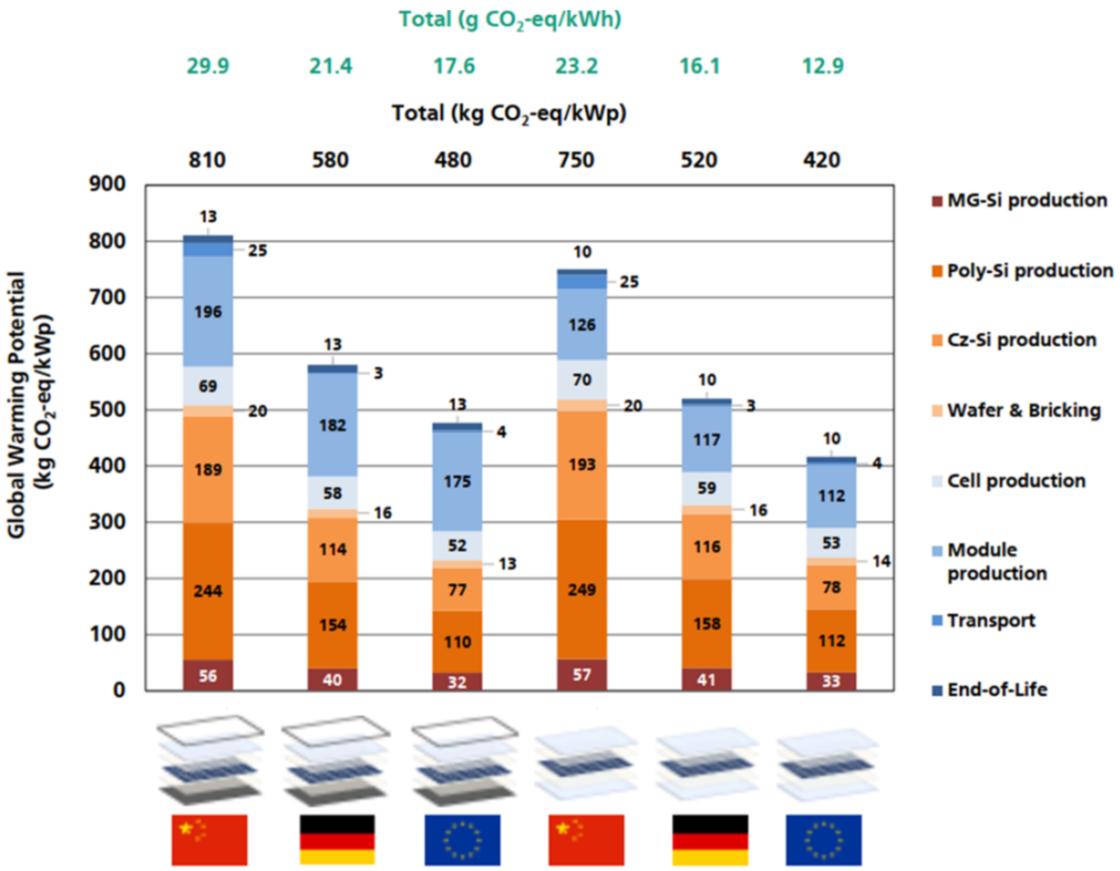
Source: JRC based on (EurObserv'ER, 2025).

The operation segment exhibited the highest share in the value chain, accounting for 80% of the total GVA, followed by the construction segment that accounted for around 10% (CINEA, 2025). According to Figure 29, Germany, Spain, Italy, the Netherlands and France accounted for 72% and 75% of the EU's turnover and GVA respectively in 2023. Compared to 2010, the Netherlands and Poland are demonstrating annual growth rates over 30% (CINEA, 2025).

3.2. Environmental and socio-economic sustainability

PV modules produced in China have a higher carbon footprint than those in the EU. More specifically, PV modules manufactured in the EU produce 40% less CO_2 than the ones 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 30).

Figure 30. Carbon footprint of different PV module configurations in different continents.



Source: (ETIP-PV, 2023)

A fully-fledged and adapted methodology for PV module carbon footprint calculation, was proposed in 2025 (Ardente et al., 2025). 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, 2022a).

Based on the scenario, for mono c-Si modules the carbon footprint lays between 10.8 and $44gCO_{2eq}$/kWh and for poly c-Si between 17.8 and $50.1gCO_{2eq}$/kWh (Ardente et al., 2025). Regarding systems, an updated IEA-PVPS study indicates that, through their lifetime, mono c-Si systems emit $35.8gCO_{2eq}$/kWh, poly c-Si systems emit $43.6gCO_{2eq}$/kWh, CIS systems emit $35.5gCO_{2eq}$/kWh and CdTe systems emit $25.2gCO_{2eq}$/kWh (Frischknecht & Krebs, 2021)[10].

Additional information on the environmental sustainability of PV (Sustainability Assessment Framework (SAF) table) can be found in last year's CETO report (Chatzipanagi et al., 2024), while in Annex 3 amendments are reported for this year.

3.3. Role of EU companies

The analysis of the EU companies in the PV value chain is performed based on the structure presented in Figure 31.

Figure 31. PV value chain structure.

Source: JRC, 2025

The EU PV sector as a whole experiences challenges related to grid capacity limitations, permitting delays, system integration and flexibility, fluctuating consumer demand, value chain disruptions for the procurement of PV components, high labour and energy costs, and severe competition as a result of very low prices and oversupply originating from China (EUPD Group, 2025). Addressing these bottlenecks through policy adjustments such as grid infrastructure investments, flexibility increases including via storage development, corporate power purchase agreements (PPAs) and permitting procedures acceleration will enable a more reliable, flexible and predictable EU PV market that will be able to compete at global level (EUPD Group, 2025; IEA, 2024a).

With PERC PV technology reaching its limit efficiency, TOPCon technology is already increasing its market share and is expected to become the dominant technology in the next few years. HTJ and IBC technologies will also enter the market more dynamically within the next 2-3 years. Depending on the learning curve, perovskite technology manufacturing could quickly achieve comparable costs to those of current technologies (Taylor et al., 2025). Multi-junction technology, silicon-based tandems with III-V top material together with perovskite-silicon tandem devices (are the two most promising and efficient technologies. However, at the moment, more research is needed regarding their lifetime and reliability.

The severe pressure and competition in the PV sector forced several EU companies to decrease or even cease their manufacturing capacities in the entire value chain as they could not compete with the very low prices from China and the resulting oversupply in Europe. Some examples are Aleo solar, Belga Solar, Ecosolifer, Exasun BV, Meyer Burger, NorSun SA, Norwegian Crystals, Photowatt, REC

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[10] 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), 976 kWh/kW$_p$ annual production, 1 331 kWh/m^2 in-plane irradiation, linear degradation 0.7% per year, service life: panel 30 years, inverter 15 years. Module efficiencies assumed: mono c-Si: 20.9 %, poly c-Si: 18 %, CIS: 17 % and CdTe: 18.4 %.

Silicon ASA, Solarwatt, Systovi SAS, etc (Bernreuter Research, 2023; PV Magazine, 2023; S&P Global, 2024).

Along the entire PV supply chain, Wacker Chemie (Germany) is the EU global leading polysilicon manufacturing company. The largest inverter manufacturers in the EU are SMA (Germany), Fronius (Austria), Power Electronics (Spain) and Fimer (Italy).

As far as mounting systems are concerned, the EU is in a rather good position with twenty-three companies operating in the field. Most of the companies are focusing on mounting systems for ground-mounted PV systems and rooftop systems, while less companies specialise in structures for carports and innovating forms of PV deployment, like agrivoltaics that are growing fast. The largest EU mounting systems manufacturer is Gonvarri Solar Steel (Spain), followed by Voestalpine (Belgium). Several EU companies operating in the field of trackers focus on ground-mounted PV systems. The largest producer is Soltigua (Italy).

The EU solar glass industry faces severe competition from other regions as well as challenges related to high costs as it is an energy intensive sector. In addition, the market penetration of bifacial PV modules has increased substantially, and the EU manufacturers are not sufficient to meet the high demand for solar glass, resulting in imports.

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 (ENF, 2023).

As far as the promising perovskite technology is concerned, Europe has a strong research base, including multiple research institutes and projects focusing on the materials, module architecture, roll-to-roll manufacturing and sustainability. While strong in research and technology development, Europe is behind in large-scale industrial manufacturing of perovskite modules, which is more mature in China. China’s large manufacturing base, lower manufacturing costs and large internal market gives it an edge in commercialisation of perovskites. The EU is actively funding and supporting numerous strategic research and innovation projects in perovskites (e.g. LAPERITIVO, SUNREY, PEARL).

The EU should maintain strong R&D in perovskite (materials, stability, module architectures, roll-to-roll manufacturing, sustainability) because this is a high-potential technology with strategic value. Strategic control over next-generation solar technology (perovskites) will strengthen EU energy independence. Strong research excellence in this technology, will give the EU a competitive advantage, even if China dominates mass production of standard modules. By investing now in perovskites, the EU will ensure its competitiveness in future PV markets.

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). Enel Green Power in Italy is among the twenty global market players for the perovskite technology, with the majority of the rest of the companies being in the United States. 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).

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 (Perovskite-info, 2023c):

- Evolar[11] (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[12] (France) plans to build a state-of-the-art module gigafactory in France,
- Saule Technologies (Poland) is also working on a large-scale, prototype production line,
- Voltec Solar (France) planned to have a first 200 MW production in 2025, increasing to $1GW_p$ in 2027 and $5GW_p$ by 2030.

Other European players in the field of perovskites are:

- Aerosolar (United Kingdom),
- Enel Green Power (Italy),
- Power Roll (United Kingdom),
- Solertix (Italy),
- Solliance (Netherlands) and
- 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[13] solar cell manufacturing. In April 2025, Oxford PV has made a patent licensing agreement with Trina Solar (Oxford PV, 2025).

Global competitors are also investing in perovskites. In China there have been several announcements of companies planning to commercialise perovskite technology in the next few years. Some of these companies are Longi, Trina Solar, 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 States, Caelux, Energy America and Halldata Solar are proceeding to commercialisation of perovskites (Perovskite-info, 2023c).

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.

3.4. 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 Table 6. 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, SolarPower Europe estimates that 362 000 were direct. IEA-PVPS's estimation for the direct jobs in 2023 is 500 000. IRENA reports direct and indirect jobs and estimates the EU PV jobs in 2023 to have amounted to 720 000. At the

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

[12] Secured a patent licensing agreement with Trina Solar, giving Holosolis access to Trina's n-type TOPCon portfolio

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

end of 2024, according to SolarPower Europe, there were 865 000 PV jobs (SolarPower Europe, 2025b). Taking these differences into consideration, caution is advised when evaluating the data. The present analysis uses data from EurObserv'ER and IEA-PVPS and complements where necessary with data from IRENA, namely for the global numbers. For the EU jobs of the different segments in the PV value chain, SolarPower Europe data was used.

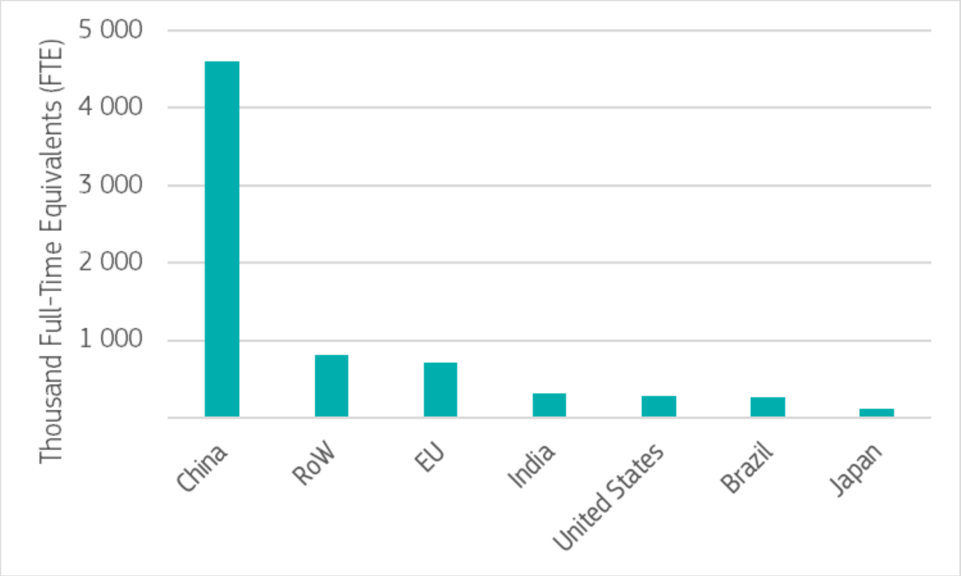
Table 6. EU and global PV employment data (PV jobs) from 2020 to 2024 based on different sources.

EU	**2020**	**2021**	**2022**	**2023**	**2024**
SolarPower Europe	357 000	466 000	648 000	826 000	865 000
EurObserv'ER	165 700	223 100	346 900	560 300	*n.a.*
IEA-PVPS	185 000	185 000	330 000	500 000	500 000
IRENA	166 000	236 000	517 000	719 900	*n.a.*
World	**2020**	**2021**	**2022**	**2023**	**2024**
IRENA	3 980 000	4 290 000	4 900 000	7 100 000	*n.a.*
IEA-PVPS	3 980 000	4 290 000	5 800 000	7 200 000	9 100 000

Source: (EurObserv'ER, 2022, 2024b, 2024a, 2025; IEA-PVPS, 2021, 2022, 2024; IRENA and ILO, 2024, 2021, 2022, 2023; SolarPower Europe, 2021, 2022, 2023, 2024, 2025b)(IEA-PVPS, 2025)

As depicted in Figure 32, in 2023, the EU had the 2nd biggest PV employment sector in the world, with 720 000 jobs, following China which employed 4.6 billion people. This translates into China having 6.4 people for each person working in the PV sector in the EU. China accounts for 62% of the global PV employment, while the EU for 10%. In the same year, India, Brazil and the United States accounted for 4% of the global PV employment each.

Figure 32. Global employment (direct and indirect jobs) in the PV sector in 2023.

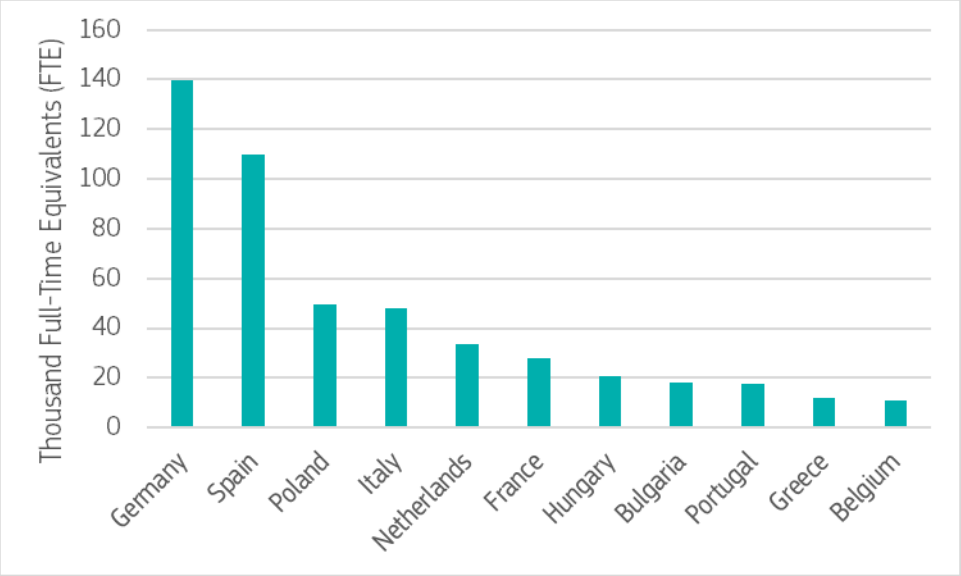


Source: JRC based on (IRENA and ILO, 2024)

In 2023, the share of jobs in the upstream segment was 28% (vs. 72% share of jobs in the downstream activities) (IEA-PVPS, 2025). A 2022 report from Fraunhofer ISE (Fraunhofer ISE, 2022) suggests that 7 500 full-time equivalents (FTEs) are needed to produce 10GW$_p$ of PV generation assets from silicon ingot via wafer and cell to module, whereas the installation of 10GW$_p$ 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).

The eleven Member States with more than 10 000 full-time equivalents are presented in Figure 33. These countries account for 87% of the EU's total jobs in 2023. Regarding the top 5 Member States, these are Germany, Spain, Poland, Italy and the Netherlands and together account for 68% of the EU's total jobs in PV in 2023.

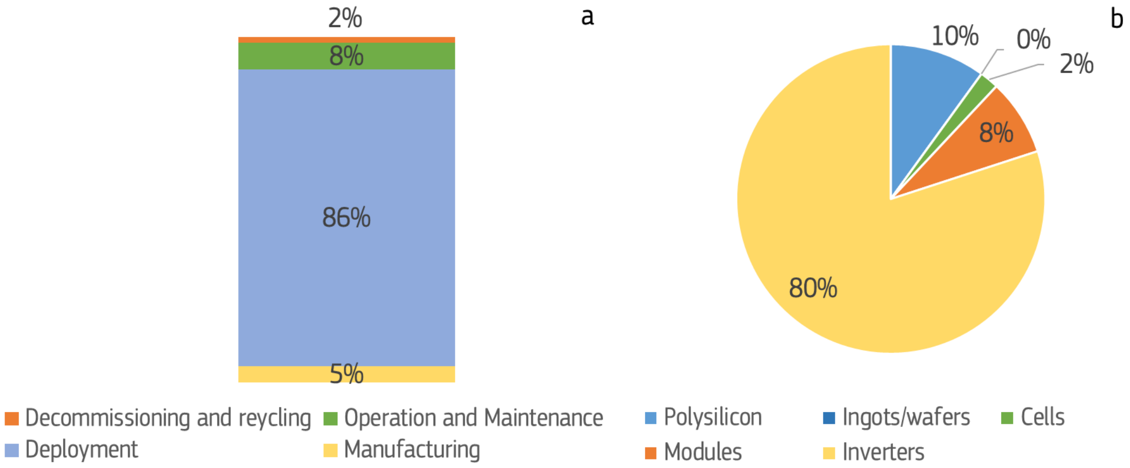
Figure 33. EU employment (direct and indirect jobs) in the PV sector in 2023 for countries with more than 10 000 full-time equivalents.



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

According to SolarPower Europe, from the 865 000 total solar jobs in 2024, 44% were direct and 56% indirect jobs (SolarPower Europe, 2025b). Figure 34a and b present the disaggregated shares in the different segments of the PV value chain in 2024. Most EU jobs were in PV deployment (87%) (Figure 34a). In the manufacturing segment, inverter manufacturing jobs accounted for 80% (an increase from 66% in 2023), while jobs in modules decreased dramatically from 20% in 2023 to 8% of the total manufacturing solar jobs in 2024. This steep reduction is attributed to the closure of several EU manufacturing facilities. Jobs in polysilicon manufacturing remained constant, accounting for 10% (Figure 34b) (SolarPower Europe, 2025b).

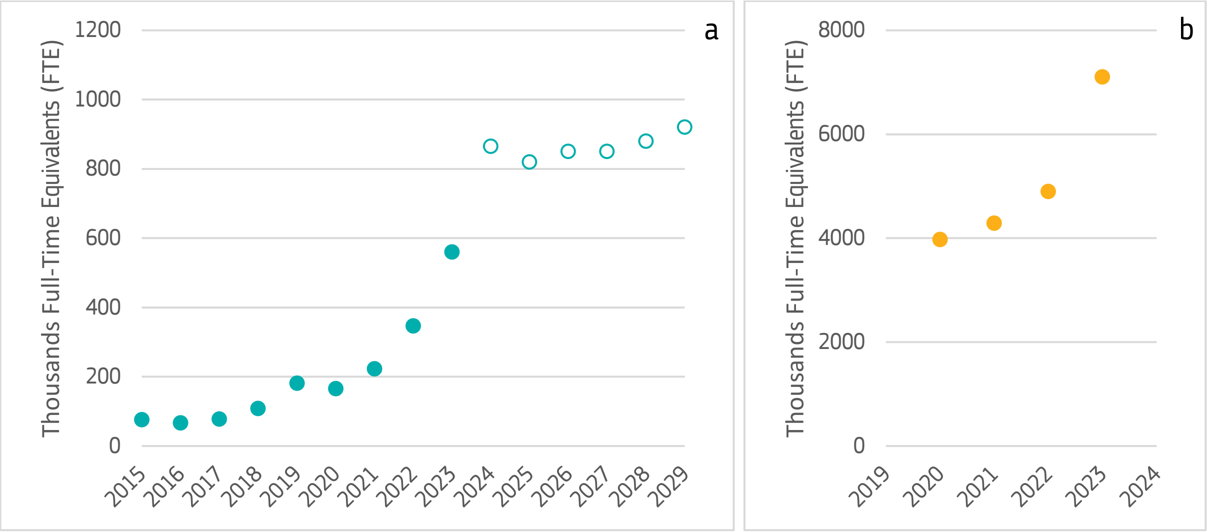
Figure 34. Employment in (a) PV value chain segments and (b) share of the different steps in the manufacturing segment in 2024.



Source: JRC based on (SolarPower Europe, 2025b)

Figure 35 presents the historical evolution in PV employment from 2015 until 2023, according to EurObserv'ER, while the projections until 2029 are based on SolarPower Europe data. In 2025, for the first time, solar-related jobs will see a 5% decrease compared to the previous year and, according to the medium scenario, for the next years a moderate 4% annual increase is projected in 2028 and 2029 (Figure 35). The 2029 projections per segment show that the deployment segment will remain strong, making up for 80% of the total EU PV jobs but not without losses, mainly in 2025 with the segment experiencing a 7% decrease in jobs. Operations and Maintenance will increase by 5% from the 7.5% share in 2024, while manufacturing jobs will make up to 5% of the EU PV jobs. Decommissioning and Recycling is the segment with the fastest growth with a 93% increase between 2024 and 2029 (SolarPower Europe, 2025b).

Figure 35. (a) Historical data and projections in PV employment between 2015 and 2029 for the EU and (b) historical data in PV employment between 2020 and 2023 for the world.



Source: JRC based on (EurObserv'ER, 2024a; SolarPower Europe, 2025b).

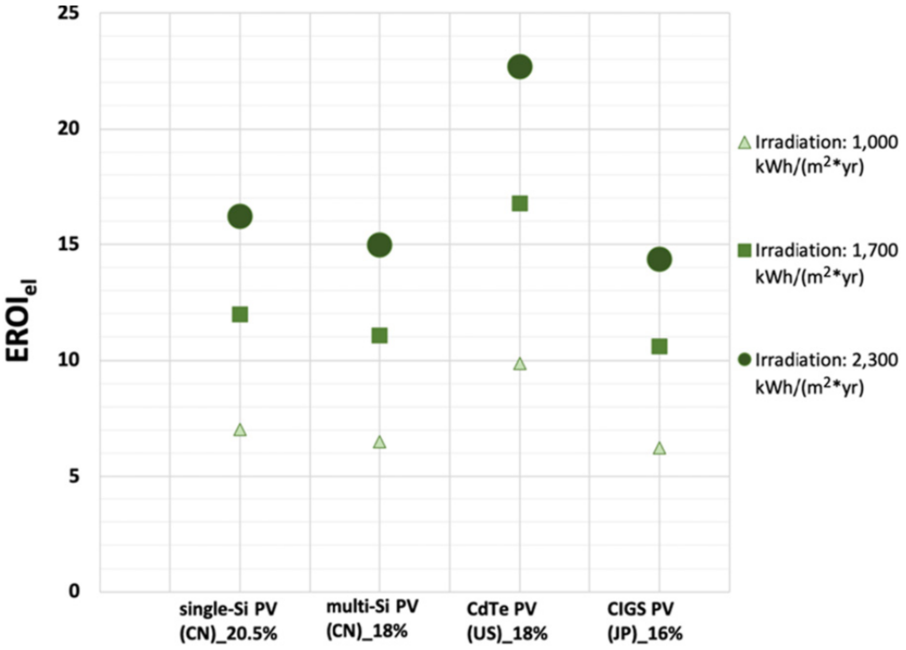
Concerns have risen over the years regarding forced labour particularly in the Uyghur Region in China, which now accounts for approximately 35% of the world's polysilicon (down from 45%) and as much as 32% of global metallurgical grade silicon production. The vast majority of PV modules produced globally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

Reskilling and upskilling workers are essential for the PV sector, as a significant portion of the workforce is approaching 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. In addition, gender imbalance in the renewables sector is still high with women accounting for 32% of the workforce. The European Commission has launched the Pact for Skills in 14 industrial ecosystems, aiming to enhance skills. One ecosystem is on renewable energy. The Renewable Energy Skills Partnership aims at ensuring a sustainable and systematic sectoral cooperation to have a well-trained and sufficient renewable energy workforce. This is a key element of competitiveness within the renewable energy ecosystem and a crucial requirement for the manufacturing, deployment, and management of renewable energy technologies essential to meeting the EU's energy and climate goals (European Commission, 2025a, 2025b). In addition, The European Solar Academy, a training initiative launched by the European Institute of Innovation & Technology (EIT) and EIT InnoEnergy to upskill and reskill 100 000 workers for the solar PV value chain over the next three years has been launched (INNO, 2025).

3.5. Energy intensity and labour productivity

The Energy Return on Investment (EROI) (in terms of electricity) of different PV technologies and at different irradiation levels can be seen in Figure 36. The highest EROI is observed for the CdTe technology in the United States, whereas the lowest for CIGS PV systems in Japan.

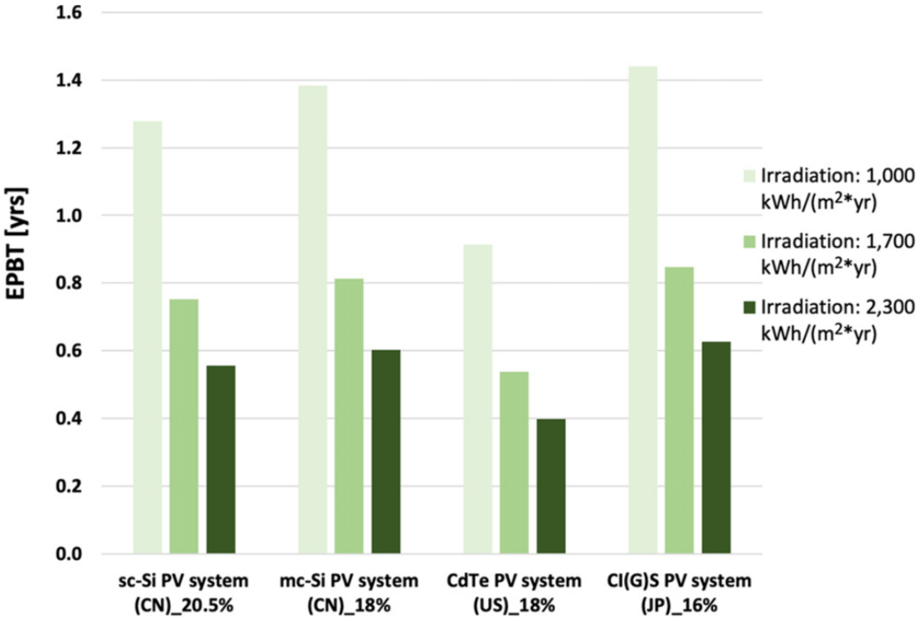
Figure 36. Energy Return on Investment of different technology PV systems, under three irradiation levels in different global locations.



Source: (Fthenakis & Leccisi, 2022)

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, 2025). EPBT for PV systems produced in Europe is shorter than for those produced in China because of better grid efficiency[14] in Europe (Fraunhofer ISE, 2025). Additional information can be found in Annex 6 of last year's report (Chatzipanagi et al., 2024) and amendments in Annex 3 of this report. Figure 37 presents an EPBT comparison between different PV technologies at different irradiation levels in different global locations.

Figure 37. Energy Pay Back Times of different technology PV systems, assuming three irradiation levels in different global locations.



Source: (Fthenakis & Leccisi, 2022)

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, 2022).

Denmark and Sweden have been the leaders in PV labour productivity over the past 5 years. Germany and Italy demonstrate a stable labour productivity while Ireland and Luxembourg have demonstrated an increasing labour productivity in 2021 and 2022 (Figure 38).

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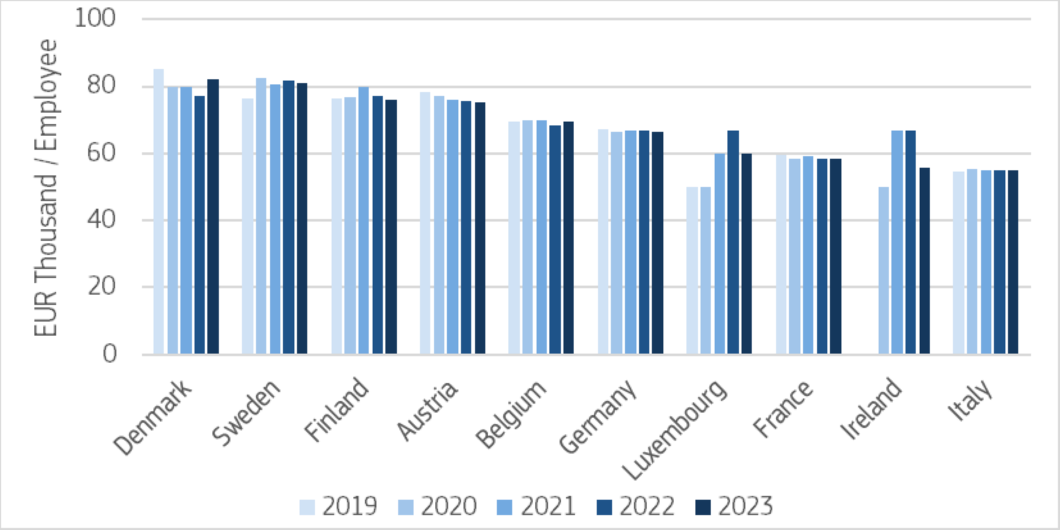
[14] The higher, the better in countries where upstream production is located; (better energy mix to generate electrical power; less losses in the electrical transmission network). At downstream (where PV is installed) a low grid efficiency reduces the EPBT (Fraunhofer ISE, 2023).

Figure 38. PV labour productivity in the EU between 2019 and 2023.



Source: JRC analysis based on EurObserv'ER

3.6. EU production data

The selection of Prodcom codes for monitoring PV production is based on the Net-Zero Industry Act (NZIA) list of components and is grouped into two main categories:

- PV modules: Prodcom code 26112240 (Photosensitive semiconductor devices; solar cells, photo-diodes, photo-transistors, etc.) and
- PV inverters: Prodcom codes 27904153 (Inverters having a power handling capacity ≤7.5kVA) and 27904155 (Inverters having a power handling capacity >7.5kVA).

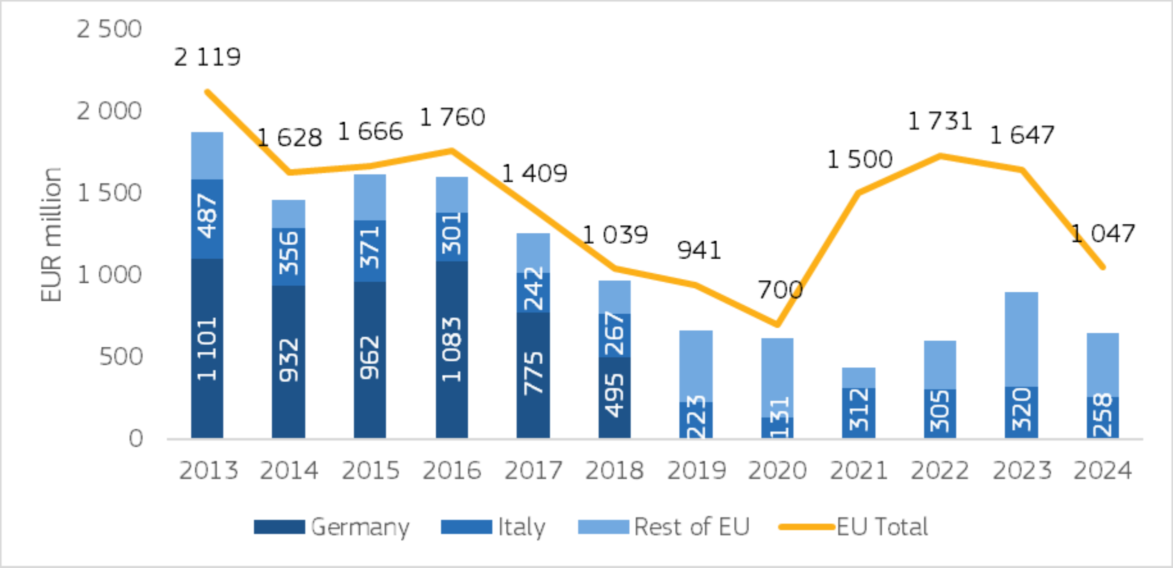
Compared to the previous study (Chatzipanagi et al., 2024), the code for PV modules (26112240) is retained, while the code for parts (26114070) has been excluded.

Figure 39 illustrates the value of EU PV module production. The sum of countries' production (boxes) is lower than the EU total (line) because some Member States keep their production data confidential. However, Eurostat includes confidential data in the EU total estimates.

In 2024, the value of EU PV module production declined by approximately 37% compared to 2023, decreasing to nearly EUR 1 billion (Figure 39). Over the past decade (2015-2024), the overall EU production value fell by 37% with an annual compound decline rate of -5% and an average annual value of over EUR 1.4 billion. During this period, Germany and Italy were the leading EU producers. However, Germany has not disclosed its production data since 2018, and many Member States continue to keep their data confidential, complicating efforts to identify the current top producers. In 2024, Italy and France contributed 25% and 23%, respectively, to the total EU production.

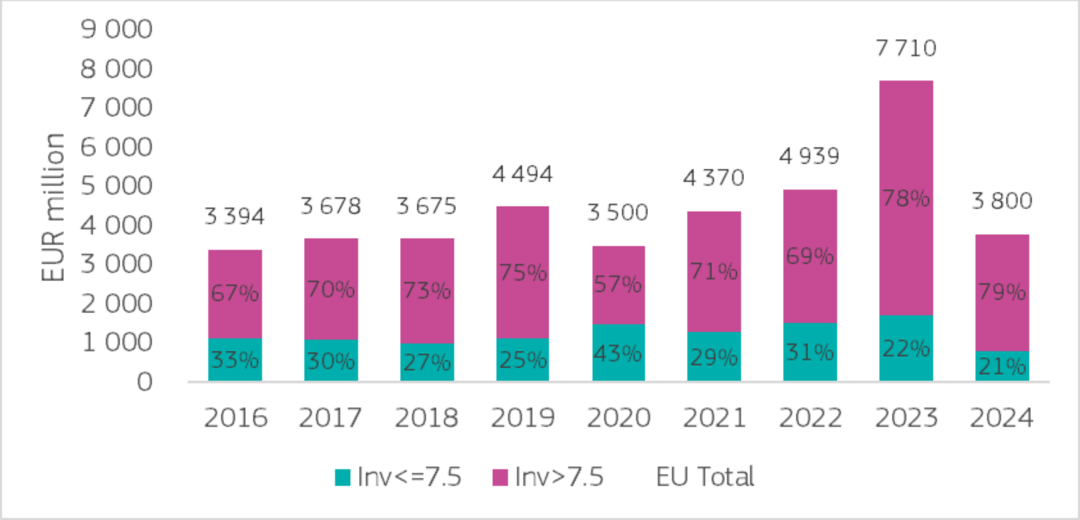
In 2024, the total EU production value of PV inverters declined by over 50% compared to 2023, reaching approximately EUR 3.8 billion (Figure 40). This decline affected both inverter types– large and small - equally (-50% each). Over the past nine years (2016-2024), large inverters (27904155 >7.5kVA) accounted for 70% of EU production, while small inverters (27904153 ≤7.5kVA) made up 30%. Germany and Finland were the leading EU producers during this period. However, the trend shifted over the past three years (2022-2024), with Spain emerging as the top producer. In 2024, Spain accounted for 28% of the total EU 2024 production, followed by Finland (16%) and Germany (11%). Spain and Finland focused predominantly on large inverters (94% and 84%, respectively), while Germany's production was concentrated on small inverters. Notably, Germany withheld its production data for small inverters in 2024.

Figure 39. PV module production value in the EU for the period 2015-2024[15].



Source: JRC based on PRODCOM data, 2025.

Figure 40. PV inverter production value by type in the EU for the period 2016-2024.



Source: JRC based on PRODCOM data, 2025.

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[15] EU total (line) does not correspond necessarily to the country sum (total bar) due to confidentiality (values included in the total but not reported separately).

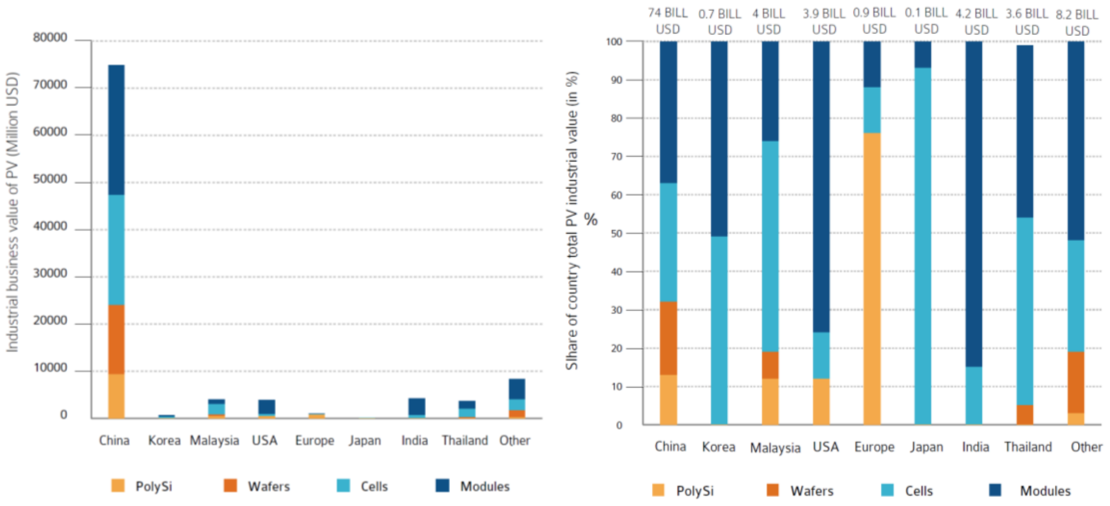
4. EU market position and global competitiveness

4.1. Global markets and growth prospects

4.1.1. Current EU positioning in the global market

The EU PV turnover in 2023 was approx. EUR 66 billion, from EUR 41 billion in 2022. The compound annual growth rate of the PV turnover in the EU was 23% between 2019 and 2023. Globally, the PV market is estimated to have reached a turnover of approx. USD 254 billion (EUR 235 billion[16]) in 2023 (Fortune Business Insights, 2025) and thus, the EU's share is 28%. In 2022 the EU's share was 18.4% (Chatzipanagi et al., 2024). The global turnover of the PV sector in 2024 is estimated at USD 273 billion (EUR 252 billion[17]), while projections mention a CAGR of approx. 6% between 2024 and 2032, amounting to USD 436 billion of global PV turnover in 2032 (Fortune Business Insights, 2025).

Figure 41. Absolute (left) and share (right) of turnover along the upstream (polysilicon to module) value chain for major economies in 2024.



Source: (IEA-PVPS, 2025)

Figure 41 presents the PV turnover in different regions and supply chain steps. China is dominant in all segments of the upstream PV value chain (from polysilicon to modules production), accounting for 74% of the global turnover in 2024. South Korea and Japan's turnover in the upstream PV sector is attributed to modules, whereas Europe's turnover relies entirely on polysilicon. Approx. 0.4% of 2024 global GDP is due to the PV manufacturing sector. For China, the PV industry is responsible for 0.4%

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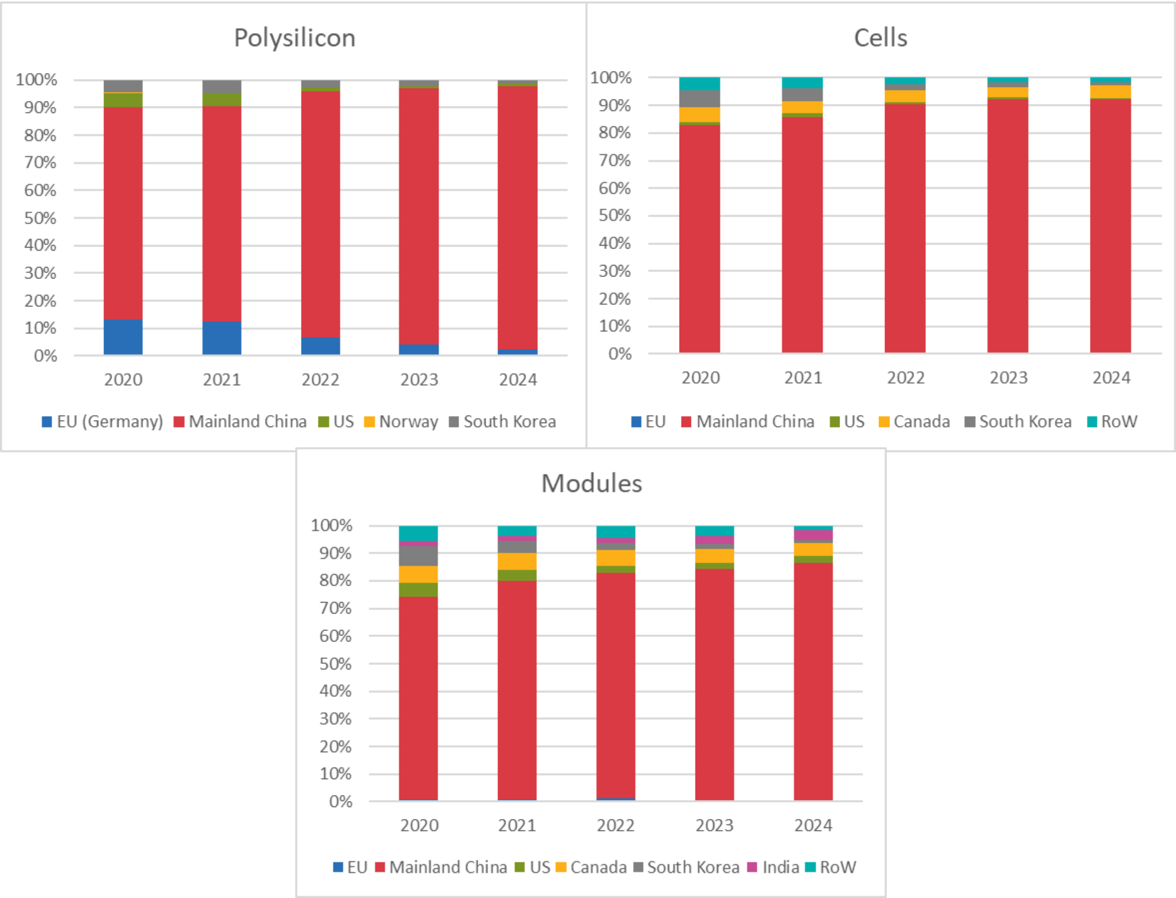
[16] Euro foreign exchange reference rates: 1 USD2023 = 0.9248 EUR2023 (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

[17] Euro foreign exchange reference rates: 1 USD2024 = 0.9239 EUR2024 (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

of its GDP (from 0.46% in 2023), while for Malaysia the respective percentage is around 1% and for Thailand 0.7% (IEA-PVPS, 2025).

As depicted in Figure 42, the global PV market is dominated by China. The EU had a 13% market share in polysilicon in 2020 but the considerably high production in China has decreased this share to 2% in 2024. The situation is the same also for the United States that witnessed its polysilicon market share decrease from 5% in 2020 to 1% in 2024. China monopolises the market with a 96% share.

Figure 42. Market share of manufacturing capacity of the top 10 OEMs in PV (polysilicon, cells and modules) over the period 2020-2024 regarding their respective origin.



Source: JRC based on (Bloomberg New Energy Finance, 2025c)

According to IEA-PVPS, wafers production is monopolised by China, accounting for 97% of the global production, with Vietnam following with a share of 2% of the global wafer production (IEA-PVPS, 2025).

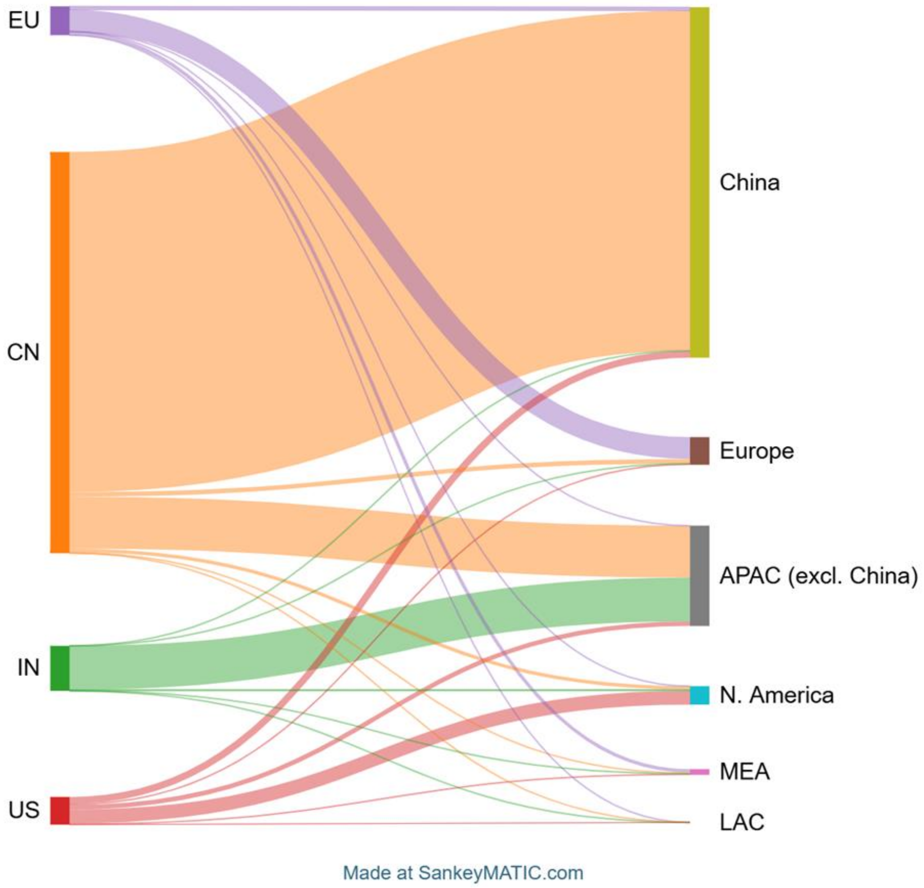
As far as cells are concerned, China accounted for 92% in 2024 from 83% in 2020. Canada managed to maintain its 5% market share during the period 2020-2024, while South Korea's and the rest of the world's shares receded to 1-2% respectively. The EU's share was already practically inexistent in 2020, and the situation remained unchanged also in 2024.

In the modules sector, China increased its market share from 73% in 2020 to 86% in 2024, while South Korea decreased it from 7% (2020) to 1% (2024). The United States also witnessed a market share decrease (from 5% to 3%). Canada on the other hand managed to maintain a stable 6%

between 2020 and 2024 and India doubled its market share in 2024 from the 2% it held in 2020. The EU, facing the severe competition and the oversupply from China, decreased its module market share from 1% in 2020 to 0.5% in 2024.

Figure 43 presents the headquarter versus factory locations of PV manufacturers for the entire upstream value chain. EU PV manufacturers have their assets mainly in Europe, with a few factories located in China and in Middel East and Africa (MEA). Chinese manufacturers operate primarily in China, while they also have assets in the Asia-Pacific region (Malaysia, Laos, Thailand and Indonesia) and in Türkiye. The United States' PV manufacturers have assets in North America, China and the Asia-Pacific region.

Figure 43. Headquarter versus factory locations of PV manufacturers.



Source: JRC analysis based on (Bloomberg New Energy Finance, 2025c)

The PV markets of the different countries/regions have been shaped by their diverse economic and political circumstances.

- China:
  - Substantial and steady economic support through governmental investments to the industry for technological development and upgrading;
  - National and municipal policies regarding special high-tech development zones with relevant incentives (Taylor et al., 2025);
  - Low labour and energy costs, faster permitting and construction times.

- India:
    - Policies related to PV deployment (Solar Park Scheme, PM-KUSUM, Rooftop Solar Programme, etc.);
    - Product Linked Incentive (PLI) with a 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, 2025a).
- United States:
    - Investment credit and support schemes for PV deployment;
    - Pause of Inflation Reduction Act (IRA)[18] disbursement and exclusion of PV from the Defence Production Act (DPA)[19];
    - Imposture of trade measures on imported PV cells and modules (especially from China).

China's leadership in solar PV manufacturing will continue while industrial policies and trade measures stimulate diversification. By 2030, China will most likely maintain its leading role in the global PV supply chain, with market shares of 75% for modules, 85% for cells, 90% for polysilicon and 95% for wafers (IEA, 2025b). According to the IEA, China and Malaysia are the only countries that will be able to produce the volumes needed for their deployment needs by 2030, whereas limited wafer manufacturing capacity will remain the main bottleneck (IEA, 2025b). Manufacturing PV modules in the United States and India currently costs two to three times more than in China (IEA, 2024a). According to IEA, the price gap is set to remain in place for the foreseeable future. Policy makers should consider striking a fine balance between the additional costs and benefits of local manufacturing, weighing key priorities such as job creation and energy security (IEA, 2024a). A recent study demonstrates that the NZIA implementation would reduce the cost gap, depending on the manufacturing scalability but still the cost for EU made PV modules will remain notably higher than any other option compliant with the NZIA resilience criterion. For a fully scaled manufacturing facility (10GW$_p$ annually) a fully-EU PV module price is estimated at 25.5 EUR ct/W$_p$, whereas in the case of unscaled manufacturing facilities the price increases to 30.8 EUR ct/W$_p$. In comparison, the study estimates the minimum sustainable price for a PV module manufactured in China and in South-East Asia at 15.9 EUR ct/W$_p$ and 16.5 EUR ct/W$_p$, respectively, while the current market price is 8.7 EUR ct/W$_p$. (SolarPower Europe, 2025d), suggesting a global market distortion from global overcapacities and issues related to below-cost pricing. Another study, with similar cost values, underlines the importance of complementary sustainability award criteria, stricter resilience criteria and differentiated financing conditions for EU-based PV systems as their analysis also confirms that both resilience as pre-qualification and resilience as an award criteria does not accomplish a favourable situation for EU manufacturing (Dehghanimadvar et al., 2025).

4.1.2. Market prospects

<u>Projections until 2030</u>

For the global PV installed capacity, the IEA and BloombergNEF foresee between 5.8TW$_p$ and 6.7TW$_p$ for 2030 (Bloomberg New Energy Finance, 2025a; IEA, 2024b, 2025b). SolarPower Europe projects

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[18] Direct and targeted support scheme for boosting the country's domestic manufacturing landscape

[19] Special priority and faster permitting with associated funding.

5.3TW$_p$ for the low scenario and 7.2TW$_p$ for the high scenario (SolarPower Europe, 2025c). For the EU, BloombergNEF projects between 691GW$_p$ (low scenario) and 756GW$_p$ (high scenario) (Bloomberg New Energy Finance, 2025a), while SolarPower Europe has revised its 2030 projection for the EU to 723GW$_p$ (SolarPower Europe, 2025a).

Projections until 2050

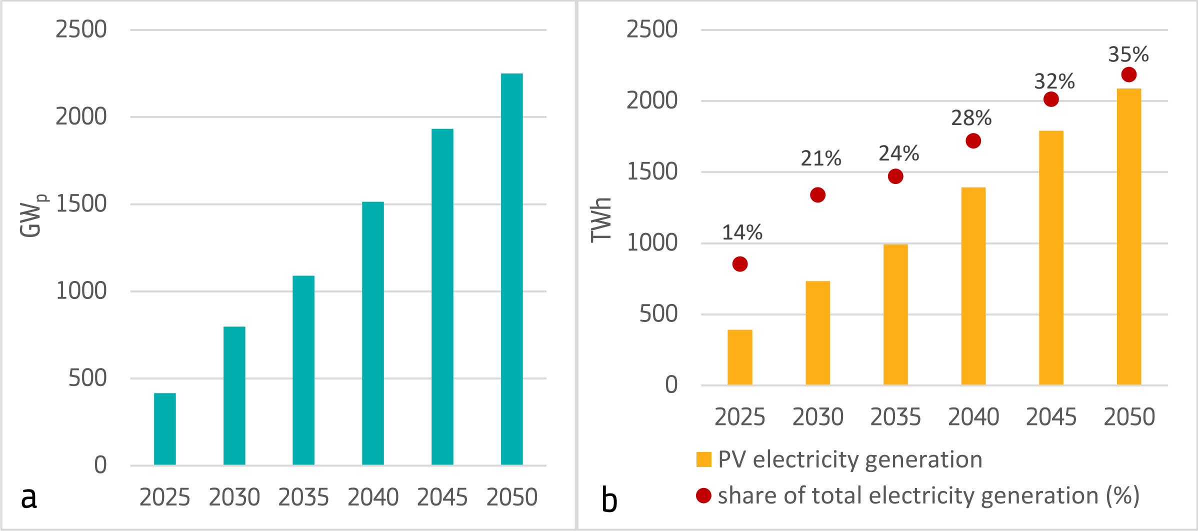
The long-term projections for global installed PV capacity by 2050 differ substantially. The IEA projects between 16TW$_p$ and 21.6TW$_p$ (IEA, 2024b), while other projections suggest that the global capacity will range between 9TW$_p$ (slow growth scenario) and 62TW$_p$, (fast growth scenario) (Vartiainen et al., 2020).

Discrepancies within long-term projections are not surprising as small differences in scenario settings 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 2025 using the models POTEnCIA[20] for the EU (Neuwahl et al., 2025) and POLES-JRC[21] for the world (Keramidas et al., 2025; Schmitz et al., 2025).

Figure 44. Projections of (a) PV gross installed capacity and (b) PV electricity generation and PV share in the EU until 2050.



Source: POTEnCIA CETO 2025 Scenario (JRC)

As far as the EU is concerned (Figure 44), the *POTEnCIA CETO 2025 Scenario*, with 798GW$_p$, is in good accordance BloombergNEF and SolarPower Europe for 2030 projections of installed PV capacity

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[20] A short description of the POTEnCIA CETO 2025 scenario and the POTEnCIA model can be found in Annex 4.1.

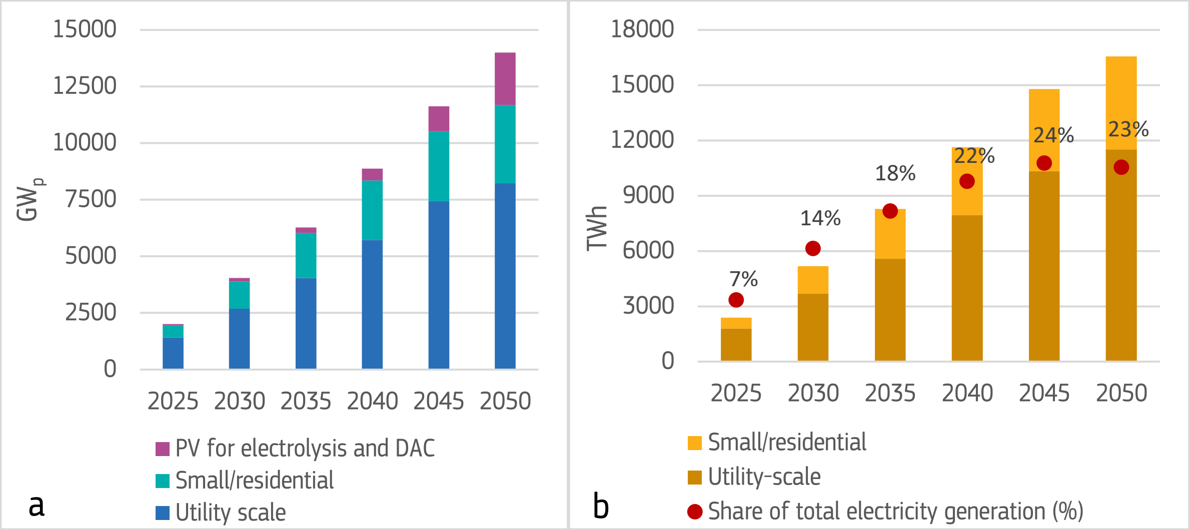
[21] A short description of the Global CETO 2°C scenario 2025 and the POLES-JRC model can be found in Annex 4.2.

mentioned above. For the long-term projections (2050), the model projects a capacity of 2.3TW$_p$. PV electricity production increases to 733TWh by 2030, and to over 2 000TWh by 2050, equivalent to 35% 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, based on the *Global CETO 2°C scenario 2025*[22] calculated with the POLES-JRC model are shown in Figure 45. The 2030 projected global installed PV capacity is 4.0TW$_p$. This is considerably lower than other projections for 2030 (5.3-7.2TW$_p$ from SolarPower Europe and 5.8-6.7TW$_p$ from IEA and BloombergNEF).

By 2050, the *Global CETO 2°C scenario 2025* projects a global PV capacity of in total 14TW$_p$, which is composed of 11.7TW$_p$ PV capacity of the power system (utility & small/residential) and 2.3TW$_p$ of PV capacity dedicated to the production of hydrogen and direct air capture.

Figure 45. Projections of (a) PV gross installed capacity and (b) PV electricity generation and PV share globally until 2050.



Source: Global CETO 2°C scenario 2025 (JRC)

4.2. Trade (Import/export) and trade balance

For monitoring trade in PV, the selection of trading goods aligns with the Net-Zero Industry Act (NZIA) list of components[23] and is organised into two primary categories:

- PV modules: 854142 (PV cells not assembled in modules or made up into panels), 854143 (PV cells assembled in modules or made up into panels), both available as of 2022

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[22] The model used for this scenario builds on the POLES-JRC model in the version used for the Global Energy and Climate Outlook (GECO) 2024 (Schmitz et al., 2025) and documented in (Keramidas et al., 2025). Additionally, to the GECO 2024 model version, updates apply for (i) new vehicles and vehicle stock by transport mode; (ii) hydrogen infrastructure costs for road transport; (iii) investment costs for renewables, batteries, and capacities for power generating technologies as well as (iv) modelling revisions for electrolysers.

[23] The Combined Nomenclature - Taxation and Customs Union

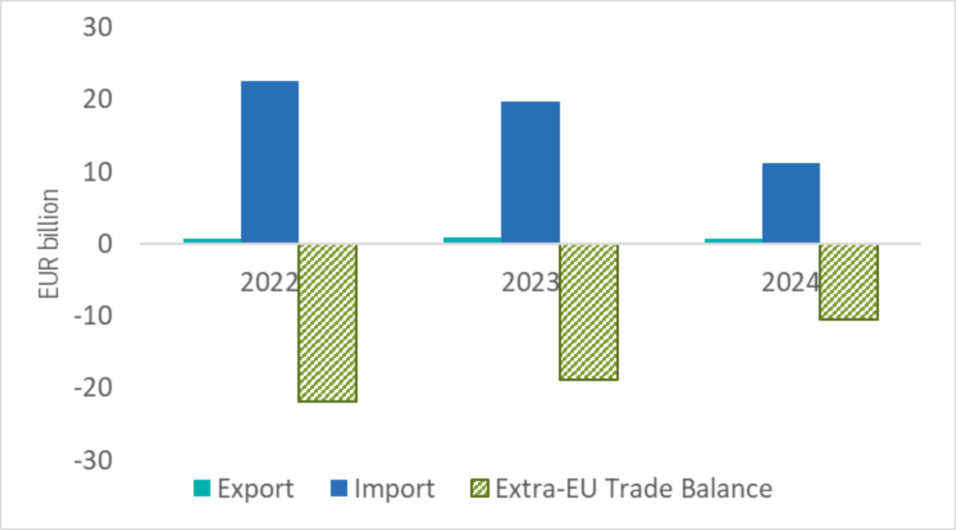
- PV inverters: 85044085[24] (Inverters having power handling capacity <= 7,5kVA), 85044086[25] (Inverters having power handling capacity > 7,5kVA), both available as of 2023.

The eight-digit codes of the Combined Nomenclature (CN) are used to monitor the EU trade through Comext[26] , while the corresponding six-digit codes of the Harmonised System (HS) classification[27] are used to monitor international trade through Comtrade[28].

Compared to the previous study (Chatzipanagi et al., 2024), HS codes for photosensitive semiconductor devices (854140 – available until 2021) and parts of diodes (854190) have been excluded.

Figure 46 illustrates a persistent EU trade deficit for PV modules, with a declining trend. In 2024, extra-EU imports fell by 43%, while exports dropped by 21% compared to 2023, reducing the trade deficit by 44% at EUR 10.4 billion. Notably, both EU imports and exports are predominantly (>97%) composed of assembled PV cells.

Figure 46. Extra-EU trade of PV modules for 2022-2024.



Source: JRC based on COMEXT data, 2025.

According to Intersolar Europe (PVTECH, 2025), 2024 saw extreme oversupply in solar PV modules, which caused module prices to plummet to historical lows. This was a global phenomenon, but its effects were particularly severe in Europe which faced a paradox: on one hand, the low prices of modules made solar installations cheaper for end-users, contributing to a record year for installed capacity. On the other hand, this same price environment was destroying the very industry the EU was trying to build, highlighting a fundamental conflict between short-term deployment goals and long-term strategic independence. While this price drop was beneficial for consumers and boosted

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[24] CN code 85044084 for data until 2022

[25] CN code 85044088 for data until 2022

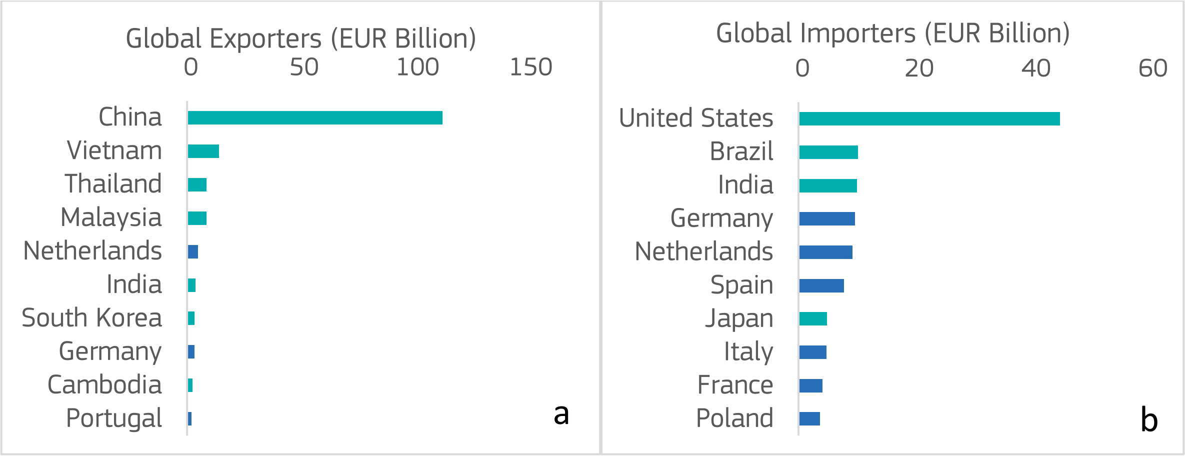
[26] https://intragate.ec.europa.eu/eurostat/comext/ati/public/home

[27] https://www.wcoomd.org/en/topics/nomenclature/instrument-and-tools/hs-nomenclature-2022-edition.aspx

[28] https://comtradeplus.un.org/

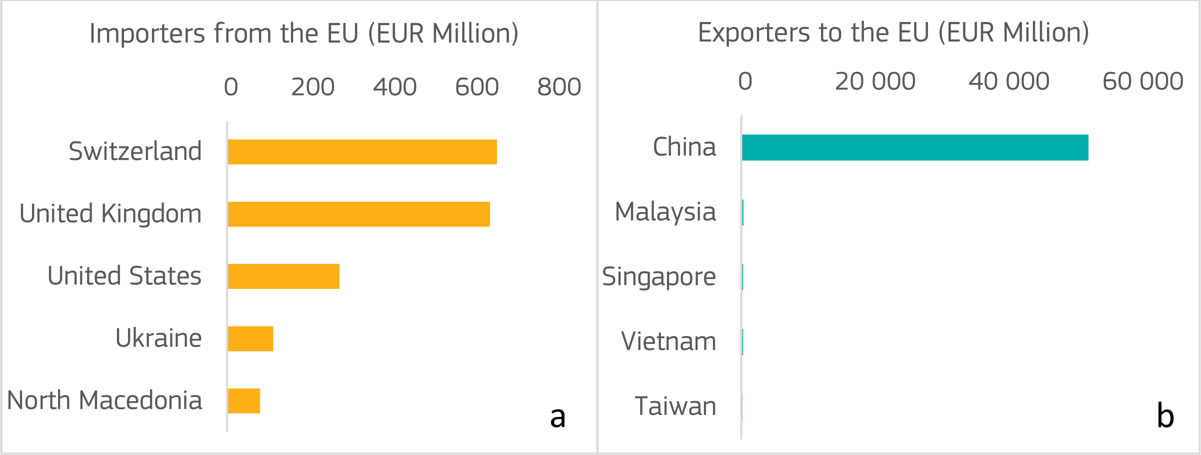
the economic viability of solar projects, it created a financial crisis for many manufacturers, particularly those outside of China (energynews, 2025). Several European solar manufacturers, unable to compete with the ultra-low prices of imported modules, were forced to close factories or declare bankruptcy. This included prominent players like Meyer Burger, which ceased module manufacturing in Germany, and Solarwatt, which closed a production facility (EUPD Group, 2025).

Figure 47. Top ten global (a) exporters and (b) importers of PV modules for 2022-2024.



Source: JRC based on COMTRADE data, 2025.

Figure 48. Top five countries (a) importing from and (b) exporting to the EU for 2022-2024.



Source: JRC based on COMEXT data, 2025.

Global exports of PV modules declined from EUR 67.7 billion in 2023 to EUR 39.3 billion in 2024[29]. Over the 2022–2024 period, the EU accounted for 9% of global exports (including intra-EU trade), while extra-EU exports (excluding intra-EU trade) represented 1% of global export transactions. The EU covered 31% of its importing needs with intra-EU trade. China was the dominant global exporter

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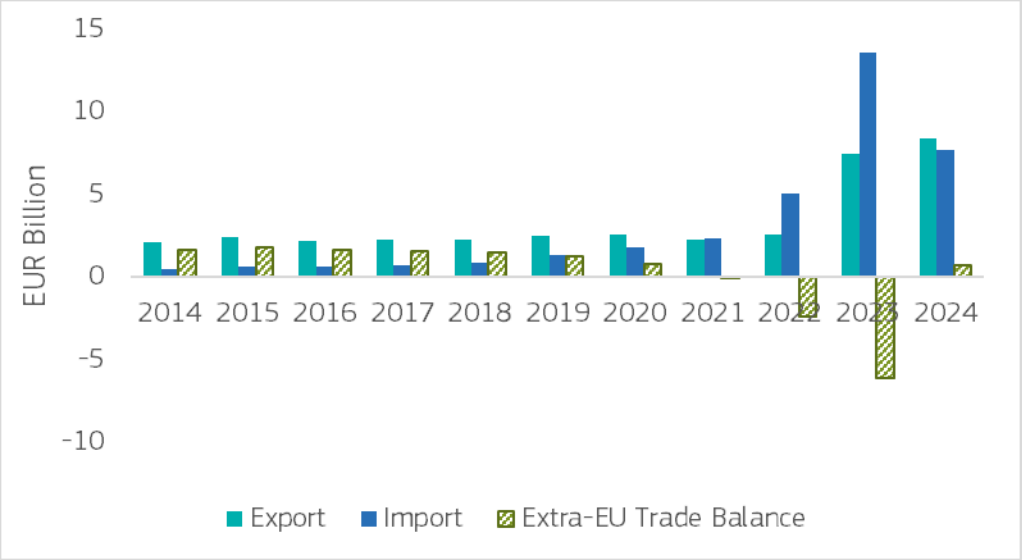
[29] COMTRADE data for 2024 are incomplete as of the current dataset. The reported figures may be subject to revision in subsequent updates to the database.

for the same period, accounting for 97 % of global exports. The US, Brazil and India were the leading global importers (Figure 47).

During the same period, Switzerland was the largest importer from the EU, receiving 27% of the extra-EU exports, followed by the UK and the US with 26% and 11%, respectively. China was the largest exporter to the EU, accounting for 97% of extra-EU imports (Figure 48).

In 2024, the EU shifted from a EUR 6.1 billion deficit in PV inverters to a EUR 0.7 billion surplus (Figure 49). This reversal was driven by a 44% decline in extra-EU imports and a 12% increase in exports compared to 2023. Notably, EU imports composed 60% of large inverters (CN 85044086) while exports 76%. Global exports of PV inverters declined from EUR 132.4 billion in 2023 to EUR 85.1 billion in 2024[30]. Over the 2022–2024 period, the EU accounted for 30% of global exports (including intra-EU trade), while extra-EU exports (excluding intra-EU trade) represented 4% of global export transactions. The EU covered 57% of its importing needs with intra-EU trade. China was the largest global exporter for the same period, accounting for 39% of global exports followed by Germany with 9%. The US, Brazil and China were the leading global importers (Figure 50).

Figure 49. Extra-EU trade of PV inverters for 2014-2024.



Source: JRC based on COMEXT data, 2025.

During the same period, the US was the largest importer from the EU, receiving 28% of the extra-EU exports, followed by China and the UK with 13% and 8%, respectively. China was the largest exporter to the EU, accounting for 79% of extra-EU imports (Figure 51).

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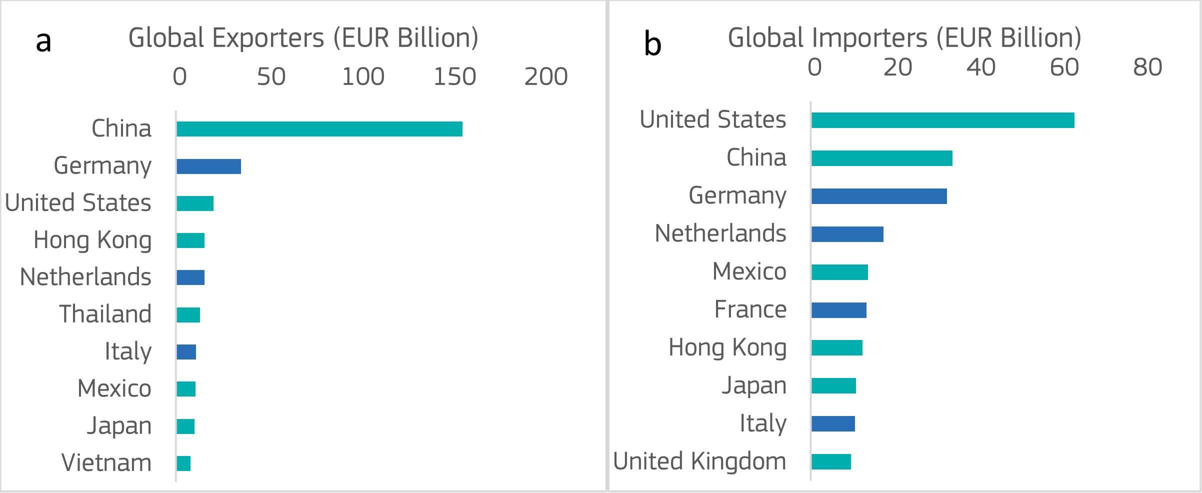
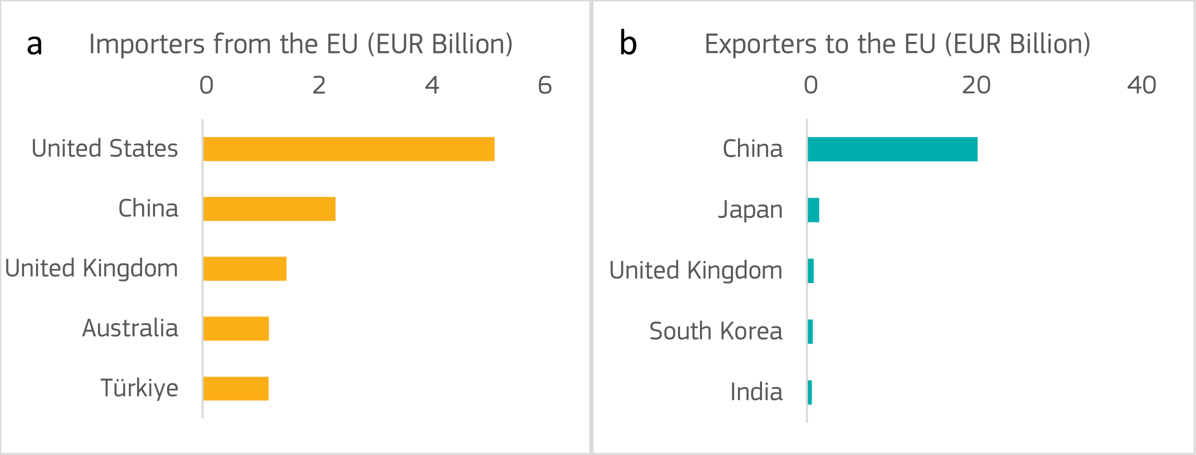
[30] COMTRADE data for 2024 are incomplete as of the current dataset. The reported figures may be subject to revision in subsequent updates to the database.

Figure 50. Top ten global (a) exporters and (b) importers of PV inverters for 2022-2024.



Source: JRC based on COMTRADE data, 2025.

Figure 51. Top five countries (a) importing from and (b) exporting to the EU for 2022-2024.



Source: JRC based on COMEXT data, 2025.

Table 7 shows the growing markets[31] of PV inverters during 2021-2023[32]. Canada had the largest net import increase, followed by Brazil and Australia, where the EU captured 11%, 9% and 27% of each country's growing market, respectively.

Table 7. Growing markets of PV inverters based on a 2-year average of net import change.

Country	**Total import (2021-2023) (EUR Million)**	**% import from the EU**	**2-year average of net import change**
Canada	9 667	11%	880

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[31] Calculated as $net\ import\ change = [(import_{2022} - import_{2021}) + (import_{2023} - import_{2022})]/2$

[32] Latest year data (2024) is incomplete for comtrade, because it does not provide estimates for the missing values as comext does.

Country	Total import (2021-2023) (EUR Million)	% import from the EU	2-year average of net import change
Brazil	7 572	9%	488
Australia	7 269	27%	434
South Africa	2 835	9%	406

Source: JRC based on COMTRADE data

4.3. Status of net zero technology systems and components in the EU

The two NZIA benchmarks are aiming to *"ensure the reduction of strategic dependencies in the Union of net-zero technologies and their supply chains by reaching a manufacturing capacity for those technologies of:*

(a) a benchmark of at least 40% of the Union's annual deployment needs for the corresponding technologies necessary to achieve the Union's 2030 climate and energy targets;

(b) an increased Union share for the corresponding technologies with a view to reaching 15% of world production by 2040 on the basis of monitoring pursuant to Article 42, except where the increased Union manufacturing capacity would be significantly higher than the Union's deployment needs for the corresponding technologies necessary to achieve the Union's 2040 climate and energy targets." (European Union, 2024).

4.3.1. Relevant final products and primarily used components

Table 8 presents the Final Products (FPs) and Primarily Used Components (PUCs) for the PV technologies, as these are defined within the Net-Zero Industry Act (NZIA) (European Union, 2025b, 2025a).

Table 8. Final Products (FPs) and Primarily Used Components (PUCs) for the PV technologies in the NZIA.

Technology	Final Products (FPs)	Primarily Used Components (PUCs)
Photovoltaics (PV)	Solar photovoltaic (PV) system	PV grade polysilicon
		PV grade silicon ingots or equivalent
		PV wafers or equivalent
		PV cells or equivalent
		Solar glass
		PV encapsulants
		PV ribbons
		PV backsheets
		PV connectors

Technology	Final Products (FPs)	Primarily Used Components (PUCs)
		PV junction boxes
		PV modules
		PV inverters
		PV trackers and their mounting structures

Source: (European Union, 2025a)

4.3.2. EU manufacturing benchmark

Table 9 presents the results of the EU manufacturing benchmark exercise for 2030 for some of PV Primarily Used Components (PUCs) listed above. The exercise includes the analysis of PV grade polysilicon, ingots, wafers, cells, modules, inverters, trackers and their mounting systems.

Solar glass, PV encapsulants, ribbons, backsheets, connectors and junction boxes are not included as these components are difficult to be expressed in the production capacity units (GW_{DC}) used for the analysis. The available information for these components is limited to the number and location of the companies that are active in the field and is based on the available data at the time of the report elaboration.

Table 9. EU manufacturing benchmark for 2030 for specific Primarily Used Components (PUCs) for PV.

PUC	EU manufacturing capacity (GW_{DC})	*Number of factories*	2030 EU deployment needs (GW_{DC})	2030 EU manufacturing capacity benchmark (%)
PV grade polysilicon	25		76	33
PV grade silicon ingots or equivalent	0		76	0
PV wafers or equivalent	0		76	0
PV cells or equivalent	2		76	3
Solar glass		*4*		
PV encapsulants		*5*		
PV ribbons		*4*		
PV backsheets		*12*		
PV connectors		*4*		
PV junction boxes		*6*		
PV modules	12		76	15

PUC	EU manufacturing capacity (GW_{DC})	*Number of factories*	2030 EU deployment needs (GW_{DC})	2030 EU manufacturing capacity benchmark (%)
PV inverters	142		76	187
PV trackers and their mounting structures	121		38	319

Source: JRC analysis based on custom-made EU manufacturing dataset from Becquerel Institute and POTEnCIA CETO 2025 Scenario

With the current manufacturing capacity, the EU accomplishes the NZIA 2030 target of at least 40% of the Union's annual deployment needs being manufactured locally only for PV inverters and PV trackers and their mounting structures. In the case of ingots, wafers, cells and modules, the EU manufacturing is considerably lower than what is needed to satisfy the 76GW_{DC} deployment in 2030. For polysilicon, the EU is lacking some additional manufacturing capacity to reach the at least 40% target.

Assuming that the announced new and/or expansion manufacturing in the EU will be realised, the benchmark could be at 33% for wafers, 17% for cells and 43% for modules.

4.3.3. EU share in global manufacturing benchmark

Table 10 presents the EU share of global production of the PV PUCs in 2040. As above, the EU can satisfy the 15% share of global manufacturing only in the case of PV inverters and PV trackers and their mounting structures. For all the rest of the PUCs analysed here (polysilicon, ingots, wafers, cells and modules), the EU falls considerably behind the target set.

Table 10. EU share of global 2040 production for specific Primarily Used Components (PUCs) for PV.

PUC	EU manufacturing capacity (GW_{DC})	*Number of factories*	2040 global annual deployment (GW_{DC})	2040 EU share in global manufacturing (%)
PV grade polysilicon	25		608	4
PV grade silicon ingots or equivalent	0		608	0
PV wafers or equivalent	0		608	0
PV cells or equivalent	2		608	0
Solar glass		*4*		
PV encapsulants		*5*		
PV ribbons		*4*		
PV backsheets		*12*		

PUC	**EU manufacturing capacity (GW_{DC})**	***Number of factories***	**2040 global annual deployment (GW_{DC})**	**2040 EU share in global manufacturing (%)**
PV connectors		*4*		
PV junction boxes		*6*		
PV modules	12		608	2
PV inverters	142		608	23
PV trackers and their mounting structures	121		353	34

Source: JRC analysis based on custom-made EU manufacturing dataset from Becquerel Institute and Global CETO 2°C scenario 2025

Depending on the source for PV annual installed capacity projections, the above presented 2040 EU share in global manufacturing can vary. According to the IEA Net-Zero Emissions (NZE) scenario (IEA, 2024b), the global annual deployment in 2040 is projected to be almost 900GW_p, which is about 50% higher as the global annual deployment of 608GW_p shown in Table 10. Nevertheless, the general trend remains identical, the EU's global shares in PV inverters and PV trackers and their mounting structures is over 15% and very low for the rest of the PUCs.

Assuming that the announced new and/or expansion manufacturing in the EU will be realised, the benchmark could be at 4% for wafers, 2% for cells and 5% for modules.

4.4. Resource efficiency and dependence in relation to EU competitiveness

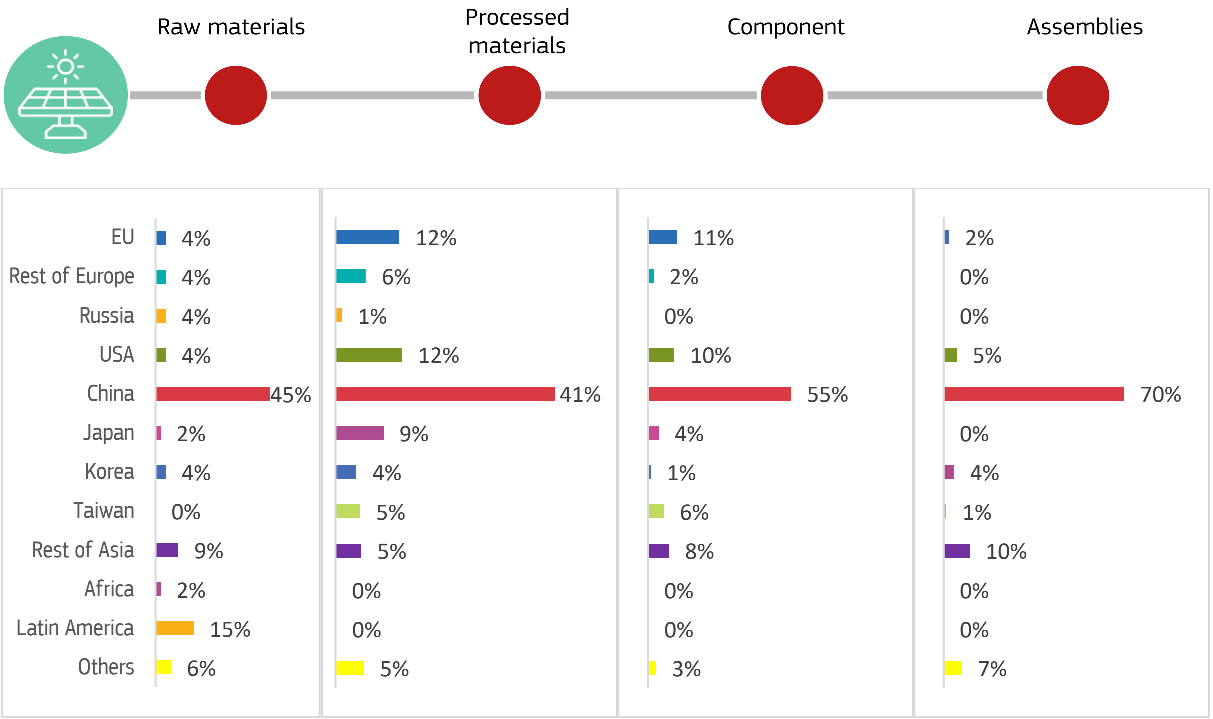
According to a previous JRC report on the PV supply chain analysis and as depicted in Figure 52, there is a significant supply risk along the whole supply chain, which is dominated by China (Carrara et al., 2023).

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 PV 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, 2023a), 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 and strategic materials used in the PV value chain must be taken seriously into consideration. A recent JRC study performed a risk analysis and raw material demand for PV manufacturing in the EU and globally based on material demand and PV deployment in the medium- and long-term. The results highlight a high supply risk for silicon (strategic and critical material) and a moderate supply risk for aluminium (critical material). The supply risk for silver and indium is relatively low and low respectively, whereas in the case of copper (strategic material), the supply risk is very low (Taylor et al., 2025)).

Figure 52. An overview of supply risks, bottlenecks, and key players along the supply chain of solar PV.



Source: (Carrara et al., 2023)

Based on specific deployment scenarios, technology mix and material usage, the ratios of annual quantity of above-mentioned materials used in EU installations to the 2020 EU production levels of them are high (up to 45% for silicon and silver, 25% for copper and between 85% and 190% for indium), reflecting the relatively low extraction and processing levels of these raw materials in the EU. However as almost all of the solar modules currently being installed in the EU are imported, supply of the raw materials for manufacturing is not a significant issue at present (Taylor et al., 2025).

However, keeping in mind the NZIA and the target of having 40% of the annual installations' components manufactured in the EU, for silicon, increasing production is likely to be limited more by economic factors than of material availability, although high quality quartz (primary raw material in this case) for silicon production may still be imported. For indium, increasing production may be more challenging (Taylor et al., 2025).

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 (European Commission, 2022b).

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 and still is. In 2022 the global cumulative PV installed capacity reached 1TW$_p$ and only two years later, in 2024, it exceeded the 2TW$_p$. According to projections, 3TW$_p$ could be accomplished at the end of 2025. 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, help reduce electricity prices and support the EU's energy security needs.

The average PV module efficiency of commercially available products has increased from 9.0% in 1980 to 22.6% in 2024. In the next few years, silicon-based PV technology (efficiency 25% and over) will remain the predominant technology. Looking ahead, perovskite technology (laboratory cell efficiency: 27.3 ± 0.6%, laboratory module efficiency: 19.2%) is developing rapidly and is a future alternative option to silicon with comparable costs, provided they overcome the challenges related to their stability and reliability. Other promising technologies with high efficiencies are silicon-based tandems with III-V top material (laboratory module efficiency: 32.65 ± 0.7%) and perovskite-silicon tandem devices (laboratory cell efficiency: 34.85%, laboratory module efficiency: 30.6%).

The global weighted-average LCoE for utility-scale projects fell by 87% between 2010 and 2024 from USD$_{2024}$ 417/MWh to USD$_{2024}$ 43/MWh and is foreseen to further decrease by 15% in 2030 and 40% in 2050. The Energy Payback Time (EPBT) of a rooftop PV system in Europe is approx. one year.

EU PV manufacturing companies are facing considerable competition, especially from Chinese companies. China is the largest market for PV systems. Most of the leading solar cell and module manufacturing companies are Chinese. The higher energy, environmental protection costs and labour costs (that can be however compensated with higher automation) in the EU and the very low prices and oversupply originating from China, have resulted in several EU manufacturing companies struggling with severe competition and ultimately arrive to bankruptcies.

The attempt to boost EU's domestic manufacturing capacities and rebuild its competitiveness in the global PV value chain through the NZIA, are encouraging, but do not adequately match the pace of the global market growth (projections refer to around 6TW$_p$ of PV installed capacity globally and around 720GW$_p$ 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 not least, the political interest and promotion for manufacturing expansion will play a significant role. Stable and reliable political and regulatory conditions are important factors to attract investors. It is imperative that EU Member States finally react fast now and commit to truly support the EU PV manufacturing by implementing firm policy measures. With the currently operational manufacturing capacity, the EU accomplishes both NZIA targets (at least 40% of the Union's 2030 annual deployment with domestically manufactured components and 15% share of 2040 global manufacturing) only for PV inverters and PV trackers and their mounting structures. In the case of ingots, wafers, cells and modules, the EU falls considerably behind. Some additional efforts are needed for polysilicon to boost domestic production.

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List of abbreviations and definitions

Abbreviations	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
EC	European Commission
EGD	European Green Deal
EPC	Engineering, Procurement and Construction
EPBT	Energy Payback Time
EROI	Energy Return On energy Invested
ETIP-PV	European Technology and Innovation Platform for Photovoltaics
EU	European Union
Extra-EU	Transactions with all countries outside of the European Union
FTE	Full-Time Equivalent
FWCI	Field Weighted Citation Impact
GDP	Gross Domestic Product
GVA	Gross Value Added
H2020	Horizon 2020 funding programme
IF	Innovation Fund
ITRPV	International Technology Roadmap for Photovoltaic
Intra-EU	Transactions within the European Union
IRENA	International Renewable Energy Agency
IWG	Implementation Working Group
JRC	Joint Research Centre
LCA	Life-Cycle Analysis
LCoE	Levelised Cost of Electricity
NZIA	Net Zero Industry Act

O&M	Operation and Maintenance
OPEX	Operational Expenditure
Prodcom	PRODuction COMmunautaire (Community Production)
PV	Photovoltaics
SET-Plan	Strategic Energy Technology Plan
SRIA	Strategic Research and Innovation Agenda
SRM	Strategic Raw Material
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
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
DC	Direct current
gCO_{2eq}	Grams of CO_2 equivalent
HJT	Heterojunction technology
mono c-Si	Mono-crystalline silicon
PERC	Passivated Emitter and Rear Contact
Pks	Perovskites
poly c-Si	Poly-crystalline Silicon
TOPCon	Tunnel Oxide Passivated Contact
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 overview and 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, IEA-PVPS, IEA, 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, Cordis, JRC
Value chain analysis	Turnover and Gross Value Added	IEA-PVPS, EurObserv'ER
	Environmental and socio-economic sustainability	Scientific publications, JRC, various
	Role of EU companies	Various
	Employment	IRENA, EurObserv'ER, SolarPower Europe, Fraunhofer ISE, scientific publications, IEA-PVPS
	Energy intensity and labour productivity	Scientific publications, various
	EU production	Prodcom, JRC
Global markets and EU positioning	Global market growth and growth prospects	IEA, Bloomberg NEF, SolarPower Europe, JRC, various
	EU trade (imports, exports) and trade balance	Comext, UN Comtrade, JRC
	Status of net zero technology systems and components in the EU	Becquerel Institute, JRC
	Resource efficiency and dependencies (in relation EU competiveness)	JRC, various

Annex 2 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 $51GW_{AC}$ 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 $51GW_p$ 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 $47GW_p$ for large scale systems. The total then is $98GW_p$.

- 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 $3.5GW_p$ 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.

Annex 3 Sustainability assessment framework (amendments)

The detailed explanation of Sustainability Assessment Framework (SAF) is available in the report "Proposal for a Sustainability Assessment Framework for energy technologies" (European Commission, 2023b), 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 PV. The complete SAF can be found in (Chatzipanagi et al., 2024). Below are reported the amendments for this year.

Sustainability aspect	**Method/approach**	**Indicators**	**Assessment of photovoltaics**	**Additional insights**
Climate change	LCA / Product Environmental Footprint (PEF)	Global warming potential (GWP100)	PV systems Regarding systems, an updated IEA PVPS study indicates that, through their lifetime, mono c-Si systems emit 35.8gCO_2/kWh, poly c-Si systems emit 43.6gCO_2/kWh, CIS systems emit 35.5gCO_2/kWh and CdTe systems emit 25.2gCO_2/kWh (Frischknecht & Krebs, 2021)[33]. PV modules In terms of technologies, thin-film modules have the lowest emissions, followed by poly c-Si and then mono c-Si. There is considerable scope to reduce these values, and projections for 2050 indicate that life cycle emissions for PV can drop to 10gCO_{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 10.8 and 44gCO_{2eq}/kWh and poly c-Si between 17.8 and 50.1gCO_{2eq}/kWh (Ardente et al., 2025).	

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[33] 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), 976 kWh/kW_p annual production, 1 331 kWh/m^2 in-plane irradiation, linear degradation 0.7% per year, service life: panel 30 years, inverter 15 years. Module efficiencies assumed: mono c-Si: 20.9 %, poly c-Si: 18 %, CIS: 17 % and CdTe: 18.4 %.

Sustainability aspect	Method/approach	Indicators	Assessment of photovoltaics	Additional insights
			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 7g/W_p in 2010 to 2.5g/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 30gCO_{2eq}/kWh (Müller et al., 2021).	

Annex 4 Energy System Models and Scenarios

Annex 4.1 POTEnCIA CETO 2025 Scenario

The *POTEnCIA CETO 2025 Scenario* has been generated with the Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA). Developed in-house by the European Commission's Joint Research Centre (JRC) to support EU policy analysis, POTEnCIA is an energy system simulation model designed to compare alternative pathways for the EU energy system. The core modelling approach of POTEnCIA (Mantzos et al., 2019) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method.

The technology projections provided in the *POTEnCIA CETO 2025 Scenario* 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 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 (RED) and of the Energy Efficiency Directive (EED). Similarly, the adoption of alternative powertrains and fuels in transport is consistent with the updated CO2 emission standards in road transport and with the targets of the ReFuelEU Aviation and FuelEU Maritime regulations.

Compared to the *POTEnCIA CETO 2024 Scenario* (Neuwahl et al., 2024), the *POTEnCIA CETO 2025 Scenario* incorporates many model enhancements and scenario-specific updates, most notably:

- The usage of the more recent JRC-IDEES 2023 data (Rózsai et al., 2025).
- Closer alignment to the National Energy and Climate Plans (NECPs) of the individual MS, which have been published in recent months.

A more detailed description of the *POTEnCIA CETO 2025 Scenario* will be available in the forthcoming report (Neuwahl et al., 2025).

Annex 4.2 CETO 2°C Scenario 2025

The *Global CETO 2°C Scenario 2025* has been generated by the global energy model *POLES-JRC* (Prospective Outlook for the Long-term Energy System).

POLES-JRC covers the entire global energy system with a high level of regional detail, encompassing 66 countries and regions, from primary supply (fossil fuels, renewables) to transformation (power, biofuels, hydrogen, and hydrogen-derived fuels, such as e-fuels and ammonia) and final consumption sectoral demand (industry, buildings, transport). International markets and energy fuel prices are calculated endogenously. The model comprises a comprehensive portfolio of technologies, with technology dynamics and interactions across sectors modelled using endogenous technology learning.

Detailed documentation of the *POLES-JRC* model is provided in (Després et al., 2018). Techno-economic assumptions used in the current version of the model are provided in (Schmitz et al., 2025). The latter report provides also a comprehensive overview of the dynamics and interaction of various clean energy technologies until the end of the century. POLES-JRC results are published in the annual "Global Climate and Energy Outlooks" (GECO) report, which provides detailed country energy and GHG balances, and an online visualisation interface.

The *Global CETO 2°C scenario 2025* 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. The *Global CETO 2°C scenario 2025* builds on the *POLES-JRC* model version used for GECO 2024 (Keramidas et al., 2025) and has been enhanced as following:

- Cost optimisation for electrolysers powered by renewables (PV, wind) has been implemented considering an over-sizing of renewable capacities and battery storage.
- Electrolyser investment costs have been increased reflecting recent literature revisions.
- Updated investment costs for renewable technologies and utility battery according to (IRENA, 2025) as well as updated installed capacities for power generating technologies.
- Revised global wind profiles (off-shore and on-shore).
- Updated data on new vehicles and vehicle stock by transport mode (battery and fuel cell vehicles, ICE, hybrid) and vehicle type (passenger cars, light and heavy trucks, buses).
- Updated hydrogen infrastructure cost related to road transport.

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