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

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Contents

Abstract

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

Foreword on the Clean Energy Technology Observatory

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

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

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

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

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

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

More details are available on the CETO web pages

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Executive Summary

Following the EU's commitment towards climate neutrality by 2050, the publication of the 6th Intergovernmental Panel on Climate Change (IPCC) Assessment Report in April 2022 combined with the geopolitical developments in 2022 accentuated the urgent need of the clean energy transition. To this end, in 2022, the European Commission presented the REPowerEU and the EU Solar Energy Strategy with the aim of reducing net emissions by at least 55 % by 2030 and more than 500 GW_p additional increase of the photovoltaic capacity by 2030. Furthermore, it proposed a target of 40 % participation of renewable energies in EU's energy mix in order to reduce net emissions by at least 55 % by 2030 through the "Fit for 55" package. In addition, the recently proposed Net-Zero Industry Act aims to set the required environment to scale up manufacturing of net-zero industry in the EU and face up to the future demand. The target set is for 30 GW_p of European manufacturing along the entire value chain by 2025 and 40 % of installed solar PV being manufactured within the continent by 2030.

Photovoltaics is the fastest-growing source of electricity production from renewable energies and a pillar for the EU's energy transition and the accomplishment of the European Green Deal (EGD).

The global cumulative PV installed capacity exceeded 1 TW_p in March 2022 and estimates for 2023 are above 1.5 TW_p. The EU alone reached a cumulative installed PV capacity over 211 GW_p at the end of 2022 and a cumulative electricity generation of 196 TWh from PV systems. The average PV module efficiency has increased from 9 % in 1980 to 14.7 % in 2010 and 21.1 % in 2022. Silicon-based photovoltaic technology remains the predominant technology (efficiency of 24 % and over) but research regarding performance, integration and sustainability is still essential. As far as thin-film technologies are concerned, the way forward for Copper Indium (Gallium) Selenide (CIGS) and Cadmium Telluride (CdTe) technologies is mass production to benefit from scaling effects by considering at the same time the supply of potentially critical materials for their production. Depending on the learning curve, perovskite module (module efficiency 18.6 %, record cell efficiency 24.35 ± 0.5 %) manufacturing could quickly achieve comparable costs compared to current technologies. Multi-junction technology, silicon-based tandems with III-V top material (32.65 ± 0.7 % module efficiency) together with perovskite-silicon tandem devices (28.6 % module efficiency for large area cells as required for module production) are the two most promising and efficient technologies.

Current technological advancement and market orientation are moving towards the replacement of Passivated Emitter and Rear Contact (PERC) architecture (~21 % module efficiency with projections reaching 23 % in 2033) by n-type Tunnel Oxide Passivated Contact (TOPCon) (22 % module efficiency with projections reaching 24 % in 2033) that will further increase efficiency. Bifacial modules are emerging in the market (increase of their current 35 % market share to 70 % in the next ten years). Ideal for applications that allow the absorption/exploitation of light from both sides of the module (front and rear), for different orientations and needs, like in the case of emerging innovative PV applications like agrivoltaics.

Solar PV costs have fallen significantly since 2010, mainly due to the large-scale manufacturing and also the intense Research & Development (R&D) efforts of the past decades and the significant amounts of funding. Both PV module prices and the Levelised Cost of Electricity (LCoE) have decreased considerably and further decreases are foreseen in the next years. The global weighted-average LCoE for utility-scale projects fell by 88 % between 2010 and 2022 from USD 0.417/kWh to USD 0.045/kWh. Projections for the EU indicate that in 2050 it will further decrease by approximately 60 % compared to 2020. The relevant regulatory and economic schemes, such as feed-in tariffs and minimum targets for generation from renewables in electricity systems, together with the above-mentioned cost reductions have rendered PV a competitive technology.

EU's public Research & Innovation (R&I) funding is not always reported for all member states and for this reason caution in the interpretation of the results is advised. EU's public Research & Innovation (R&I) funding in solar was approx. 30 % of the global public R&I funding solar in 2010 as well as in 2021. As far as public R&I funding in PV is concerned, in 2010 EU's funding was 35 % of the global public R&I funding and it grew to 62 % in 2021. The compound growth of public R&I funding on PV between 2010 and 2021 in the EU decreased by only 0.5 % whereas at a global level it decreased by 5 %. The EU's share in the global private Research & Development (R&D) funding in PV decreased from 15 % in 2010 to 13 % in 2019. EU's private R&D funding in PV suffered a compound decrease of 8 % in the period 2010-2019. The global private R&D funding in PV experienced a compound decrease of 6 %. The EU is in 4th position in terms of the total number of patents after China (1st), South Korea (2nd), and Japan (3rd) but ranks 1st in high-value patents above the United States (2nd) and the rest of the world (3rd). The publications regarding PV technologies, systems, and applications generated in the EU are found to be significantly fewer than those of other countries (mainly China) but significantly more highly-cited (as are also publications from the United States).

The Energy Payback Time (EPBT) of PV systems has experienced a 12.8 % decrease over the past 24 years. The EPBT of a PV system in Southern Europe is one year, whereas in Northern Europe less than a year and a half. Nonetheless, it is also important that the PV sector further reduces its environmental footprint and becomes more sustainable and circular along the entire PV value chain.

EU's PV estimated turnover increased from EUR 9 billion in 2015 to EUR 28 billion in 2021. The compound growth between 2015 and 2021 is estimated to be 21 % with the top five Member States (Germany, France, the Netherlands, Spain and Poland) accounting for 75 % of the EU's turnover in 2021. Germany together with the US, Japan, China and South Korea host almost 70 % of identified innovators. The EU as a total hosts 22 % of innovators in the field of PV. In particular, Germany holds the 4th position behind the US, China and Japan among the world's leading countries in terms of innovation. The EU has significantly increased job creation in PV in recent years mainly due to the large-scale deployment of PV systems, thus limited to the downstream and not the upstream value chain (i.e. manufacturing). The compound growth of PV employment in the EU is estimated to be around 35 % in the period between 2020 and 2022. Currently, PV employment in the EU is mainly in the downstream activities (deployment) but it is foreseen to increase also in the upstream activities (manufacturing) as the announced PV manufacturing expansions for 2025 will demand a significant amount of workforce. For 2027, jobs are expected to increase by 104 %, 79 %, 141 % and 153 % in the manufacturing, deployment, O&M and recycling activities respectively. Finding the needed workforce will be challenging and the appropriate actions must be taken at an early phase (skilling, re-skilling, up-skilling, etc.). As expected (due to their strong presence in both the downstream as well as the upstream value chain), at global level, the number of PV-related jobs created in China is more than 10 times higher than that of the EU.

Between 2011 and 2021, the compound decrease in production value in the EU was 10 %, slightly recovering from the EUR 1 474 million of production in 2020 to reach EUR 2 540 million in 2022. China has a leading market in PV and exhibits small dependence on the EU as far as imports are concerned. Almost all leading solar cell and module production companies are Chinese and they dominate the PV module shipments. In 2022, Chinese companies have produced 84 % of the total PV cells (crystalline and thin-film). The top five companies are Chinese and they account for 47 % of the global PV cell production in 2022. Regarding PV module (crystalline and thin-film) production in 2022, China accounted for 78 % of the global production. The top four companies are based in China and together accounted for 52 % of the global PV module production. Additionally, the costs for PV manufacturing in China are considerably lower than in Europe. According to a 2022 IEA report, costs in China are 10 % lower than in India, 20 % lower than in the United States, and 35 % lower than in Europe. The EU is aiming at strengthening its position in the global market with several manufacturing capacities being announced and realised in the next years. The planned expansions include all segments of the PV manufacturing value chain from polysilicon to wafer, cells and modules in different locations in the EU. In the inverter market, in the recent years, SMA (Germany) and Power Electronics (Spain) have grown less than other companies from China and therefore did not maintain the considerable market share they enjoyed until 2020. Together, the above-mentioned European companies accounted for 14 % in 2018 to 7 % in 2022. The EU as a total but also each member state (MS) individually exhibited a negative relative trade balance between 2019 and 2021. The EU's extra-EU imports have increased by 14 % between 2015 and 2021, while for the same period, its exports decreased by 6 %.

The EU is not directly affected by a high-risk supply of critical raw materials since, for now, it is importing final products and not the primary raw materials. However, taking into consideration the planned large-scale EU domestic PV manufacturing and the commitment to render EU competitive, raw materials supply may become crucially relevant in the short-term. The use of silver for connections has been identified as a potential concern due to the expected large-scale manufacturing activity in the next few years and therefore there is continuous R&D for the minimisation of silver use as well as raw materials substitution like copper. Particular attention is needed also regarding PV glass that is lacking in the EU and has to be imported, mainly from China.

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

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

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

Source: JRC 2023

1 Introduction

1.1 Scope and context

This report on photovoltaic (PV) energy is part of the annual series reports from the Clean Energy Technology Observatory (CETO) (European Commission, 2023a). It address technology maturity status, development and trends; value chain analysis and global market and European Union (EU) positioning, and builds on previous European Commission studies in this field (Taylor and Jaeger-Waldau, 2020; Chatzipanagi, Jaeger-Waldau, *et al.*, 2022).

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

The publication of the 6th Intergovernmental Panel on Climate Change (IPCC) Assessment Report in April 2022 (IPCC, 2022) and the geopolitical developments in 2022 have highlighted the urgency of the clean energy transition. The European Commission had reacted with the REPowerEU Communication (European Commission, 2022a) and the EU Solar Strategy Communication (European Commission, 2022a) in March and May 2022 respectively. REPowerEU aims to reduce net emissions by at least 55 % by 2030 and the EU Solar Strategy called for an additional photovoltaic capacity of over 500 GW_p between 2021 and 2030, which would mean a roughly fourfold increase of the nominal capacity to over 720 GW_p by 2030. As an intermediate step towards climate neutrality (European Green Deal) by 2050, in December 2020, the European leaders endorsed the Commission's proposed target to reduce net emissions by at least 55 % by 2030. Within the framework of the "Fit for 55" package (European Commission, 2022e) of EU legislative measures, in October 2023 the Council adopted the new Renewables Energy Directive (RED) to raise the share of renewable energy in the EU's overall energy consumption to 42.5 % by 2030 with an additional 2.5 % indicative top up to allow the target of 45 % to be achieved (European Council, 2023).

Furthermore, the recently proposed Net-Zero Industry Act aims to set the required environment to scale up manufacturing of net-zero industry in the EU. One of the identified strategic net-zero technologies is PV. A simplification of the regulatory framework (permitting) for the PV manufacturing and a skills development support are among the actions included in the Act that will help increase the EU PV competitiveness. The target is set so that by 2030, manufacturing capacity of the strategic net-zero technologies (as defined in the NZIA) in the EU approaches or reaches a benchmark of at least 40 % of the EU's annual deployment needs for the corresponding technologies necessary to achieve the EU's 2030 climate and energy targets (European Commission, 2023b). In addition, the European Commission endorsed the creation of the European Solar PV Industry Alliance (ESIA) (European Commission, 2023d) that will support the above-mentioned objectives and policies that will result in scaling-up and speeding-up the production of renewable energy in Europe with the aim of regaining its independence from Russian fossil fuels, and making its energy system more resilient. The ESIA aims to expand EU's manufacturing to at least 30 GW_p across the full supply chain by 2030 (European Commission, 2023b, 2023d).

Globally, new PV capacity increased by about 40 % to over 230 GW_p in 2022, which is at the lower end of the conservative (228 GW_p) and optimistic forecasts (252 GW_p). For 2023, market forecasts are considerably higher, with an annual new installed capacity estimates above 300 GW, which would bring the total cumulative installed PV capacity to exceed 1.5 TW_p (Jäger-Waldau, 2023). In 2022, the photovoltaic market in the EU grew by over one third to more than 40 GW_p and reached a cumulative installed capacity of over 211 GW_p. Compared to 2022, the Solar Strategy would require an annual market volume increase to over 100 GW_p annually by 2030, which is achievable if the current market trend can be maintained (Chatzipanagi and Jaeger-Waldau, 2023).

1.2 Methodology and Data Sources

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

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

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

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

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

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

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

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

The report uses the following information sources:

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

Details of specific sources can be found in the corresponding sections and Annex 1 provides a summary of the indicators for each aspect, together with the main data sources.

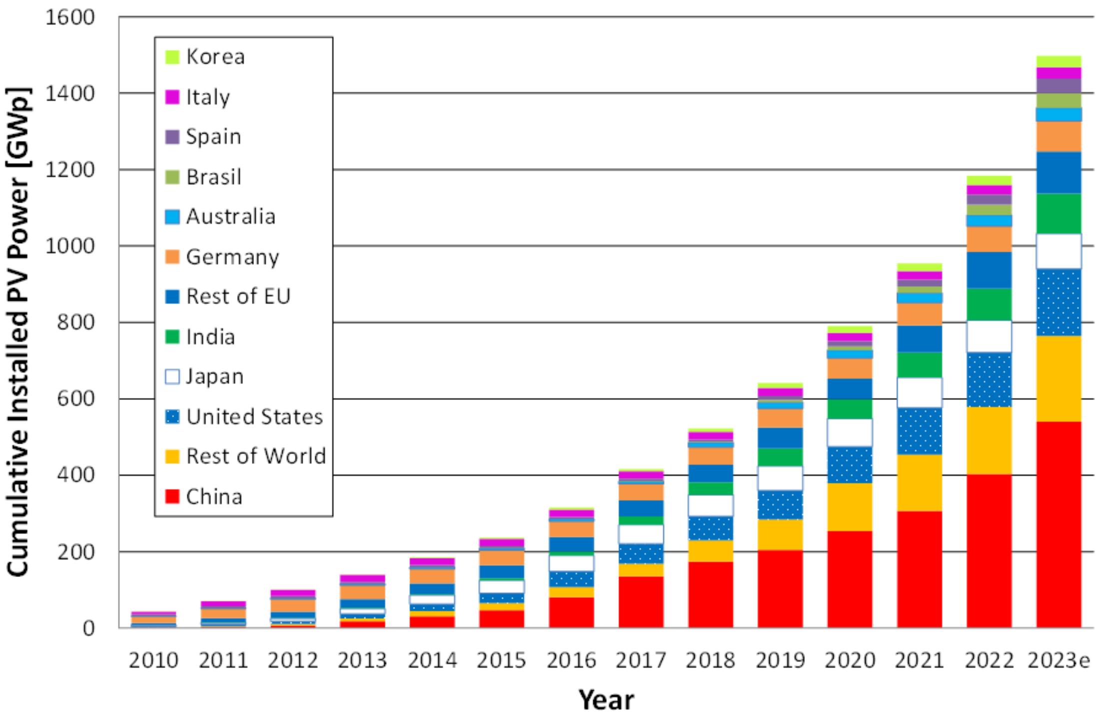
2 Technology status and development trends

2.1 Technology readiness level

The global compound annual growth rate (CAGR) of PV installations was 26 % in the period 2012 to 2022. In 2022, overall investments in renewable energy have increased by 16 % to USD 499 billion (Bloomberg New Energy Finance, 2023b). Over the same period, investments in photovoltaics increased by 47 % and accounted for USD 301.5 billion or 60 % of the renewable energy investment.

New PV capacity increased by about 40 % to over 230 GW_p in 2022, which is at the lower end of the conservative (228 GW_p) and optimistic forecasts (252 GW_p) (Bloomberg New Energy Finance, 2023a; TrendForce, 2023). For 2023, market forecasts are considerably higher, with an annual new installed capacity estimates above 300 GW_p, which would bring the total cumulative installed PV capacity over 1.5 TW_p. China has a cumulative installed capacity of more than 400 GW_p, representing roughly one third of the total global 1 185 GW_p installed PV capacity. The European Union follows with about 18 % or 211 GW_p and the United States with over 142 GW_p (12 %) (Figure 1). At the end of 2022, 24 countries globally and 12 in the EU installed more than 1 GW_p (IEA-PVPS, 2023b).

Figure 1. Global cumulative photovoltaic installations from 2010 to 2022 with an estimate for 2023.



Source: (Jäger-Waldau, 2023)

The EU is a leading installer of PV per capita with 475 W_p/capita on average, having six EU Member States in the first 10 countries in this ranking (SolarPower Europe, 2022c). Australia is the country with the highest capacity per capita (1 168W_p/capita), followed by the Netherlands with 1 051W_p/capita and Germany with 800W_p/capita (Chatzipanagi and Jaeger-Waldau, 2023).

This growth is due to the decreasing cost of the PV modules and systems (EUR/W_p), and the increasingly competitive cost of the electricity generated (in EUR/MWh). Analysing the global evolution of module price vs cumulative production, the Learning Curve suggests a price decrease of 25 % for each doubling of cumulative production in the last 40 years (Fraunhofer ISE, 2023).

In Germany, at the end of 2020 the price for a typical 10 to 100kW_p PV rooftop system is only 7.4 % of the price in 1990, thus a net-price regression of about 92 % in 30 years (Fraunhofer ISE, 2023).

The 2017 PV Implementation Plan is currently being under revision by the Strategic Energy Technology Plan (SET-Plan) Implementation Working Group (IWG) on Photovoltaics. The updated and renewed 2023 Implementation Plan, expected shortly (IWG PV-Implementation Working Group on Photovoltaics, 2023), adopts the challenges and corresponding targets and R&I topics from the 2022 ETIP-PV SRIA (SNETP, 2022). This will contribute to a common understanding of PV R&I priorities at European and Member State levels and facilitate the alignment of R&I and cross-border collaboration aimed for.

2.1.1 Photovoltaic (PV) module technologies

According to the International Technology Roadmap for Photovoltaic (ITRPV) 14th edition (VDMA, 2023), the yearly learning for module efficiency for the past 12 years is presented in Table 2.

Table 2. Yearly average module efficiencies for the period 2010-2022.

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Aver. module efficiency [%]	14.7	15.2	15.4	16.0	16.3	17.0	17.5	17.7	18.4	19.2	20.0	20.9	21.1

Source: (VDMA, 2023)

The above-mentioned module efficiencies, between 2010 and 2019, were calculated, based on average module powers of p-type polycrystalline (poly c-Si) and monocrystalline (mono c-Si) silicon modules reported by ITRPV (3rd to 11th edition) for a standardised module size of about 1.64m2 with 60 cells. After 2019 an average module area of 1.7m2 is considered. Average module efficiencies for Passivated Emitter and Rear Contact (PERC) modules in 2020 and 2021 are assumed to be 20 % based on the ITRPV 12th edition and 20.9 % respectively. For a better comprehension of the evolution of PV module efficiencies, the 1980 average PV module efficiency is reported to be 9 % (VDMA, 2023).

Crystalline silicon

The crystalline silicon technology accounts for 95 % (350 GW_p) of global PV module production (Jäger-Waldau, 2023). Of these, monocrystalline (mono c-Si) modules almost monopolise the crystalline market as polycrystalline (poly c-Si) modules have reduced their market share to less than 5 % (VDMA, 2023). The record efficiency of mono c-Si and poly c-Si cells is 26.1 % (ISFH, p-type rear IBC) (NREL, 2023) and 23.3 % (Jinko Solar, n-type) (Green *et al.*, 2023) respectively, whereas the efficiency of the modules is 24.7 % (Maxeon (112 cells)) for the mono c-Si and 20.4 % (Hanwha Q cells (60 cells)) for the poly c-Si (Green *et al.*, 2023). The efficiency of average commercial wafer-based silicon modules increased from 15 % to over 20 % over the last 10 years (Fraunhofer ISE, 2023). 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.*, 2023).

The European Strategic Research and Innovation Agenda for PV (SRIA) (SNETP, 2022) identifies that further R&D support in the EU in the field of silicon PV technology is needed and it should aim at the ultimate objective of achieving multi-GW_p of silicon cell and module manufacturing capability with low carbon footprint and circularity in the EU, further lowering the Levelized Cost of Electricity (LCoE) of both utility-scale PV and integrated PV and maintaining and reinforcing EU's leading position in silicon PV technology in terms of high performance and lower costs, while at the same time achieving sustainability and integration in the environment.

Research and innovation regarding performance, integration and sustainability are still essential in order to reach large-scale deployment. This also includes high-efficiency silicon technology being used for multi-junction devices (efficiencies may reach 30 % for hybrid tandems and 40 % for multi-junctions[1]).

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

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

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

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

Source: (SNETP, 2022)

Thin-film

The thin-film share of global production is only 5 % corresponding to 7.8 GW_p of the total PV module global production. Of these 7.8 GW_p, 78 % is CdTe, 19 % CIGS and 3 % is amorphous silicon. The record cell efficiencies of CdTe and CIGS are 22.3 % (First Solar) and 23.6 % (Evolar/Uppsala) respectively and for the modules, CdTe modules exhibit an efficiency of 19.5 % (First Solar) and CIGS 19.2 % (Solar Frontier (70 cells)) (Green *et al.*, 2023). The CdTe module efficiency has increased from 9 % to 19 % in the last 10 years (Fraunhofer ISE, 2023).

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

The technology targets and research priorities for the thin-film PV modules as they were identified in SRIA (SNETP, 2022) are presented in Figure 3.

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

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

Source: (SNETP, 2022)

Perovskites

Perovskites (Pks) are currently a very promising thin-film technology and for this reason, justify a separate treatment within this report. Perovskites' power conversion efficiency in a single-junction cell has increased from 3.8 % at their discovery in 2009 to an impressive 24.35 ± 0.5 % (NUS/SERIS) in 2023 whereas the perovskite module record efficiency is 18.6 % (UtmoLight (39 cells)) (Green *et al.*, 2023). It is expected that module efficiencies will be comparable to current existing PV technologies within the next 5 years.

The EU has remarkable expertise in perovskite PV modules and may be considered a leader. At the moment, several companies are starting pilot lines of production. Some of these companies, reported in (SNETP, 2022), are Evolar (focusing on semi-transparent perovskite on glass as an upgrade for existing PV modules like crystalline or CIGS with the 4-terminal approach, where current PV module top glass can be replaced by a glass containing the semi-transparent Pk-PV module), Saule Technologies (focusing on flexible Pk-PV made by ink jet printing, with sheet-to-sheet processes today, but with the intention of moving to roll-to-roll production) and Solaronix (producing opaque Pk-PV on glass).

China is also a producer of this technology. Active companies are Microquanta, GCL, UtmoLight, Trina and Boamax. At the end of 2022, Microquanta built a 20 MW perovskite pilot line capacity Quzhou, Zhejiang and the world's first 100 MW perovskite production line was completed and put into operation in the beginning of 2022 (Asiachem, 2022). GCL New Energy has a 10 MW_p line (soon to be joined by a 100 MW_p pilot line) producing semi-transparent and hence bifacial perovskite modules with non-certified efficiencies of 16 % on 40 x 60 cm^2 glass. The company has plans for a 1 GW_p production line (SNETP, 2022). UtmoLight has a trial production line of a 150 MW perovskite module production line and in early 2023 started constructing its GW production line in Wuxi (Asiachem, 2022).

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

The technology targets and research priorities for the perovskite PV modules as they were identified in SRIA (SNETP, 2022) are presented in Figure 4.

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

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

Source: (SNETP, 2022)

Multi-junction

The multi-junction technology consists in incorporating multiple p-n junctions made of different semiconductor materials within the same cell. This technology allows reaching the highest efficiency levels among all technologies. The silicon-based tandems with III-V top material are the most efficient technology, with a record efficiency of 38.8 % for a 5 junction cell (NREL, Spectrolab, 2-terminal, (2.17/1.68/1.40/1.06/.73 eV)) and 32.65 ± 0.7 % for a module (Sharp, 40 cells; 8 series, InGaP/GaAs/InGaAs) (Green et al., 2023).

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 33.7 % (KAUST, 2-terminal) while the record efficiency for large area cells as required for module production is 28.6 % (Oxford PV, 2-terminal) (Green *et al.*, 2023).

According to SRIA, tandem technologies should reach a market share of more than 5 % while successfully transitioning from niche to mass market applications by 2030 (starting with significant market shares in 2026 (VDMA, 2023)). The technology targets and research priorities for multi-junction PV modules as they were identified in SRIA (SNETP, 2022) are presented in Figure 5.

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

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

Source: (SNETP, 2022)

Bifacial modules[2] represent another field of technological advances. Even though they have been in the market for many years now, they have recently attracted increased interest. They are used for ground-mounted applications with or without a tracker but can also be vertically mounted. Silicon heterojunctions (HJT) and Tunnel Oxide Passivated Contact (TOPCon) modules can reach considerably higher bifaciality[3] than p-type Passivated Emitter and Rear Contact (PERC). Bifacial technology is expected to increase its market share from 35 % today to 70 % in the next ten years (VDMA, 2023). Rear contact of modules represent another major advance (Wilson *et al.*, 2020). With PERC modules being near their upper-efficiency limit (currently 21 % efficiency with projections reaching almost 23 % in 2033), the industry is investing in n-type technology with major manufacturers switching to TOPCon (currently 22 % efficiency with projections reaching 24 % in 2033) and HJT technologies (currently 22.5 % efficiency with projections reaching 24 % in 2033) (VDMA, 2023). Silicon based tandem cells and modules (with efficiencies of 26 %) will start mass production in 2027 and their expected efficiency will reach levels of over 27 % in 2033 (VDMA, 2023). The n-type TOPCon manufacturing capacity already increased considerably in 2021 and projections suggest that it will become the dominant technology by 2033 with a 60 % market share, from the 15 % in 2023 (VDMA, 2023). HJT technology (current market share of 7 %) will increase its market share to 20 % in 2033. Silicon based tandem and back contact (p and n-type) will represent 5 % of the market each (VDMA, 2023). PERC technology with a market share of more than 70 % in 2023, will remain dominant until 2025 and will eventually reduce its market share to approx. 10 % in 2033 (VDMA, 2023).

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

2.1.2 Emerging innovative PV deployment applications

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

In 2022 the dominant PV application was traditional power plants with a 65 % share of the applications market, followed by rooftop applications (approx. 33 %). Building integrated photovoltaics, agrivoltaics and floating photovoltaics accounted for only 2 % all together (VDMA, 2023). The 2022 International Technology Roadmap for Photovoltaic reports a projected small decrease of traditional power plants and rooftop applications (55 % and 30 % respectively) in favour of the building integrated photovoltaics, agrivoltaics and floating photovoltaics that will account for 5 % each in the applications market in 2033 (VDMA, 2023). PV in residential and commercial buildings are expected to make up half of PV installations globally until 2050 (SNETP, 2022).

Agrivoltaics

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

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

[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.

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

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

Building integrated photovoltaics

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

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

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

Floating photovoltaics

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

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

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

Infrastructure integrated photovoltaics

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

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

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

Vehicle integrated photovoltaics

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

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

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

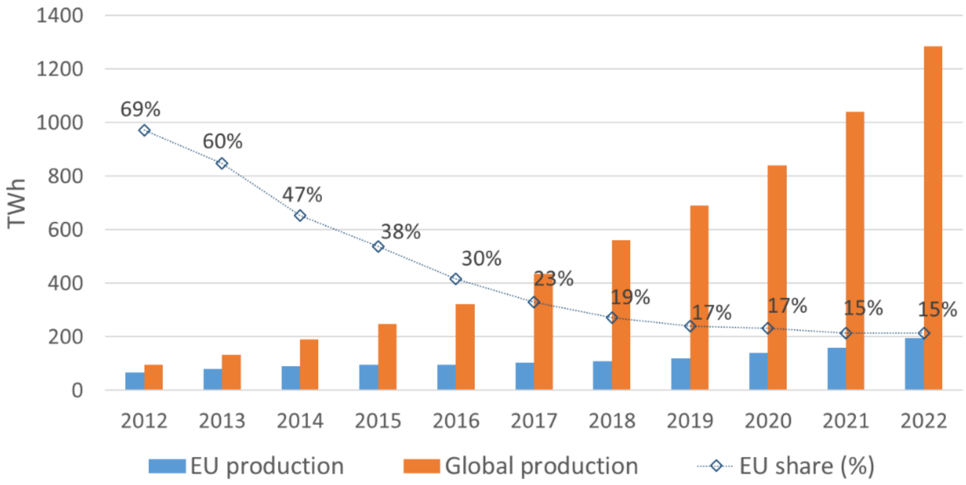
2.2 Installed Capacity and Production

Proper and straightforward comparisons are not possible as there are several factors (IEA-PVPS, 2023a; Jäger-Waldau, 2023) impacting these statistics (Box 1).

As depicted in Figure 6, the global cumulative PV electricity production increased from 96 TWh in 2012 to 1 283 TWh in 2022 (EMBER, 2023), presenting a compound annual growth rate (CAGR) of 30 %. The EU generated approximately 66 TWh from PV in 2012, corresponding to a share of 69 % of the global PV electricity production. From 2012 to 2022, the EU's share decreased gradually to 15 % of the global cumulative PV electricity production, with a cumulative EU PV electricity production of 196 TWh in 2022. China, on the other hand, increased its share in global PV electricity production from 1 % in 2012 (3.6 TWh) to 33 % (418 TWh) in 2022.

A bit less than three-quarters of the EU's cumulative PV electricity in 2021 (70 %) was produced in only four of the twenty-seven countries. These are Germany, Spain, Italy and France (Figure 7). The same countries, in 2012 produced over 90 % of the EU's cumulative PV electricity. The countries with the highest CAGR between 2012 and 2022 are Poland, Hungary and Romania. The Member State (MS) and world countries coding can be found in Annex 2.

Figure 6. Global and EU cumulative PV electricity production with EU share for the period 2012-2022.



Source: JRC analysis based on Eurostat, IRENA and Ember

Box 1. Uncertainty in reported capacity numbers.

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

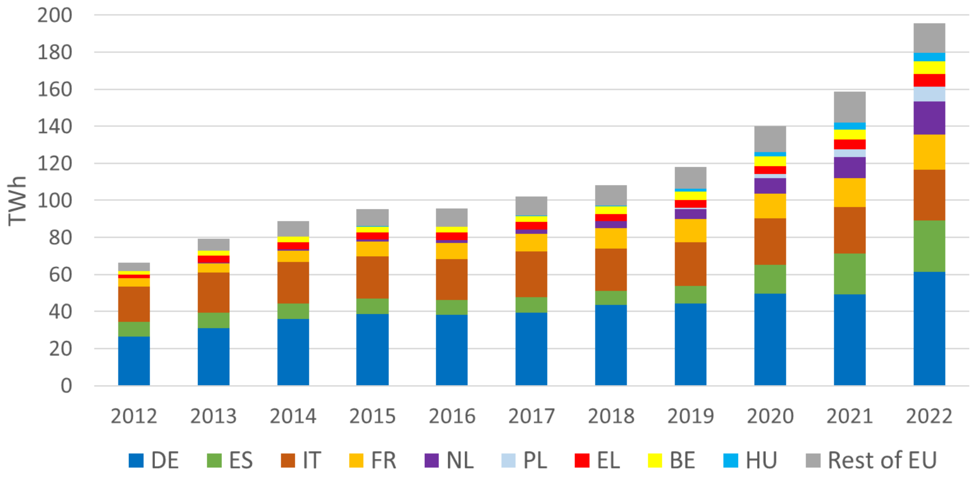
  Looking at energy scenarios, energy modellers are only interested in AC capacity, since the electricity network is AC. Therefore, significant differences can exist in the actual needed nominal power of PV systems, which determines the number of modules needed, and the modelled network capacity.

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

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

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

Figure 7. EU PV cumulative electricity generation per country for the period 2012-2022.

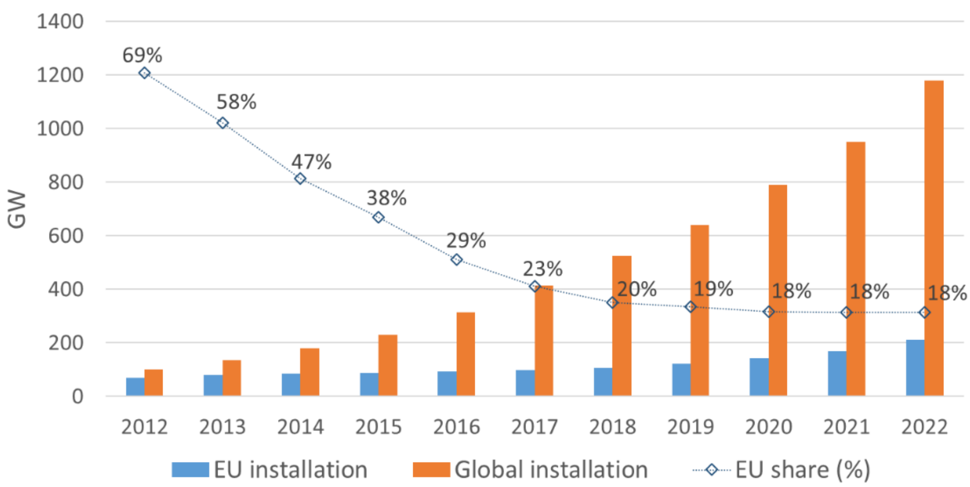


Source: JRC analysis based on Eurostat

The approx. 200 TWh of generated electricity from solar in the EU contributed to the avoidance of €10 billion in gas costs (Jones, 2023) in 2022. The share of solar electricity generation in the EU's electricity mix increased from 2.5 % in 2012, to 5 % in 2020 and 8 % in 2022. The respective percentage for the world increased from 0.4 % to 3 % and to 4.5 % (EMBER, 2023). The share of solar in electricity production increased in twenty EU countries. The country with the highest share of solar electricity generation is Luxembourg (20 % in 2022), whereas the country with the highest increase of solar electricity generation between 2020 and 2022 is the Netherlands (from 7 % to 14.5 % of solar electricity generation in the respective years).

Regarding the cumulative PV installed capacity[4], the EU had installed 69 GW_p in 2012, which grew to 212 GW_p in 2022, while globally 100 GW_p and 1 180 GW_p had been installed in these respective years. This means that the EU's share in global PV installed capacity decreased from 69 % in 2012 to 18 % in 2022 (Figure 8). China increased its share from only 4 % in 2012 to 35 % in 2022. EU's and China's CAGR between 2012 and 2022 are 12 % and 23 % respectively. In 2022, 48 % of new capacity installation globally was on rooftops (IEA-PVPS, 2023a). The estimated PV installed capacity in 2023 is over 1 500 GW_p (Jäger-Waldau, 2023).

Figure 8. Cumulative global and EU PV installed capacity with EU share for the period 2012-2022.



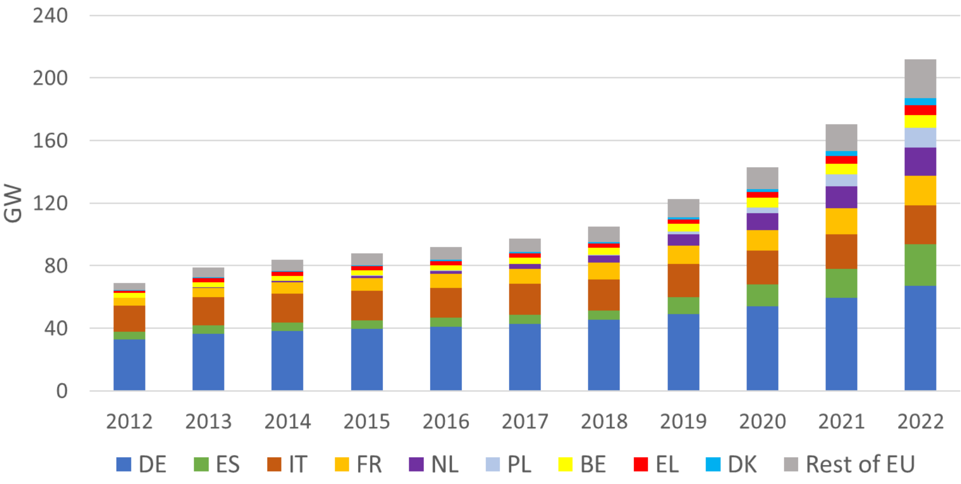
Source: JRC analysis based on (Jäger-Waldau, 2023)

Figure 9 shows the evolution of the EU's cumulative PV installed capacity from 2012 until 2022 per country. The countries contributing less to the EU installed capacity are shown as rest of EU. At EU level, Germany, Spain,

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

Italy, and France installed 65 % of the total EU installed capacity in 2022 from 68 % in 2021 and 86 % in 2012.

Figure 9. EU PV cumulative installed capacity per country for the period 2012-2022.



Source: JRC analysis based on (Jäger-Waldau, 2023)

In 2016, the share of rooftop installations was 80 % and the remaining was for utility-scale. Since then, the growth of utility-scale installations was more prominent but still, in 2022, rooftop installations make up for 60 % of the total installations. Distributed systems in 2016 represented 61 % of the total number of systems in Europe, with centralised systems at a 39 % share. In 2022, distributed systems decreased their share to 55 % and centralised systems conquered an additional 6 %, arriving at 45 %. The global situation in 2016 was notably different as distributed systems were only 27 % of the total systems but increased to 49 % in 2022.

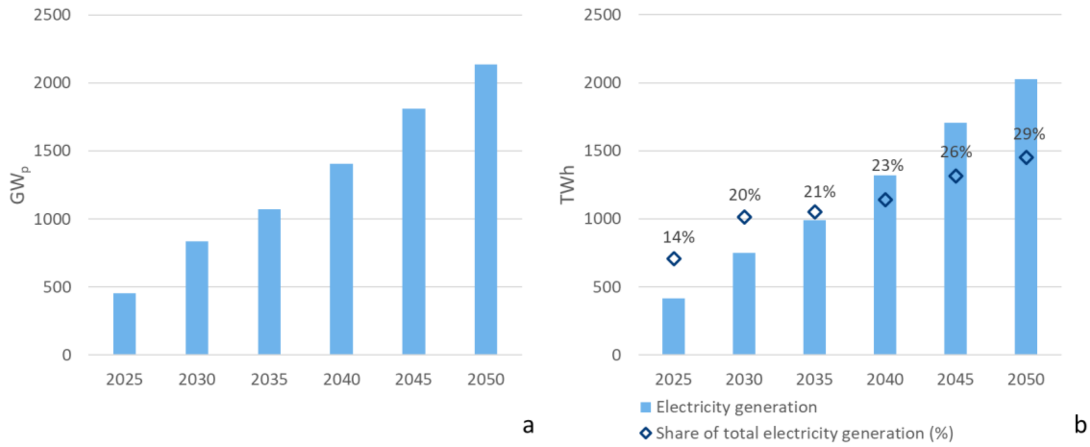
SolarPower Europe (SPE) is reporting a cumulative EU capacity of 209 GW_p in 2022 (SolarPower Europe, 2022a). According to SPE's low and high scenarios, the cumulative PV installed capacity in the EU in 2026 will be between 417 GW_p and 591 GW_p (SolarPower Europe, 2022a). In 2030 according to the business-as-usual scenario, the PV capacity will reach 672 GW_p and according to the accelerated scenario, it will exceed 1 TW_p, by also taking into consideration the current geopolitical risks (SolarPower Europe, 2022d). The ambition for 2050 is to reach 7-8.8 TW_p of PV installed capacity and 10-12 TWh of PV electricity production (Manish *et al.*, 2020). Others project an installed capacity of 500 GW_p by 2030 (EurObserv'ER, 2022b).

Regarding the projections for the global cumulative PV installed capacity, the IEA holds a conservative position that does not exceed 1.6 TW_{AC} in 2024 due to the assumption of rather low capacity additions in 2023 and 2024 (IEA, 2023b). By 2027, IEA projects that the global cumulative PV installed capacity will be between 2.4 TW_{AC} and 2.7 TW_{AC} (IEA, 2023c). On the other hand, SPE projects 2.4 TW_p by 2025, 2.9 TW_p by 2026 and 3.5 TW_p by 2027 for a medium scenario. According to the high scenario, 2 TW_p can be exceeded already in 2024 and the global cumulative PV installed capacity can reach almost 4 TW_p in 2027 (SolarPower Europe, 2023c). Beyond 2027, 22 TW_p are projected in 2050 for the base growth scenario and over 60 TW_p for the fast growth scenario (Vartiainen *et al.*, 2020).

The JRC projections for EU and global PV installed capacity and electricity generation are based on the POTEnCIA (for the EU) and POLES-JRC (for the world) models. Annex 3 includes the energy system models and scenarios used in the models.

As far as the EU is concerned (Figure 10), the POTEnCIA model is in accordance with SPE for the short-term projections, i.e. 2030 with 834 GW_p of installed PV capacity. For the long-term projections, the model output is in the order of 2 TW_p.

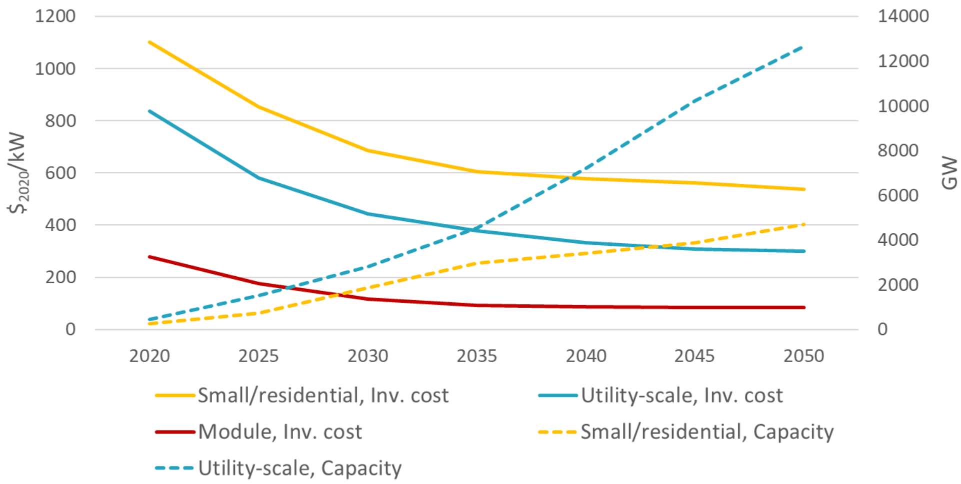
Figure 10. Projections of gross installed capacity and electricity generation in the EU until 2050.



Source: JRC POTEnCIA model

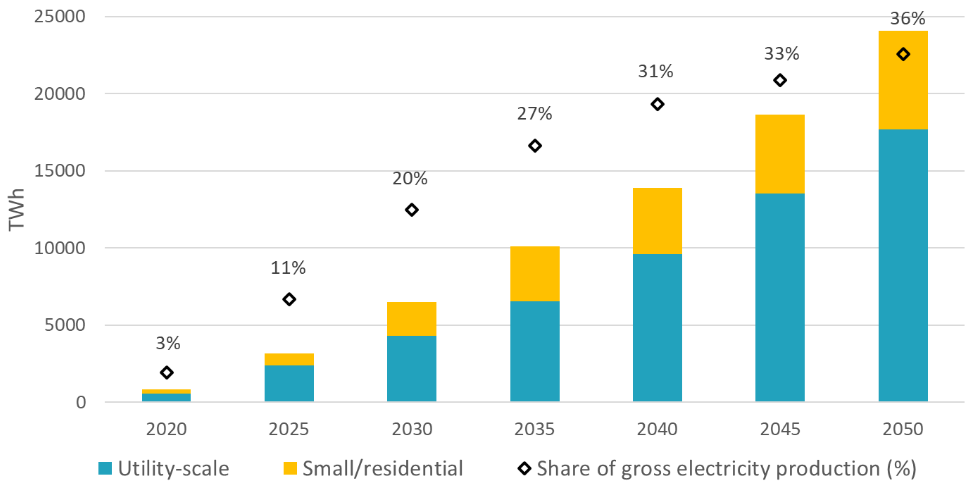
The global installed PV capacity and the electricity generation projections until 2050, based on the POLES-JRC model, are presented in Figure 11 and Figure 12 respectively. Based on the reduction of the investment costs for both small/residential and utility-scale projects as well as for modules (Figure 11), the projections of POLES-JRC model for the global PV installed capacity are in line with the projections of SPE for 2025 and 2030. For the long-term projections (2050), the global installed PV capacity is foreseen to be at 17 TW_p, 5 TW_p lower compared to the base growth scenario of the previous mentioned studies (Vartiainen *et al.*, 2020).

Figure 11. Global overnight investment cost and gross capacity for small/residential and utility-scale.



Source: JRC POLES-JRC model

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



Source: JRC POLES-JRC model

However, the dynamics of the PV sector are not entirely captured by the above projections. According to Bloomberg, this year, the installation at global level will grow by 56 % and as a result, the projected installed capacity in 2030 will exceed 5.8 TW_p (Bloomberg, 2023).

2.3 Technology Costs

Since 2010, the reduction of solar PV systems cost has been remarkable. Between 2010 and 2020, the cost of residential, commercial rooftop and utility-scale PV systems decreased by 64 %, 69 % and 82 % respectively (Feldman *et al.*, 2021). This is due to significant technology improvements made possible by the intense R&D efforts of the past decades combined with the industrialisation of the manufacturing process and massive expansion of the market. These developments were fostered by the introduction of public support schemes like feed-in tariffs or minimum targets for renewable electricity generation, combined with the introduction of relevant regulatory frameworks to enable the integration of renewable energy sources in the electricity system (IRENA, 2020a). The above-mentioned measures promoted PV awareness and acceptance thus acting as indirect influencing parameters that increased PV deployment hence also the demand for PV production.

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

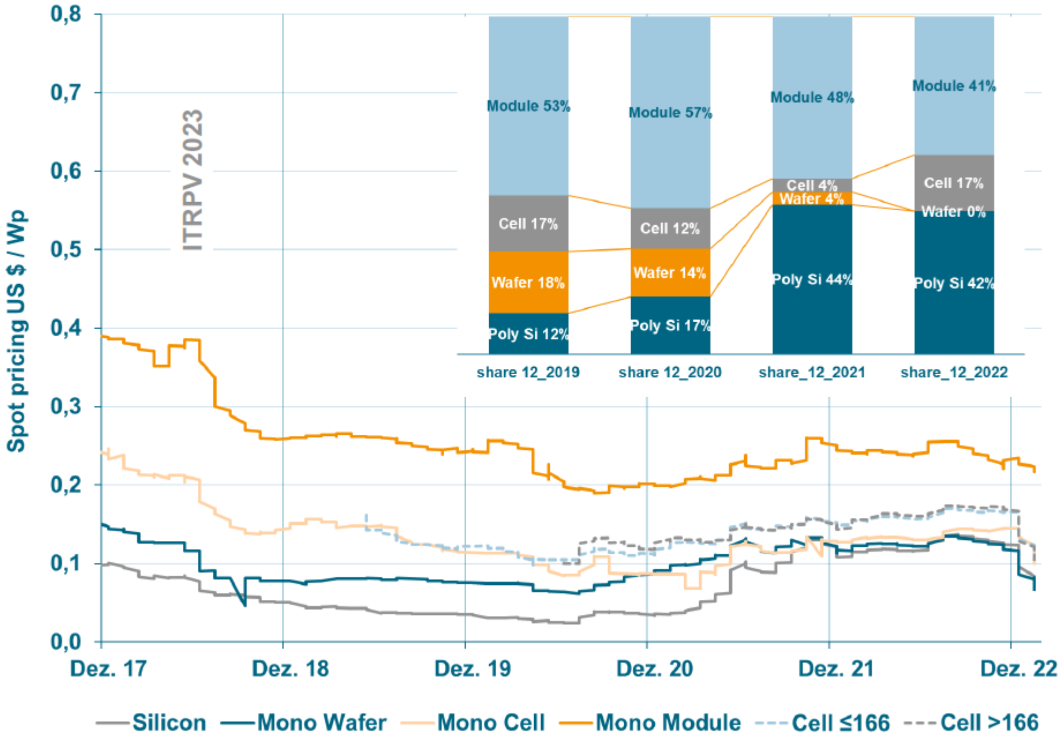
CAPEX

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

In 2022, the PV modules and the mounting /structural BoS (including labour and equipment) make up for 65 % of the total cost while the soft costs account for the remaining 36 %. (VDMA, 2023).

The reduction in PV module prices has been remarkable. In the past 41 years, there is a 25 % decrease in module prices following each doubling of cumulative PV module production (Fraunhofer ISE, 2023). Between 2012 and 2022 the price of c-Si modules decreased by 80 % while the global cumulative installed capacity increased by more than 1 TW_{AC} reaching 1.2 TW_{AC} in the same period (IRENA, 2022). Between 2021 and 2022 only, c-Si module prices went down by 7 % (VDMA, 2023). Figure 13 presents the different cost attributions to the overall module price. The bottom line of the figure represents the absolute spot price, while the stacked representation at the upper right corner presents the share of each attribution.

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



Source: (VDMA, 2023)

The PV module price reduction is mainly due to the higher efficiencies achieved over years, *i.e.* less active area needed for the same wattage production. The land area requirement has decreased as well from 2.7 hectares/megawatt (MW_{AC}) in 2010 to 1.9 ha/MW_{AC} in 2020 (IRENA, 2020c). Further land requirement reductions may be achieved with the application of bifacial modules that exploit both sides for the conversion of light into electricity in applications like agrivoltaics, floating photovoltaics, infrastructure integrated photovoltaics and building integrated photovoltaics. These applications enable the production of electricity without changing the land use and without competing with other activities such as agriculture in the case of agrivoltaics.

As seen also in Figure 13, module prices are directly influenced by the polysilicon price as it is an essential raw material in the PV manufacturing sector. The increase of polysilicon price has influenced module prices as well. After a particularly low price in July 2020 (USD 6.8/kg), polysilicon shortage in 2021 and 2022 caused significant price increases. The peak polysilicon price was met in December 2022 (USD 37/kg) and then prices started decreasing during 2023, reaching a USD 9/kg price in June 2023 (slightly higher than the January 2021 price) (Bernreuter Research, 2023c). Accordingly, module prices have experienced a similar price increase from EUR 0.22/W_p in July 2020 to EUR 0.35/W_p in October 2022 and ultimately a decrease to EUR 0.22/W_p in September 2023 (PVxchange, 2023). Polysilicon prices are expected to keep dropping due to oversupply (several manufacturers increased their capacities and new players, attracted by the rising demand for PV, entered the sector) until they reach a USD 7/kg bottom (Bernreuter Research, 2023d).

The prices for the different PV module categories, in September 2023 for the EU are presented in Table 3.

Previous research, conducted by IRENA, has shown that the total installed costs are higher in Japan due to the higher costs mainly in installation. The United States experiences similar contributions of hardware and soft costs but have significantly lower installation costs, resulting in total installed costs of about 37 % lower than in Japan. India and China demonstrate total installed costs that are lower by approx. 65 % than Japan. India in particular has the lowest installation costs and soft costs (IRENA, 2022). At EU level, Ireland is the country with the highest total installed cost due to high installation costs as well as soft costs. The Netherlands have similar total installed costs, mainly due to hardware costs related to grid connection, cabling/wiring, safety and security and monitoring and control rather than modules and inverter. Spain and France have approx. 25 % lower total installed costs compared to Ireland. Germany has the lowest costs in the EU, 34 % lower than Ireland (IRENA, 2022).

Table 3. EU spot market module prices by technology in September 2023.

PV module technology	EUR/W_p
High efficiency[5]	0.31 *0.43 (September 2022)*
Mainstream[6]	0.22 *0.34 (September 2022)*
Low cost[7]	0.14 *0.21 (September 2022)*

Source: (PVxchange, 2023)

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

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

Soft costs[8] are varying significantly depending on the country. Utility-scale PV systems in the United States were close to USD 0.50/W_{DC} (around USD 0.09/W_{DC} higher than in the EU and Asia) (VDMA, 2023).

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

In 2022, the capital cost for a utility-scale PV system is estimated at USD 770/kW_{DC} in the EU, USD 705/kW_{DC} in the Asia and USD 1 410/kW_{DC} in the United States. An estimated worldwide average for 2022 is at USD 966/kW_{DC} (VDMA, 2023).

According to projections, the global median price of modules will decrease from USD 0.32/W_p in 2022 to USD 0.18/W_p in 2032(VDMA, 2023). As far as inverters are concerned, no significant cost reductions are expected in the next ten years impacting the total capital cost of the PV systems (Figure 14). Capital cost reductions will be in the range of 35 % and will effectively be a result of module price and soft costs reductions. Projections for worldwide average utility-scale system costs suggested USD 608/kW_{DC} in 2033 (VDMA, 2023).

Other work regarding the projected capital cost in Europe is shown in Figure 15. For rooftop installations, the capital costs may fall to an average value of EUR 0.8/W_p in 2030 from approximately EUR 1.1/W_p in 2020, while the projection for 2050 is a compound average decrease of 6 % over the 2020-2050 period (from EUR 1.1/W_p to EUR 0.6/W_p from 2020 to 2050). For utility-scale installations, the compound decrease is projected to be 4 % and 7 % for the periods 2020-2030 and 2020-2050 respectively.

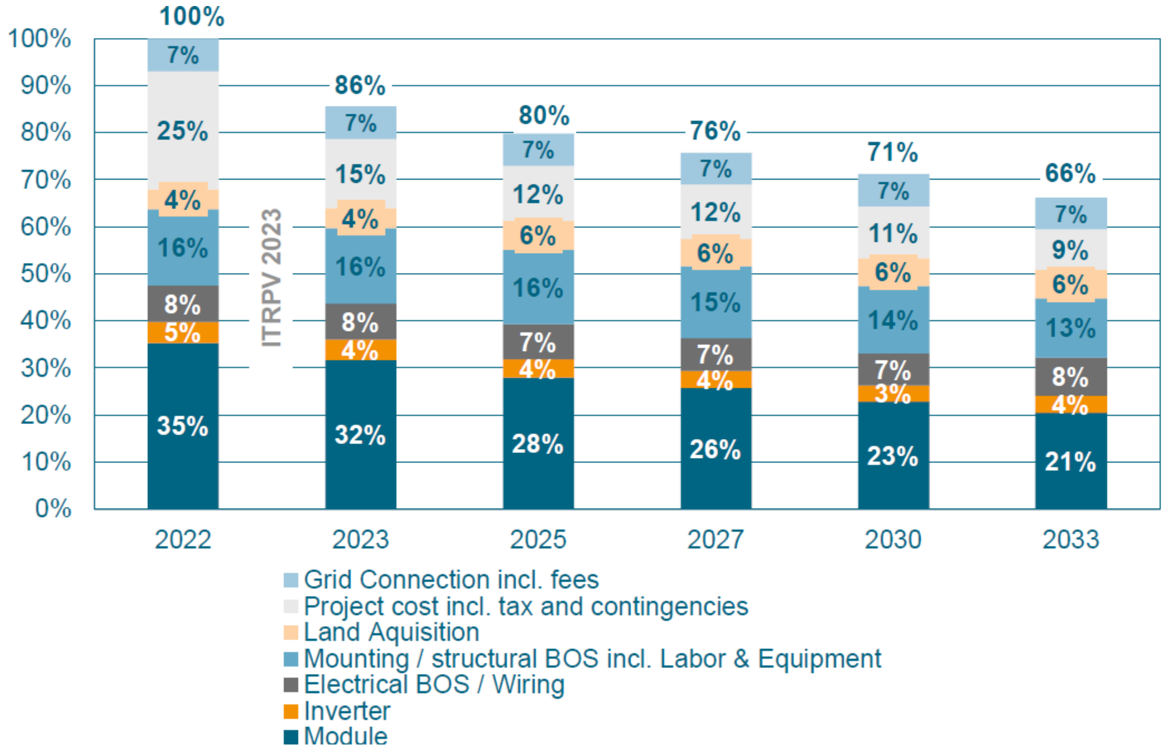
[5] Crystalline modules with mono- or bifacial HJT, N-type TOPCon or IBC (Back Contact) cells and combinations thereof, which have efficiencies higher than 21 %.

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

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

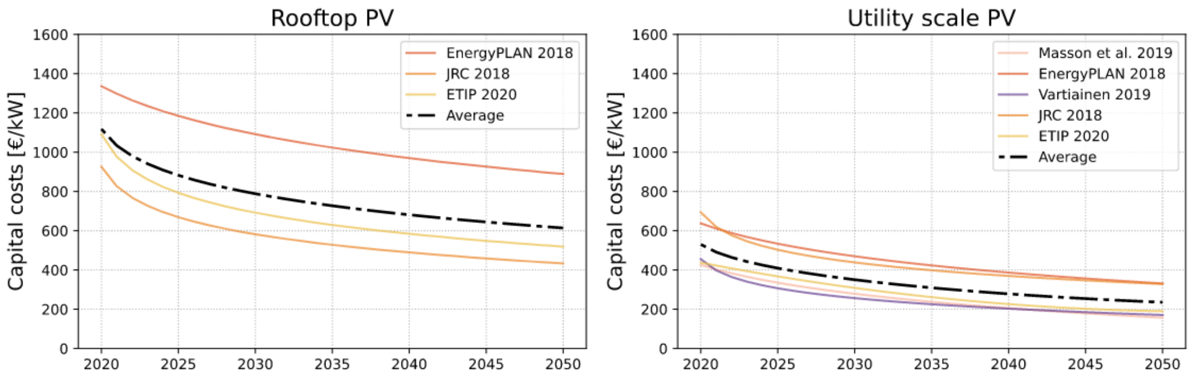
[8] Include project developer costs, overhead and profit, sales tax and permitting fees.

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



Source: (VDMA, 2023)

Figure 15. Capital cost projections for rooftop and utility-scale PV installations for the period 2020-2050.



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

OPEX

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

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

An evaluation of solar energy costs at EU level revealed that the average EU O&M costs[10] for utility-scale installations are between EUR 6.8/kW_p/year and EUR 14.8/kW_p/year. The lowest O&M costs are in Bulgaria in the

[9] A scope which is different from the EU, as in the rest of the present report.

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

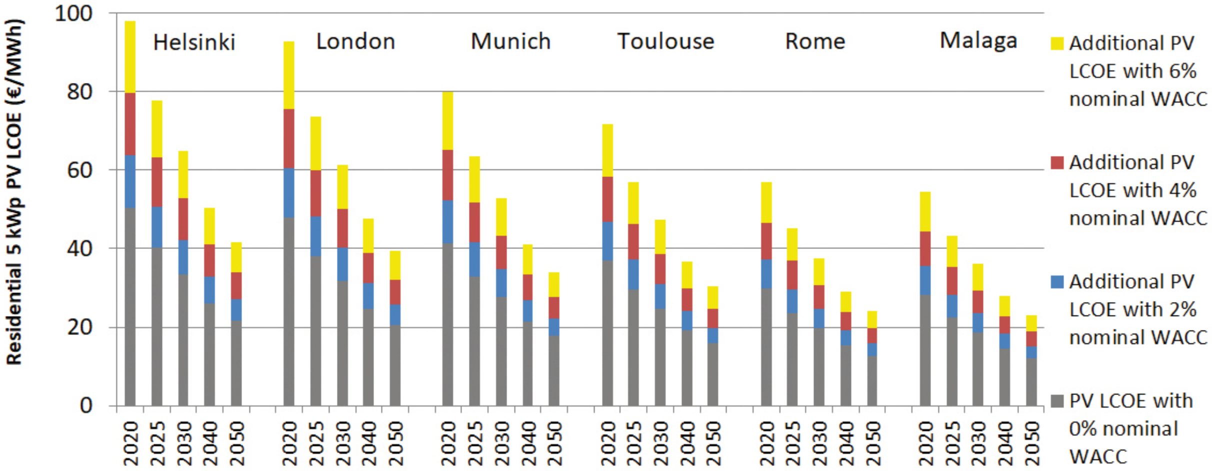
range of EUR 5.2-11.2/kW$_p$/year and the highest in Germany between EUR 8.7/kW$_p$/year and EUR 18.9/kW$_p$/year (Lugo-laguna, Arcos-Vargas and Nuñez-hernandez, 2021). The low range value refers to a fixed system and the high range value to a 2-axis tracking system.

LCoE

The trend for global convergence of PV solar system CAPEX continued over the last year, despite elevated material costs and increased fuel prices. Of course, local factors like market size and maturity, import taxes, local content rules or existing tax credits have an influence on local prices, and can still lead to significant price variations. In the first half of 2022, the global benchmark LCoE for PV systems increased significantly but decreased for non-tracking PV systems in the second half of 2022 (Bloomberg New Energy Finance, 2023a)(Bloomberg New Energy Finance, 2022a, 2022b). At the end of 2022, it showed an overall increase of 12 % compared to 2021 and stood at USD 45/MWh. The full range of LCoE for non-tracking PV systems among different countries around the world varied between USD 27/MWh to USD 229/MWh (upper limit due to a weakening of the local currency against the USD). Similarly, the global cost benchmark for tracking PV systems increased by about 13 % to USD 44/MWh. This development was driven mainly by price increases in the USA, which saw higher material prices, increased transport costs and higher module prices due to alternative sourcing of solar modules triggered by trade frictions with China (Jäger-Waldau, 2023).

A comparative analysis of calculated LCoE values at different EU locations and with different Weighted Average Costs of Capital (WACC) rates (ETIP-PV, 2020) has shown that for a residential rooftop installation (Figure 16) when applying a 6 % WACC, the EUR 0.100/kWh of LCoE in 2020 will decrease to EUR 0.040/kWh of LCoE in 2050 in Finland. For southern locations, like in Spain, for the same conditions, the 2020 LCoE of EUR 0.055/kWh will be reduced to EUR 0.022/kWh in 2050. Indicatively, LCoE values for residential rooftop installations are expected to be higher than utility-scale installations by a factor of roughly 2 (Vartiainen *et al.*, 2020).

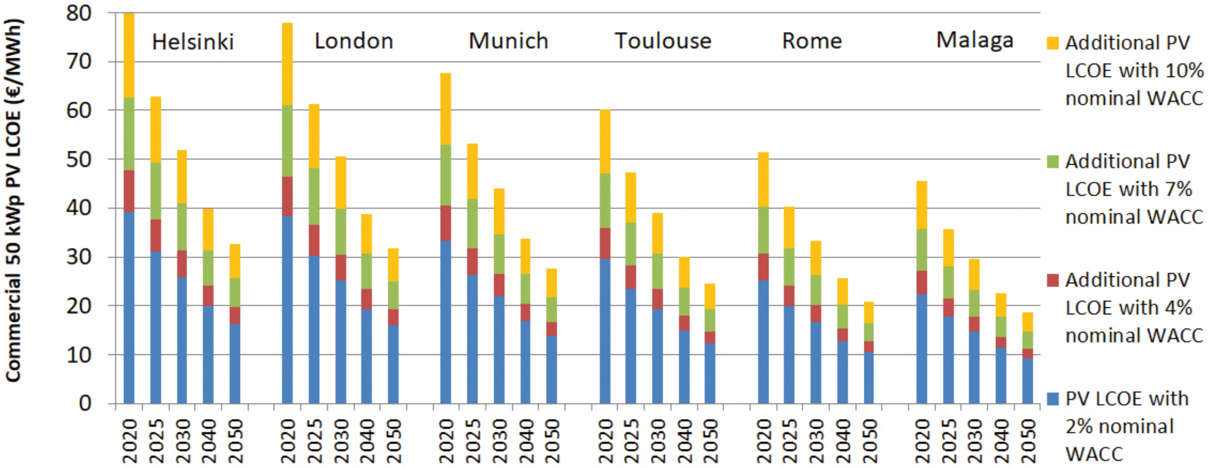
Figure 16. PV LCoE at six European locations with different nominal WACCs for 5 kW$_p$ residential rooftop PV installation.



Source: (ETIP-PV, 2020)

The relevant LCoE values for a commercial rooftop installation presented in Figure 17 are lower than for the residential installation in Figure 16. In Finland from EUR 0.080/kWh in 2020 the LCoE will decrease to EUR 0.034/kWh in 2050, whereas in Spain in 2050 it will drop by EUR 0.028/kwh from EUR 0.046/kWh.

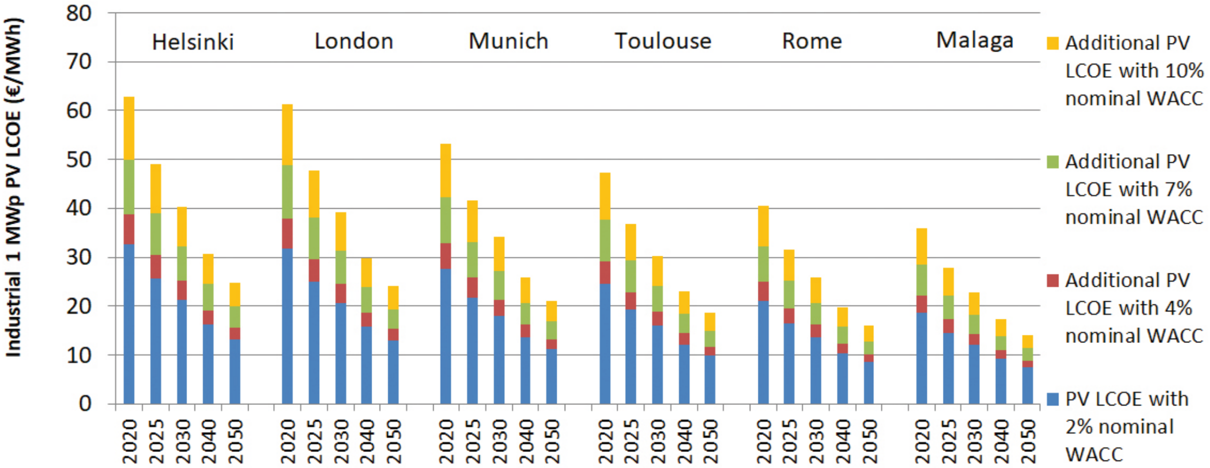
Figure 17. PV LCoE at six European locations with different nominal WACCs for 50 kW$_p$ commercial rooftop PV installation.



Source: (ETIP-PV, 2020)

A decrease of EUR 0.038/kWh between 2020 and 2050 (from EUR 0.063/kWh to EUR 0.025/kWh) is projected for the LCoE of industrial installations in Finland. In Spain, the LCoE will drop by EUR 0.022/kWh in 2050 in comparison to 2020 (EUR 0.015/kWh) (Figure 18).

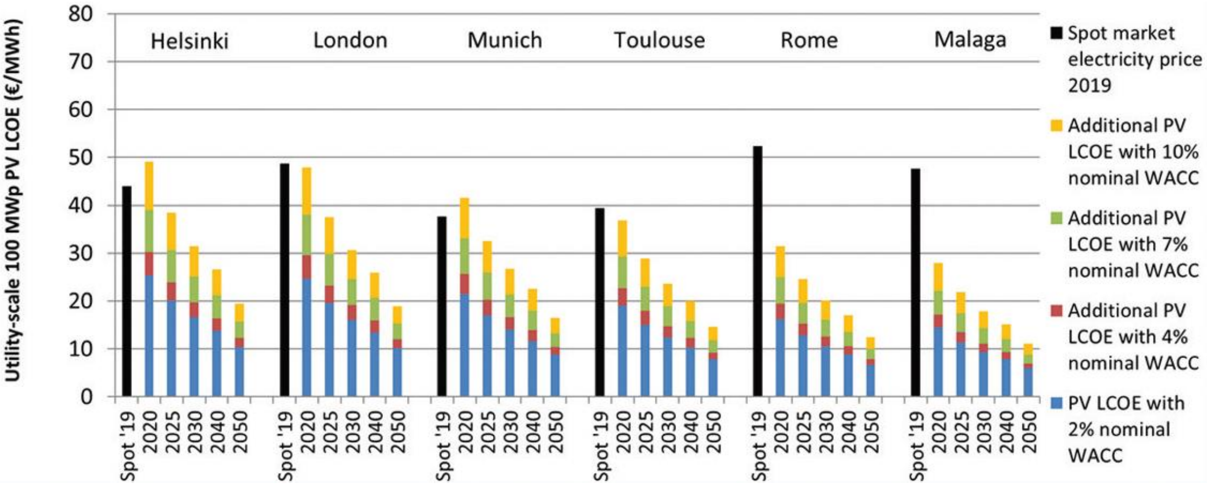
Figure 18. PV LCoE at six European locations with different nominal WACCs for 1 MW$_p$ industrial PV installation.



Source: (ETIP-PV, 2020)

In the case of utility-scale installations and taking into consideration the wholesale electricity prices, the cost of electricity produced from PV was already competitive in Munich and Helsinki even when applying a WACC of 7 % and in London, Toulouse, Rome and Malaga when applying a WACC of even over 10 % (Figure 19).

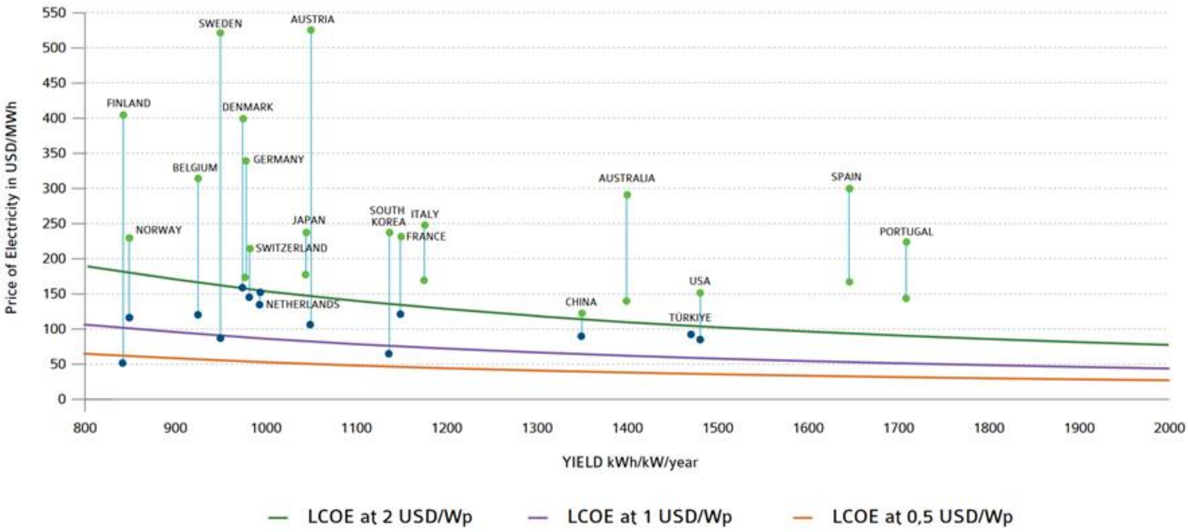
Figure 19. PV LCoE six European locations with different nominal WACCs for 100 MW_p utility-scale PV installation compared and average spot market electricity price in 2019.



Source: (ETIP-PV, 2020)

According to Figure 20 grid parity is already a reality in various countries and for many others costs are decreasing to such levels that PV electricity is becoming competitive and expected to be even more so in the years to come. The figure shows the price of electricity for several countries, for three different system prices depending also on each country's solar resource. The green points on the figure represent the cases where PV is competitive, while the blue points are the cases where PV competitiveness depends on the system prices and the retail prices of electricity (IEA-PVPS, 2023b).

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



Source: (IEA-PVPS, 2023b)

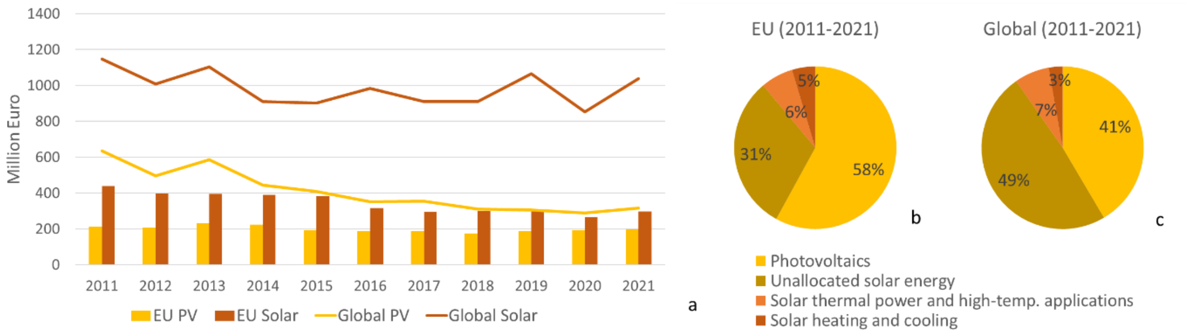
2.4 Public RD&I Funding and Investments

The public investment in solar energy and PV (treated as a sub-category) at EU and global level from 2011 until 2021 is illustrated in Figure 21a. It must be noted that the 2020 and 2021 values do not include funding reported from Italy thus an artificial decline is created for 2020 and an equal to 2019 investment is shown for 2021.

Overall, EU public investments in solar increased by 180 % between 2000 and 2011, year when they peaked. Thereafter they started decreasing gradually. Between 2011 and 2021 the decrease was 32 % at EU level. At global level, solar public investments increased by 146 % between 2010 and 2011 and decreased by only 10 % between 2011 and 2021. The year 2011 was a peak investments year both at EU and global level.

Regarding PV public funding, the EU experienced a 92 % increase between 2000 and 2011, following a slight decrease of 8 % for the period 2011-2021. Globally, PV public investments increased by 68 % in 2000-2011 and decreased by 50 % over the period 2011-2021. For PV, the peak investments year was 2009 at global level and 2009 and 2013 at EU level.

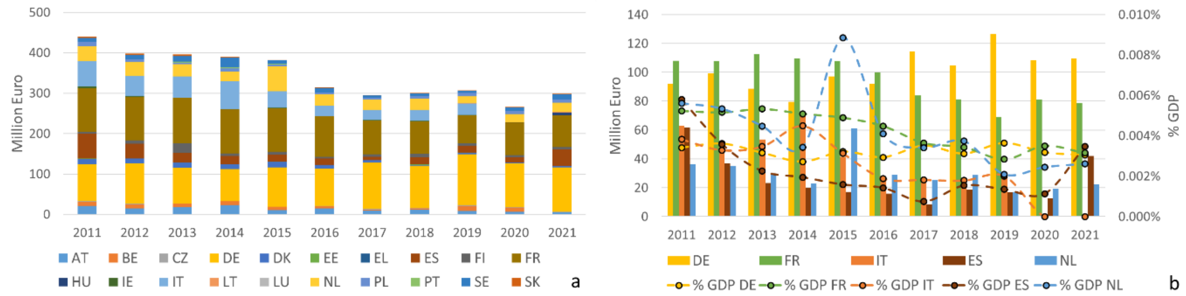
Figure 21. (a) EU and global public investment in Solar and PV R&D, (b) EU and (c) global allocation of solar energy technologies for the period 2010-2019.



Source: JRC analysis based on IEA

While 58 % of the total solar energy sector public investment was attributed to PV in the EU, the respective percentage at global level was 41 % for the period between 2011 and 2021 (Figure 21b and c). The total cumulative EU public investments in PV accounted for 49 % of the total cumulative global public investments in PV during the period 2011-2021, while in the case of the total cumulative public investments in solar, the EU accounted for 35 % of the global total cumulative public investments. The above-mentioned percentages are lower than expected since Italy is not included in the datasets for the years 2020 and 2021.

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

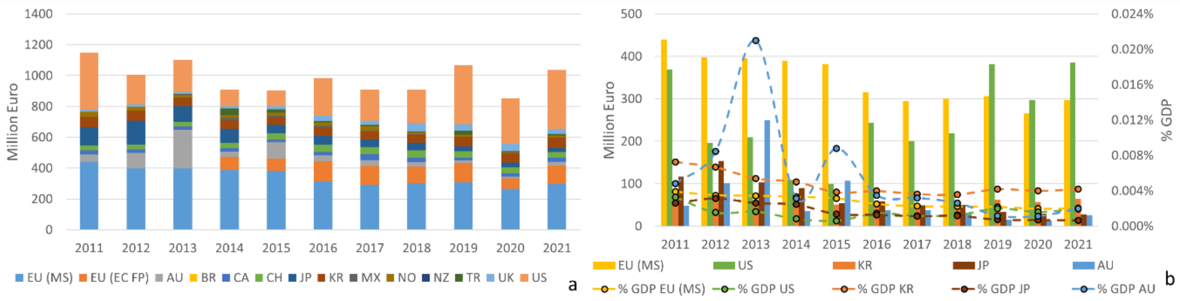


Source: JRC analysis based on IEA and (The World Bank, 2023)

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

Germany, France, Italy, Spain and the Netherlands are the top five EU countries with the highest public investment in solar energy technologies. Germany and France have kept a nearly constant solar energy public investment as a percentage of their GDP, between 0.003 and 0.004 % of its GDP and between 0.003 % and 0.005 % of its GDP respectively. Spain shows a peak in 2011 (0.006 % of GDP) and a decrease in the following years. The same applies also for Italy with 0.004 % of its GDP until 2015 and decreasing thereafter. In the case of the Netherlands, the public investment as a percentage of the country's GDP is rather unstable ranging from 0.002 % to 0.006 % with a distinct peak in 2015 (0.009 % of GDP).

Figure 23. (a) Global public investment per country and (b) global public investment and % of GDP in Solar and R&D for the top five countries.



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

From the Figure 23a, in which thirteen major economies are analysed, the EU and the United States accounted together for 60 % of the total global public investments in solar cumulatively in the period from 2011 until 2021. For PV public investments, the EU accounted for 49 %, Japan for 17 % and the United States for 12 % of the global public investments for the same period (2011-2021). In 2013 and 2015, Australia dedicated significant amounts of money for public investments in solar, reaching 0.021 % and 0.009 % of its GDP (Figure 23b). The rest of the major economies did not overcome the 0.008 % of their GDP for public investments in solar. Switzerland is, globally, the sixth country with the highest public investment on solar but the first with the highest average % of GDP (0.007 % on average in the period 2011-2021).

In Figure 23a and b, 'EU (MS)' denotes the sum of the Member States' national investments, while 'EU (EC FP)' denotes funding from EU framework programmes (H2020) and is only available from 2014 onwards.

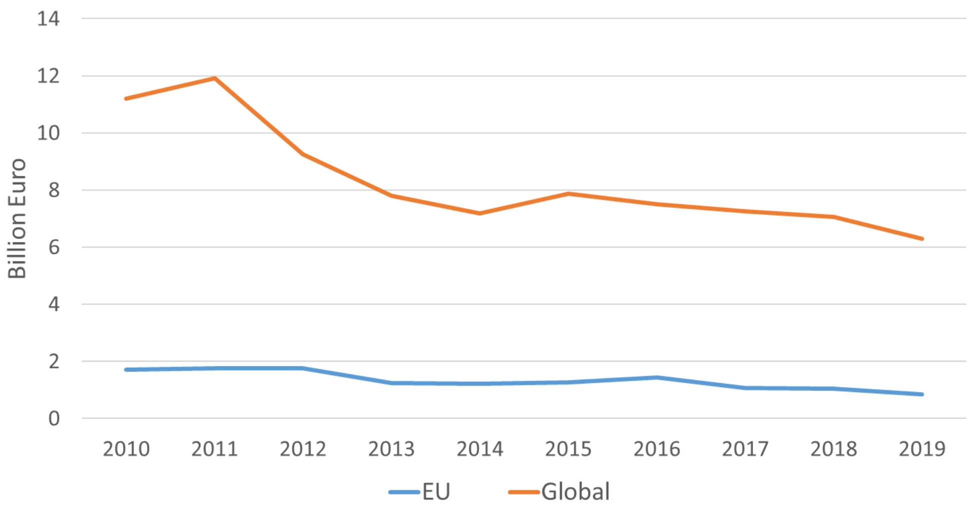
2.5 Private RD&I funding

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

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

According to the collected data for public R&I funding in the previous chapter and the data for private R&D funding in this chapter, the relationship between public and private funding is different from that presented in (Moser *et al.*, 2021). While the public investments for the EU and globally ranged from EUR 173 to 233 million and from EUR 305 to EUR 634 million respectively for the period 2010-2019, the private investments in the EU and globally ranged from EUR 0.8 to EUR 1.8 billion and from EUR 6.3 to EUR 12 billion respectively for the same period Figure 24. Analysing the relationship between public and private funding from 2010 until 2019 in the EU, it is observed that public R&D funding was between 11 % and 18 % of the total R&D funding. This suggests a much higher contribution of the private sector to the PV R&D funding (82 %-89 %). Private funding at global level is even more important as it covers between 93 % and 96 % of the total funding.

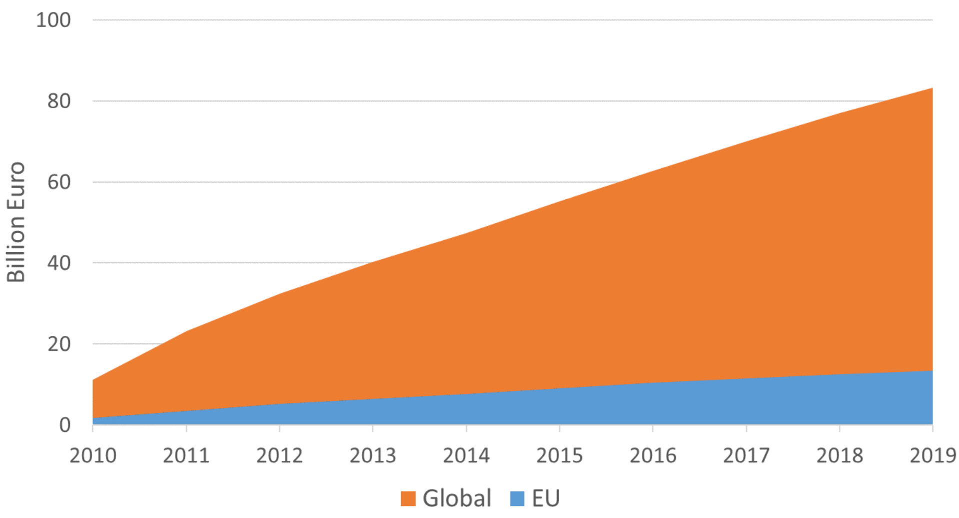
Figure 24. EU and global private investment in PV for the period 2010-2019.



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

Between 2010 and 2019, as far as PV is concerned, the indication is that the EU exhibits a more extended decrease in private than in public investments (-53 % against -8 %), while over the same period, private investments at global level suffered a smaller decrease than public investments (-44 % against -47 %). Regardless of the public or private nature of the investment, investments have suffered significant decreases both in the EU and globally. However, there is an indication that, unlike the EU, the rest of the world is more and more benefitting from private rather than public investments.

Figure 25. EU and global cumulative private investment in PV for the period 2010-2019.

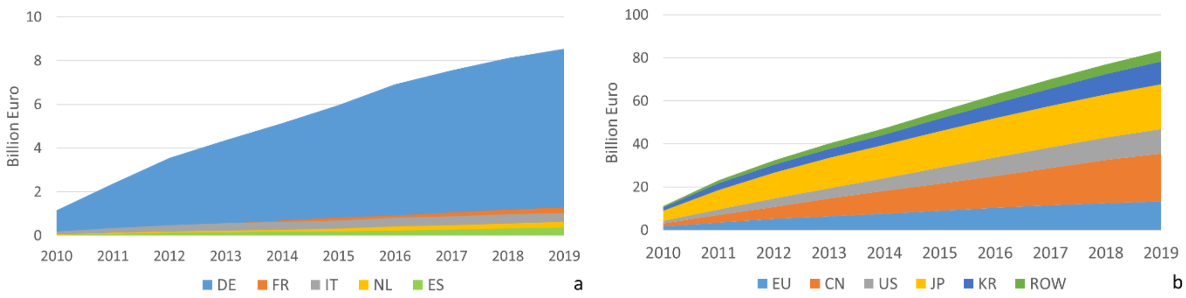


Source: JRC analysis based on (Fiorini et al., 2017; Pasimeni, Fiorini and Georgakaki, 2019)

As shown in Figure 25, at global level, the cumulative private investments in PV exceeded the EUR 80 billion in 2019. In the same year, the EU private investments amounted to EUR 13.3 billion (16 % of the cumulative private investments at global level).

Figure 26a presents the five EU countries with the highest levels of cumulative private investment in the EU. These five countries account for 90 % of the total cumulative private investments in the EU from 2010 to 2019. Germany had the highest level of private investment in PV, accounting for 66 % of the cumulative investments (2010-2019), followed by France with 9 % and Italy with 8 %.

Figure 26. (a) EU cumulative private investment in PV per MS and (b) global cumulative private investment in PV EU and top five countries for the period 2010-2019.

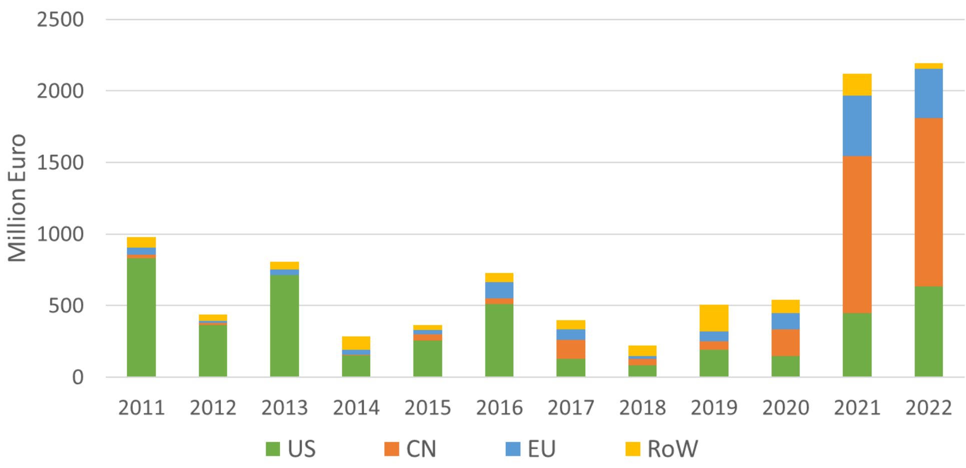


Source: JRC analysis based on (Fiorini et al., 2017; Pasimeni, Fiorini and Georgakaki, 2019)

Globally Figure 26b, the cumulative private investments in PV from Japan (30 %) and China (23 %) represent more than half of the global cumulative private investments. The EU represents 16 % of the total cumulative private investments from 2010 to 2019, representing approximately EUR 13.3 billion out of a total of approximately EUR 83.3 billion. The next two regions are the US (13 %) and South Korea (12 %).

Global VC investments[11] in photovoltaics companies increased sharply over the past 2 years, surpassing the highest levels seen in the early 2010s, and amounted to EUR 2.2 billion in 2022 (Figure 27). This represents an increase of + 3.5 % compared to 2021 levels, a five-fold growth compared to the beginning of the 2017-2022 period, and puts an end to a period of lower investments whose beginning can be traced back in 2014. This trend is essentially driven by an outstanding growth of VC investments in Chinese firms in 2021 and 2022, both at early and later stages[12], and, to a smaller extent, by the rebound of later stage investments in US firms after a long period of lower investment levels.

Figure 27. EU and global total Venture Capital investments for the period 2011-2022.



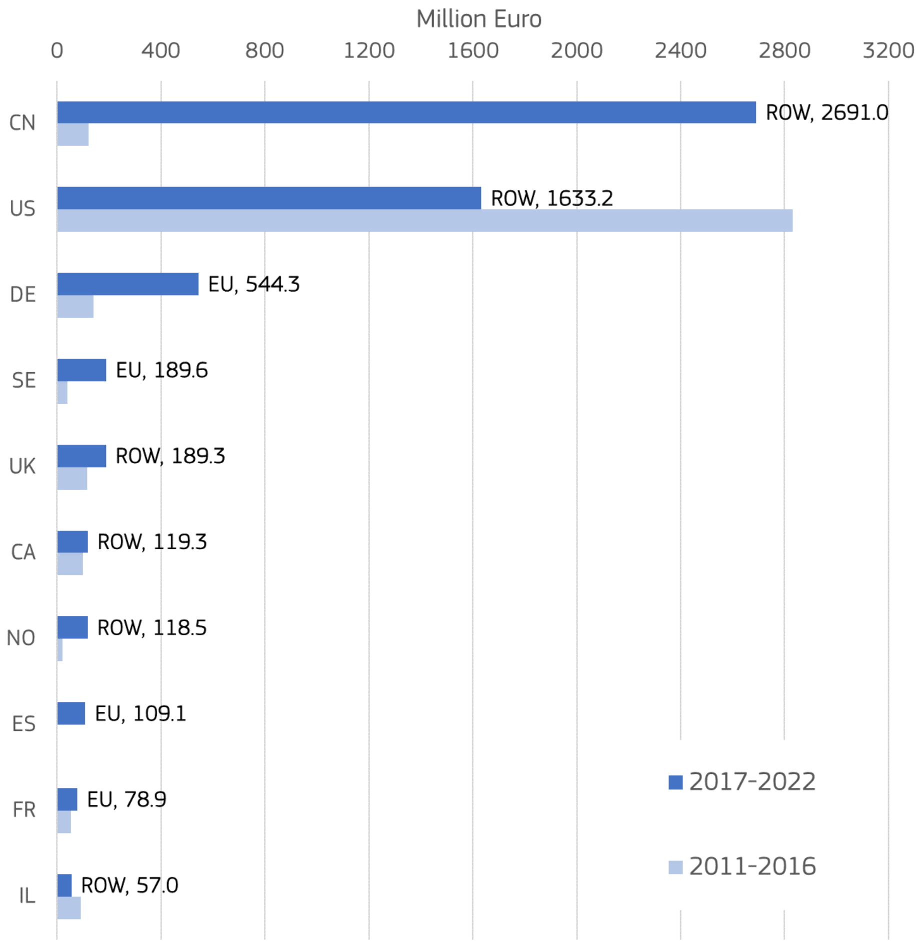
Source: JRC analysis based on Pitchbook

The United States and the EU host respectively 30 % and 23 % of active venture capital companies over the 2017-2022 period. With 22 % of identified ventures, China has however taken a clear lead in the VC investment race with a high level of constant investment over the past 2 years. Regarding the total VC investments (early and later stage), China and the United States accounted for 45 % and 27 % respectively in the 2017-2022 period, while the EU accounted for 17 % of the global 2017-2022 total (see Figure 28).

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

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

Figure 28. Top ten countries total Venture Capital investments for all stages for the periods 2011-2016 and 2017-2022.



Source: JRC analysis based on Pitchbook

China accounts for 62 % of global early-stage investments and 39 % of global later stage investments over 2017-2022. While later stage investments in Chinese companies have decreased in 2022 (- 39 % compared to 2021), they remain almost 3.5 times higher than in 2020. This trend is driven by companies such as SolarSpace, Yonz Technology or Sinopont that were founded over the 2011-2016 period but had not attracted venture capital so far and are now raising late-stage venture capital to support their growth. The growth of early-stage investments in Chinese companies in 2022 compensate the drop of later stage investments in 2022. Early-stage investments rose sharply since 2021 and have more than doubled in 2022 (x 2.6 as compared to 2021). This trend is driven by investments in manufacturers of solar photovoltaic polycrystalline silicon wafers such as Gokin Solar or Meike Solar that were founded recently (2019 and 2017 respectively) and are scaling very fast.

Early-stage investments in EU VC companies amounted to EUR 135 million over the 2017-2022 period. They have continuously decreased after a peak in 2020 and are back to their 2019 level. Over the 2017-2022 period, the EU accounted for 9 % of global early-stage investments (vs 15.5 % over 2016-2021) and its competitive positions further weakens in an accelerating global investment race. 40 % of the identified VC companies were founded after 2017 and the United States, the EU and China host similar shares (24.5 %, 24 % and 23 % respectively) of those 166 active companies over the 2017-2022 period. EU companies however only captured 16 % of the identified grant funding[13] over the 2017-2022 period behind the United States (34.5 %) and Canada (26 %) and closely followed by the United Kingdom (14 %). The remaining 9.5 % is attributed to the rest of the world. PitchBook only reports negligible (or none) amount of grant funding for Japanese, Korean or Chinese start-ups.

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

Later stages investments in EU companies amounted to EUR 910 million over the 2017-2022 period, supported by a smaller number of larger investments in manufacturers and installers of solar panels in Germany (Enpal, Zolar) and Spain (Alter EnerSun). While they have decreased in 2022 (- 15 % compared to 2021), they remain 7 times higher than in 2020. Accounting for 21 % of global later stage investments over 2017-2022 (vs 16 % over 2016-21), the EU improved its competitive position as later stage investments for Chinese companies are decreasing. Late-stage VC investments in EU companies are essentially concentrated in Germany and Sweden, which outrank the United Kingdom, but remain far behind the United States and China. France and the Netherlands, despite sharing a number of active VC companies which is similar to Germany's, only rank in 9th and 11th position in terms of late-stage VC investments over the 2017-2022 period.

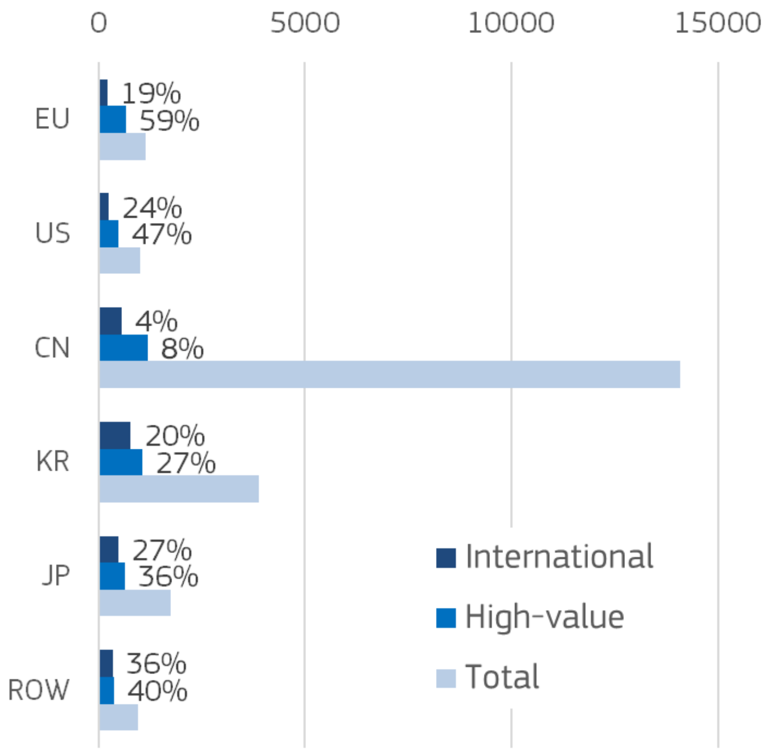
2.6 Patenting trends

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

The dataset used for the creation of the patent indicators (Fiorini *et al.*, 2017; Pasimeni, 2019; Pasimeni, Fiorini and Georgakaki, 2019, 2021; Pasimeni and Georgakaki, 2020) is based on the following Cooperative Patent Classification (CPC) codes: Y02B 10/10, Y02E 10/50, Y02E 10/52, Y02E 10/541, Y02E 10/542, Y02E 10/543, Y02E 10/544, Y02E 10/545, Y02E 10/546, Y02E 10/547, Y02E 10/548, Y02E 10/549 (European Patent Office, 2023). It has to be noted though that data for 2020 is not complete.

As depicted in Figure 29 China has the largest number of patents with more than 14 000 inventions, followed by South Korea and Japan. The EU is in 4th position with 1 134 inventions in total between 2018 and 2020.

Figure 29. Number of inventions and share of high-value and international activity for the period 2018-2020.



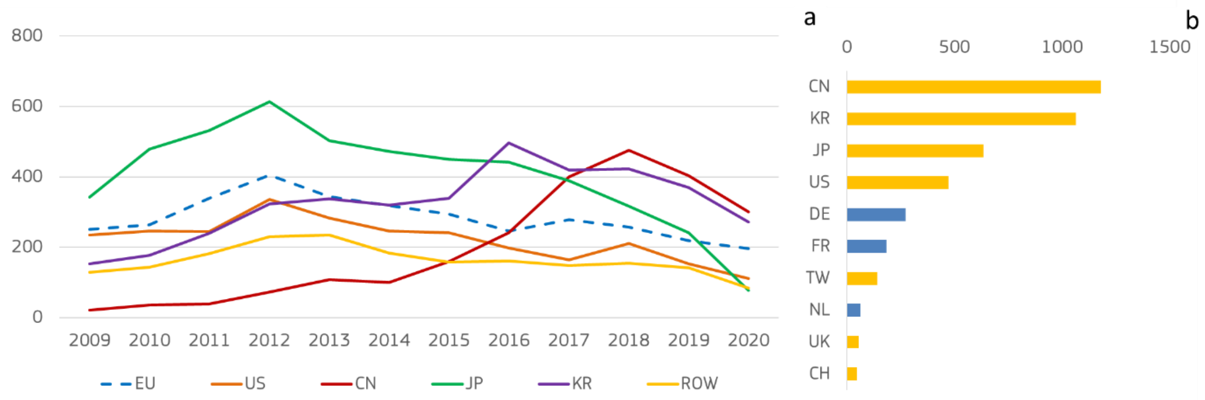
Source: JRC analysis based on EPO Patstat

However, when only the high-value inventions[14] are taken into consideration, the EU moves 1st with 59 % of its total inventions being high-value inventions and China results into the last position, thus suggesting that the

[14] 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.

EU, unlike China, is generally filing to more than one patent office[15]. The same trend is evident also as far as international inventions[16] are concerned. The EU is aiming for patent applications outside while China appears to be concentrated on applying mainly within the country rather than internationally. The EU is surpassed by Japan and the United States regarding the international inventions. While Figure 29 shows the high-value inventions as a percentage of the total number of inventions, Figure 30a presents the number of high-value inventions in absolute numbers for each year from 2009 until 2020. A decreasing trend is observed for most countries apart from South Korea and China. Germany, France and the Netherlands are among the top ten countries with the highest number of high-value inventions between 2018 and 2020 (Figure 30b).

Figure 30. Number of high-value Inventions and (b) Top ten countries with high-value inventions for the period 2018-2020.



Source: JRC analysis based on EPO Patstat

Table 4 and Table 5 respectively present the top ten entities globally and in the EU which filed the highest number of inventions in PV between 2018 and 2020.

Table 4. Global top ten entities with high-value inventions in PV for the period 2018-2020.

Entities	Number of high-value inventions	Country
Samsung Display Co Ltd	478	KR
Boe Technology Group Co Ltd	211	CN
Wuhan China Star Optoelectronics Semiconductor Display Technology Co Ltd	203	CN
Samsung Electronics Co Ltd	94	KR
Lg Philips Lcd Co Ltd	92	KR
Lg Electronics Inc	62	KR
Sharp Kabushiki Kaisha	46	JP
Kaneka Corporation	36	JP
Chengdu Boe Optoelectronics Technology Co Ltd	36	CN
Panasonic Intellectual Property Management Co Ltd	35	JP

Source: JRC analysis based on EPO Patstat

Almost half of the top ten entities in the field of high-value inventions are based in South Korea. The rest of the top ten list includes entities from China and Japan (Table 4). In the period 2016-2018, the only EU company,

15 An invention is considered of high-value when it contains patent applications to more than one office.
16 Patent applications protected in a country different to the residence of the applicant.

Merck Patent Gmbh (Germany), was in the tenth position in the global top ten entities (Chatzipanagi, Jaeger-Waldau, *et al.*, 2022). However, for the period 2018-2020, no European entity has made it to the top ten. As far as the EU is concerned, the top ten list highlights the leadership of German entities in high-value inventions (Table 5). The company Cynora Gmbh has conquered the first position in the EU top ten and Merck Patent Gmbh, first company for the period 2017-2019 (Chatzipanagi, Jaeger-Waldau, *et al.*, 2022) has dropped to the fourth position.

Table 5. EU top ten entities with high-value inventions in PV for the period 2018-2020.

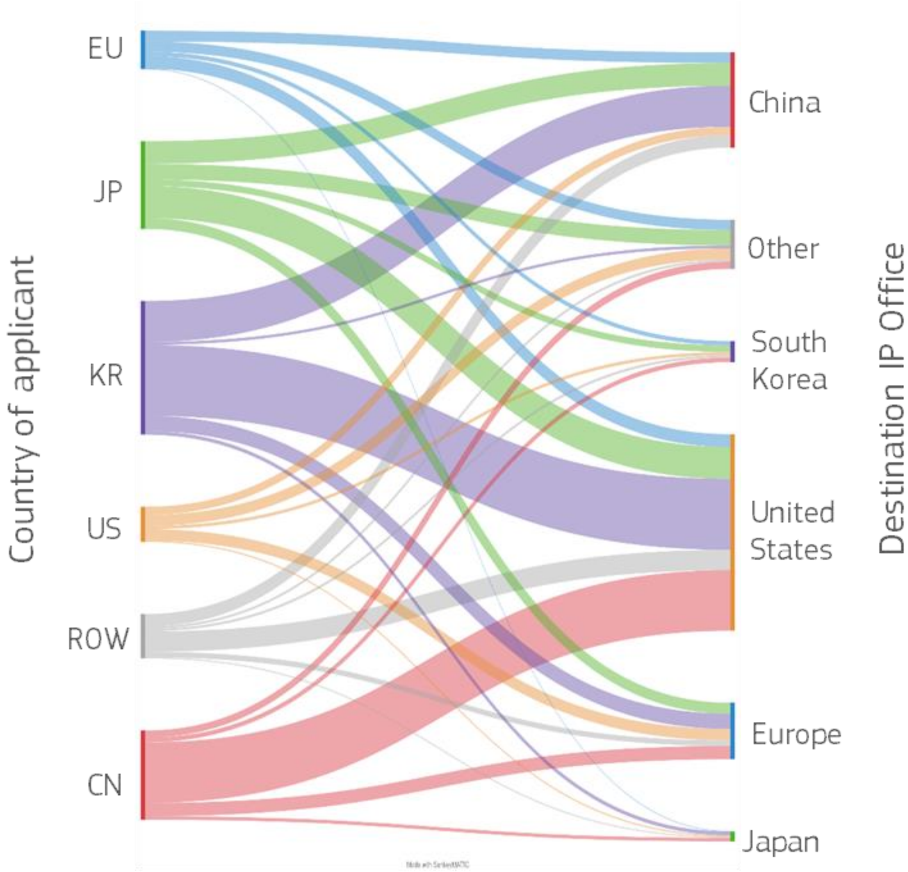
Entities	Number of high-value inventions	Country
Cynora Gmbh	27	DE
Hanwha Q Cells Gmbh	22	DE
Azur Space Solar Power Gmbh	21	DE
Merck Patent Gmbh	21	DE
Heliatek Gmbh	15	DE
Novaled Gmbh	12	DE
Total Sa	11	FR
Isorg	10	FR
Eni Spa	10	IT
Borealis Ag	8	AT

Source: JRC analysis based on EPO Patstat

Figure 31 presents the countries in which patents for high-value inventions were submitted, and subsequently enjoyed patent protection, between 2018 and 2020. Chinese applicants have mainly chosen to patent their inventions in the US. The number of patent applications in the EU and other countries is very small. US inventors have split their patent applications evenly between China, Europe and other geographical areas. The same applies also for EU inventors, where patent applications are split evenly between China, US and others. Applicants from South Korea are mainly applying in the US and China and to a lesser extent in Europe. In conclusion, the US is receiving the largest number of high-value invention applications. Europe is 3rd to last as far as the reception of patent applications is concerned.

A more detailed evaluation of the high-value patenting activity for the single CPC codes for CIS, dye-sensitised, II-VI group, III-V group, micro c-Si, mono c-Si, poly c-Si, a-Si and organic PV cells from 2009 until 2020 reveals a general decreasing trend for all PV technologies. More in particular, III-V group PV cell patents exhibit fluctuations (increases and decreases) between 2009 and 2020, with the United States being the leader. High-value patents related to the organic technology, have experienced an increase between 2009 and 2017 and started decreasing thereafter. Japan is leading in the field of dye-sensitised, mono c-Si and a-Si PV cell patents. The US is the country with the highest number of patents on II-VI group and III-V group PV cells and South Korea patented inventions mostly relating to organic PV cells, with China equalling South Korea's number of high-value patents in 2018. The EU has significantly increased the number of high-value patents related to III-V group PV cells and surpassed the US to reach the leading position in this domain in 2019.

Figure 31. International protection of high-value inventions for the period 2018-2020.



Source: JRC analysis based on EPO Patstat and Sankeymatic

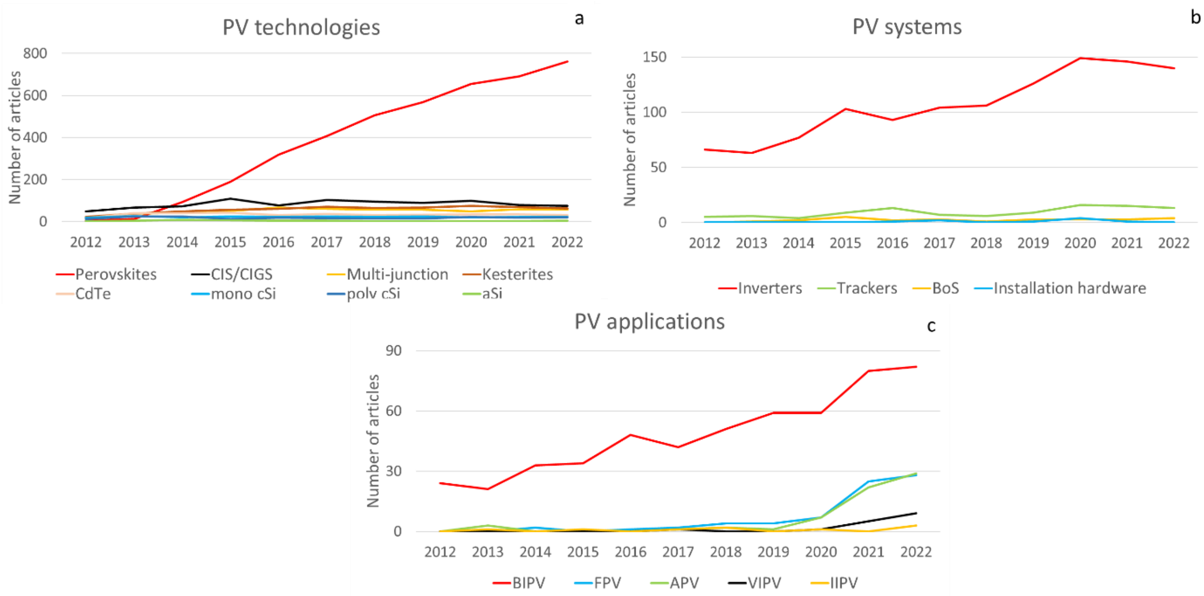
2.7 Scientific publication trends[17]

In the EU, the number of publications on PV technologies has increased steadily from 2012 to 2022 for all technologies apart from perovskites. For this later particular PV technology, there has been a rapid increase in the number of papers published from 2014 onwards (Figure 32a), due to the promising outlooks of this technology. It is thanks to this intense research activity that the perovskites technology has reached such high efficiencies in recent years. The analysis of PV technologies publications at global level confirms the same trends as at EU level. In general, global publications dealing with the perovskite technology accounted for only 5 % of all technologies publications in 2012 but slowly increased, reaching an 81 % share in 2022. CdTe and CIS technologies publications decreased from around 25 % of all technologies publications in 2012 to 4 % in 2022. Publications related to kesterite and multi-junction technologies decreased from approx. 15 % in 2012 to 4 % in 2022. Those on mono cSi, poly cSi and a-Si are very limited, resulting to being less than 3 % of total publications in 2022.

The number of publications on mono c-Si, poly c-Si, a-Si, CdTe and kesterite technologies has been comparable for the EU and China from 2012 until 2022. However, the number of publications on these technologies remained very limited compared to the rest of the technologies in the above-mentioned period. On CIS/CGS and multi-junction technologies, the EU has had more publications than other countries and China seems to have developed an increasing interest in publications related to these technologies over the past 3 years. As far as the CdTe technology is concerned, the leading country in publications is the United States for the period 2012-2022 (being the dominant country in the CdTe production and market). However, it must be noted that publications on CdTe technology in the United States have decreased after 2016. For the perovskite technology, which is the highest-trending topic, China has the highest number of papers between 2012 and 2022 (Figure 33).

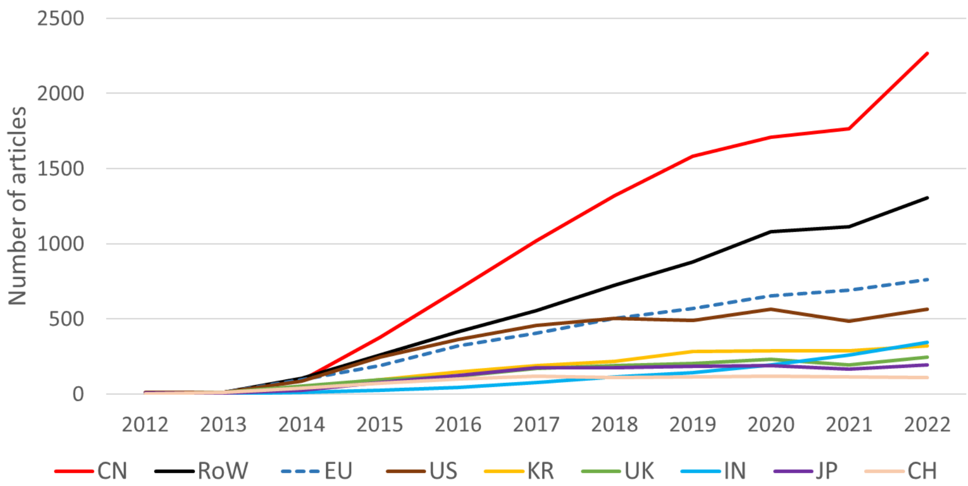
[17] The scientific publication trends have not changed since last year's report. However, the number of publications between 2012 and 2021 has slightly changed compared to the 2022 CETO PV report due to the constant update (additions, removals, etc.) of the academic publishing databases.

Figure 32. EU publications on PV (a) technologies, (b) systems and (c) applications for the period 2012-2022.



Source: JRC analysis

Figure 33. Global publications on perovskites for the period 2012-2022.

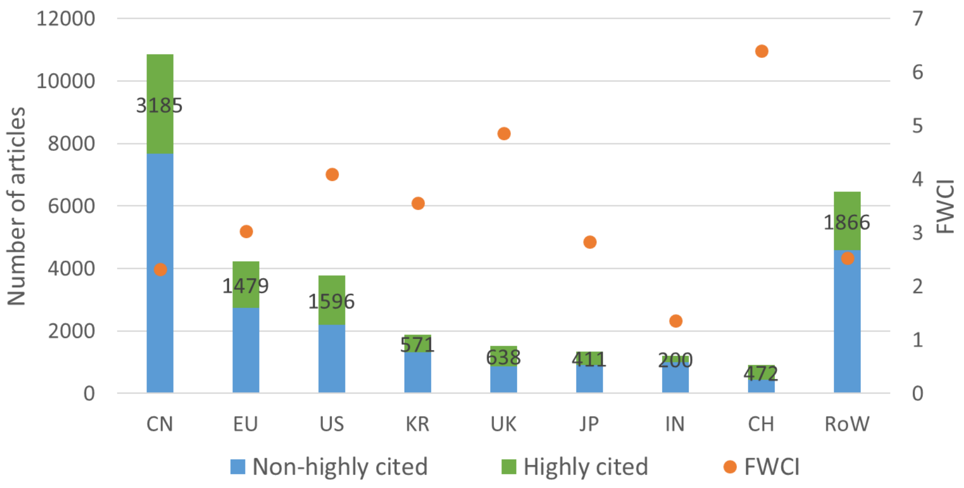


Source: JRC analysis

However, the total number of publications does not necessarily depict the quality of the work. As depicted in Figure 34, the EU has less than half of China's publications on perovskites but the EU's highly cited publications are slightly more numerous than China's highly cited publications (35 % against 29 %). The best performing country is Switzerland, for which 52 % of its total number of publications is also highly cited. The United States and the United Kingdom follow with 43 %. In terms of Field Weighted Citation Impact (FWCI), China's FWCI is significantly lower (2.3) than the EU's (3.0), meaning less frequent citations despite the large number of papers as a total. Almost half of the total number of publications on perovskites in the United States are highly cited publications and the country's FWCI is 4.1, denoting the high quality and frequent citation of the relevant papers.

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

Figure 34. Global highly cited publications on perovskites and EU position for the period 2012-2022.



Source: JRC analysis

In the field of PV systems, publications in the EU as illustrated in Figure 32b evidence a predominance of literature on the topic of inverters. The same is true at global level as well. Globally, from 2012 until 2022, approximately 9 000 papers on inverters were published. Papers dealing with PV tracking systems were only 525. For BoS and hardware installation, there were around 130 and 62 papers respectively over the same period. Germany, Spain, Denmark and Italy account for slightly more than half of the EU's publications on inverters. Germany ranks 1st in the EU, with 17 % of the EU's papers. Spain ranks 2nd with 14 % and Denmark and Italy follow with 12 % and 11 % respectively. In 2012, 20 % of the papers on inverters globally were published by institutions based in the EU, however this share decreased to 12 % in 2022. China also has a high number of publications in this field and its share in scientific publications remained stable around 30 % between 2012 and 2022, thus holding the first position. India, having a tradition in power systems research, is the 3rd country in the ranking with a share of publications in 2022 comparable with the EU's. China has the greatest number of publications on inverters, followed by the EU and the United States but only 16 % of China's publications are highly cited, whereas EU's and United States' portion of highly cited publications is 20 % and 24 % respectively. China's FWCI is 1.4 against 1.6 for the EU and 2.2 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. At EU level, even though Germany has the highest number of publications on inverters, Denmark is the country with the highest portion of highly cited papers (40 % of the country's inverter publications). A strong collaboration between the EU and the United States has been identified for BoS-related publications. For publications on inverters, China, the EU and the United States, the countries with the highest number of publications, seem to co-publish with countries labelled under 'RoW' rather than among themselves. At EU level, the strongest collaborations clusters on inverter publications are Germany-United Kingdom-Austria-Belgium-Netherlands, France-Italy-Romania-Poland and Spain-Portugal-Estonia-Finland.

Building integrated photovoltaics is the PV application that attracted the highest number of publications to date, as illustrated in Figure 32c. The interest in floating photovoltaics has increased over the past 4 years and so has the number of related publications. Agrivoltaics-related publications spiked in 2022 and vehicle integrated photovoltaics has started attracting more attention. The EU, from 2012 until 2022, has published the highest number of papers on building integrated photovoltaics making up for 23 % of the total number of papers on the topic globally. China follows with 17 %. More than 22 % of the EU's publications on building integrated photovoltaics come from Italy. Spain followed with 17 % and Germany with 11 % of the EU's building integrated photovoltaics publications. Even though the EU has the highest number of papers on building integrated photovoltaics, the highly-cited ones represent only 15 % of the total. By comparison, China's highly-cited papers on building integrated photovoltaics represent 21 % of the total. Both, however, have a FWCI of 1.5. The United Kingdom's and the United States' highly cited publications are 26 % and 23 % of the total building integrated photovoltaics publications respectively and the countries have FWCIs of 2 and 1.8 respectively. At EU level, the country with the highest number of publications on building integrated photovoltaics, Italy, has also an impressive percentage of highly cited publications on building integrated photovoltaics equal to 25 %. The respective percentage for Spain and Germany (2nd and 3rd ranking countries regarding building integrated photovoltaics publications) is significantly lower at 7 % and 12 % respectively. In this field, the main collaborations identified for publications are between China-United States-South Korea, United Kingdom-Japan and EU-Switzerland-India. At EU level, Spain, United Kingdom and Portugal are co-publishing several papers on building integrated photovoltaics, just like Italy, Switzerland and France. In the field of vehicle integrated photovoltaics, for the first time, strong collaborations are identified between EU-Japan, United States-Switzerland and China-South Korea.

2.8 Assessment of R&I project developments

Horizon Europe

The Horizon 2020 Work Programme (WP) from 2014 to 2020 included one hundred and forty PV projects for which EUR 455 million were allocated. Horizon Europe (2021-2027), Horizon 2020's successor, is expected to boost the EU's innovation and demonstration activities in PV. The indicative budgets for PV projects under the 2021-2022 and the 2023-2024 WPs are EUR 172 million and EUR 134 million respectively.

The Horizon Europe WPs 2021-2022 and 2023-2024 for Cluster 5 - Climate, Energy and Mobility, under Destination 3 – Sustainable, secure and competitive energy supply, support photovoltaic electricity generation through research and innovation activities along the value chain and the technology readiness level scale (TRL). The projects include research and innovation actions (TRL up to 5), innovation actions (TRL up to 7) and coordination and support actions to accelerate the deployment of solar energy in the EU.

In particular, the Work Programme covers research and innovation activities along most of the value chain for photovoltaics, including novel concepts at cell and module level; alternative equipment and processes for PV manufacturing (including pilot lines for innovative technologies and advanced manufacturing of PV technologies and integrated PV systems); operation, performance and maintenance of PV systems; recycling of PV modules; resource efficiency in production, use and disposal of PV modules and penetration of PV in renewable energy communities.

Regarding photovoltaic cell technologies, the focus is placed on research and innovation activities on advanced concepts for crystalline silicon technology; stable, high performance and large area perovskite solar cells and modules; high efficiency thin film technologies and high efficiency and low-cost tandem cells and modules.

Regarding applications, the Horizon Europe work programmes for 2021-2022 and 2023-2024 support demonstration activities in the fields of floating PV applications, novel agro-photovoltaic systems, PV integration in buildings and infrastructure, low-power PV applications, electric mobility and solar systems for industrial process heat and power.

Innovation Fund

The Innovation Fund is one of the world's largest funding programmes for the demonstration of innovative low-carbon technologies. The Innovation Fund provides grants for projects aiming at commercial deployment of innovative low-carbon technologies, with the objective of bringing to the market industrial solutions to decarbonise Europe and support its transition to climate neutrality. In addition, the Fund has a technical assistance component which allows unsuccessful proposals that meet certain conditions to benefit from project development assistance (PDA) support provided by the European Investment Bank.

A number of new solar actions are expected as a result of on-going or closed calls in 2023, subject to a competitive process of proposals selection:

- 3rd call for large-scale projects (deadline 16 March 2023) with a EUR 3 billion budget and
- 3rd call for small-scale projects (deadline 19 September 2023) with a EUR 100 million budget Value Chain Analysis.

Annex 4 presents an overview of the topics on PV in Horizon Europe WPs for 2021-2022 and 2023-2024, the ongoing projects of the 2021-2022 Horizon Europe PV calls and the ongoing Innovation Fund projects.

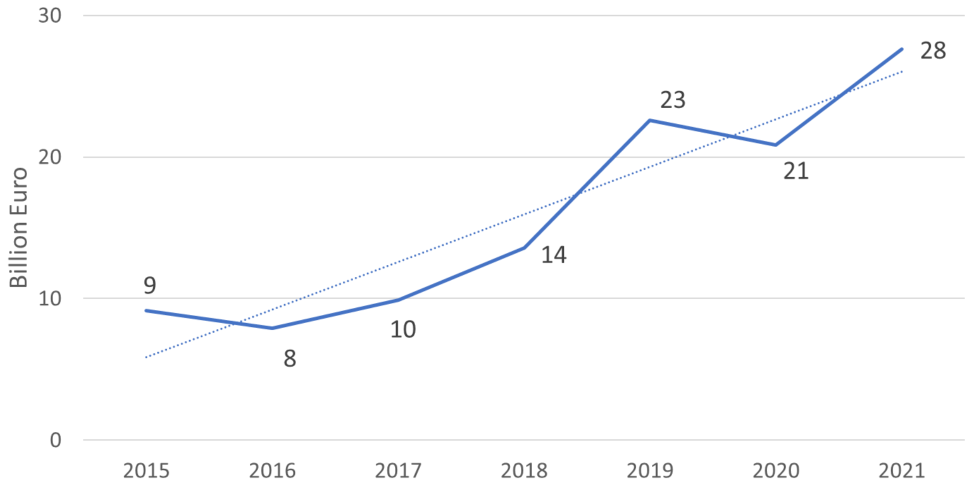
PV-related projects also exist under other programmes, like CEF-Energy, Renewable Energy Financing Mechanism, Just Transition Mechanism, LIFE or European Maritime Fisheries and Aquaculture Fund, etc..

3 Value Chain Analysis

3.1 Turnover

The EU PV turnover in 2021 was approximately EUR 28 billion, growing from EUR 21 billion in 2020. However, the slight decrease in turnover between 2019 and 2020 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 20 % between 2015 and 2021 (Figure 35). Globally, the PV market is estimated to have reached a turnover of approximately USD 200 billion (EUR 170 billion[18]) in 2021 (Fortune Business Insights, 2022) and thus, the EU's share is 16.4 % of the total. In 2020 the EU's share was 15.4 %. The global turnover of the PV sector in 2022 amounts to USD 237 billion (EUR 225 billion[19]) (IEA-PVPS, 2023b).

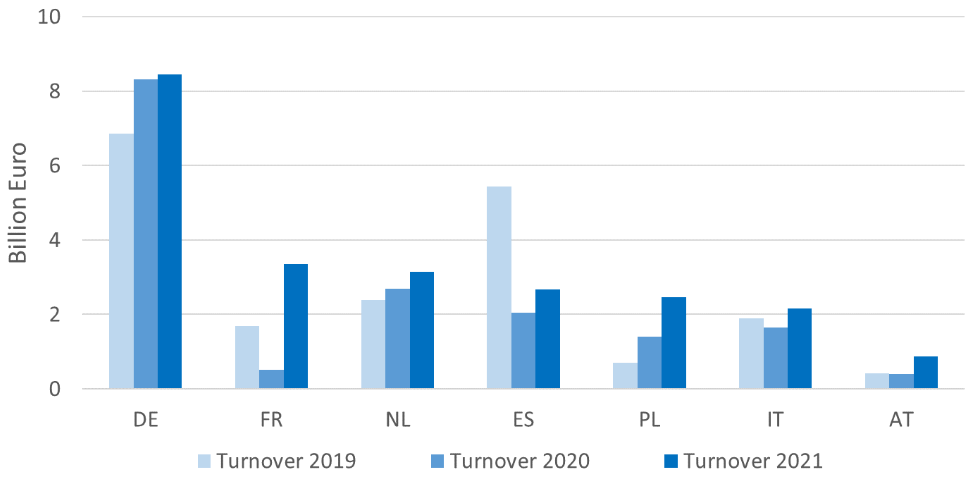
Figure 35. EU turnover in PV for the period 2015-2021.



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

Germany, France and Netherlands accounted for almost half of the EU's turnover in 2021, whereas the aggregated turnover of the top five countries in Figure 36 (Germany, France, Netherlands, Spain and Italy) makes up for almost three-quarters of the EU's turnover in the same year.

Figure 36. EU turnover in PV for the top EU countries in 2019, 2020 and 2021.



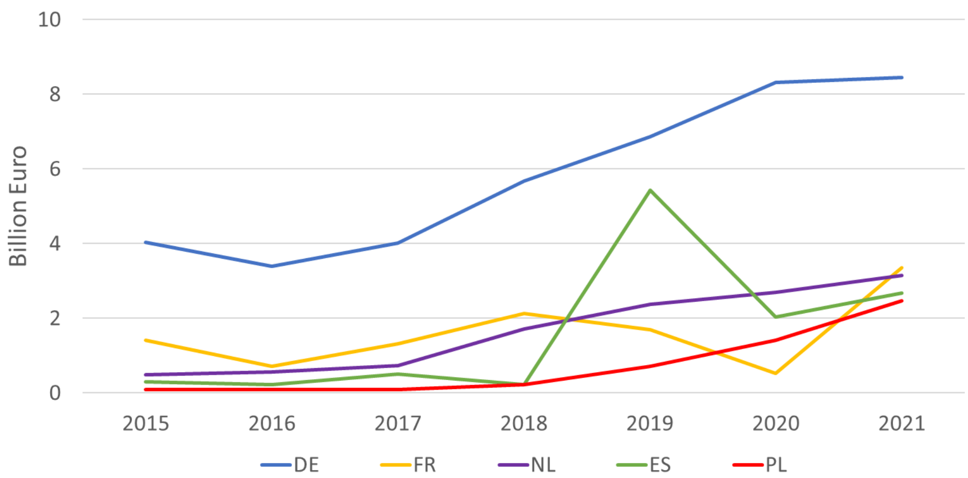
18 Euro foreign exchange reference rates: 1 USD_{2021} = 0.8455 EUR_{2021} (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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

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

Germany and Netherlands have steadily increased their turnover from 2015 to 2021 with market compound annual growth rates of 13 % and 36 % respectively. The French and Spanish markets have recovered from the 2020's decrease in turnover, with CAGR of 16 % and 45 % respectively. Even though France has managed to revert its market to higher than 2019 levels, Spain has not managed to match its 2019 turnover of EUR 5.5 billion. While the above-mentioned countries are traditionally in the top five list for all the years, Poland constitutes an emerging market with a compound annual growth rate of 77 % between 2015 and 2021 (Figure 37).

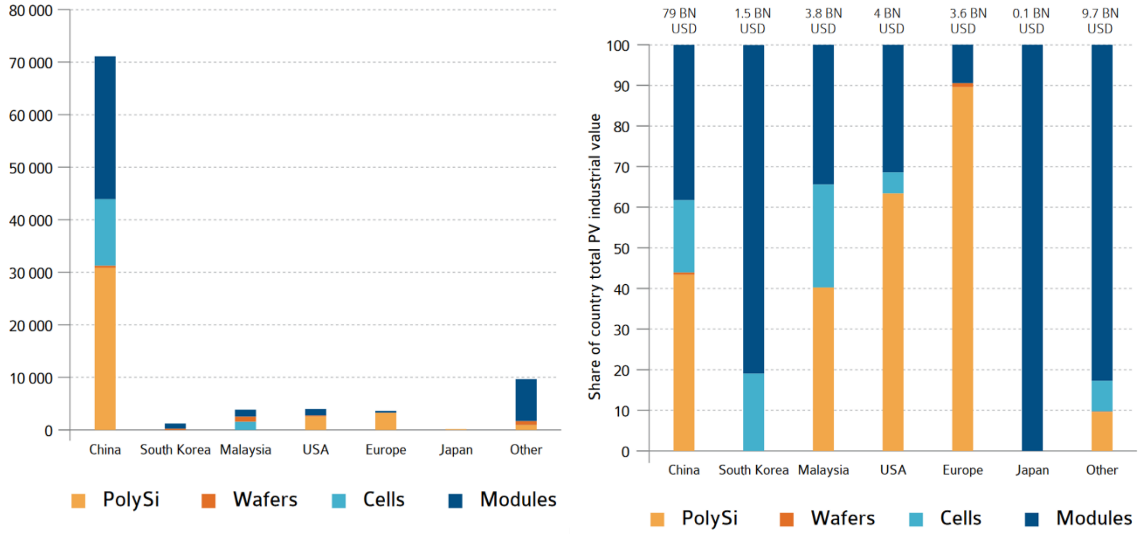
Figure 37. Turnover in PV for the top five EU countries for the period 2015-2021.



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

In addition to Poland, Estonia and Sweden are two emerging markets with strong CAGRs of 62 % and 48 % respectively for the period 2015-2021. Italy demonstrates a rather low CAGR in turnover (9 %) between the same years.

Figure 38. (a) Absolute and (b) share of turnover along the upstream (polysilicon to module) value chain for major economies in 2022.



Source: (IEA-PVPS, 2023b)

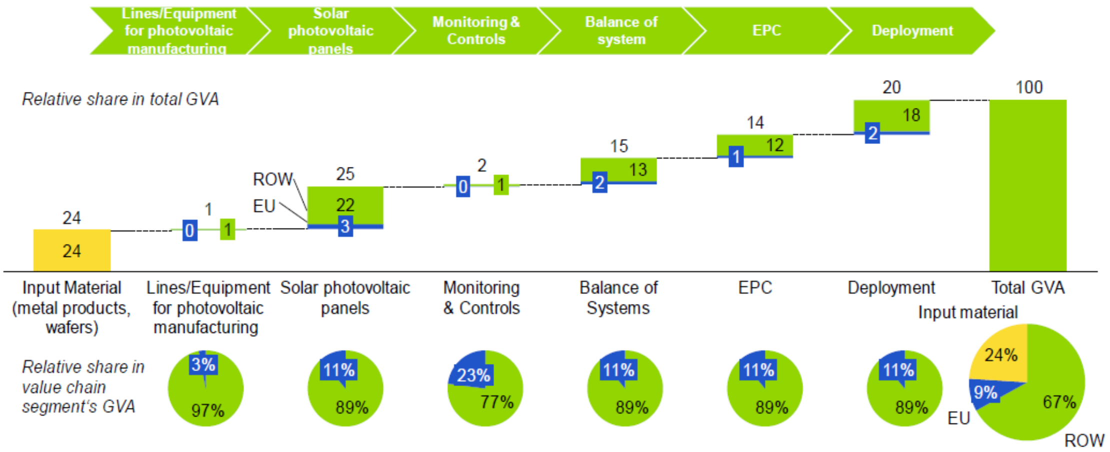
According to Figure 38a, China is dominant in all segments of the upstream (polysilicon to module) (Annex 5) PV value chain (from polysilicon to modules production) with a turnover 3 times more than all the rest of the world combined. South Korea and Japan's turnover in the upstream (polysilicon to module) PV sector is attributed to modules, whereas Europe's turnover relies mostly on polysilicon (Figure 38b). Approx. 0.40 % of China's 2022 GDP is due to the PV manufacturing sector, while for Malaysia and South Korea the respective percentages are 0.95 % and 0.07 %. In Europe, the PV manufacturing industry does not contribute more than 0.020 % to its 2022 GDP (IEA-PVPS, 2023b).

3.2 Gross value added

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

Figure 39, as already presented in previous work (European Commission, 2021) shows the EU share of the global gross value added (GVA) in the different segments of the PV value chain after being disaggregated according to their market size for the year 2020. It must be noted that inaccuracies may be present because there may be positive (equipment for PV manufacturing) and negative (for PV panels) trade balances in the different segments of the value chain.

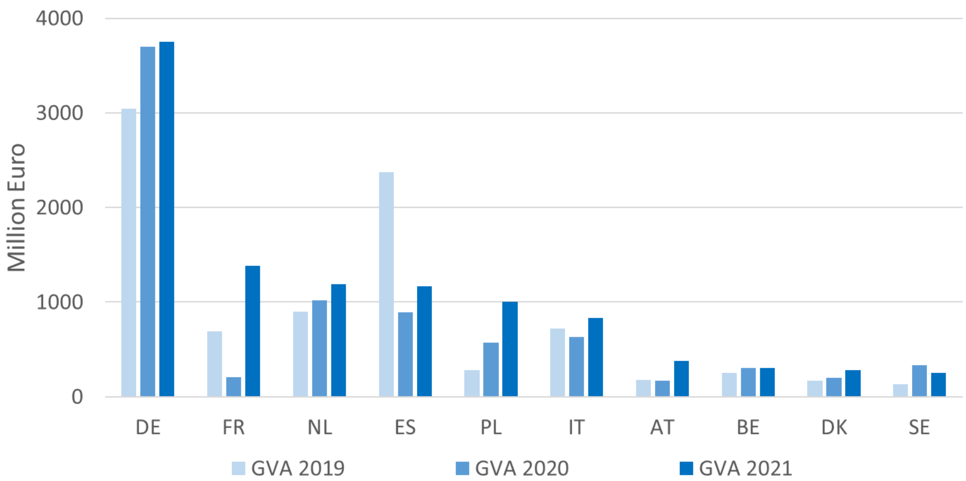
Figure 39. Breakdown of GVA throughout the solar PV value chain.



Source: Guidehouse Insights, 2020 (CPR, 2021)

EU's GVA in PV exhibited a CAGR of 20 % between 2016 (EUR 4.7 billion) and 2021 (EUR 11.5 billion). At EU level and similarly to turnover, Spain had a remarkably high gross value added in 2019 that reached EUR 2.4 billion and then decreased to around EUR 1.2 billion in 2021. By contrast, most EU countries have increased their gross value added in 2021 compared to 2020 and 2019. Germany is again the leading EU market (Figure 40).

Figure 40. Gross Value Added in PV for the top ten EU countries in 2019, 2020 and 2021.

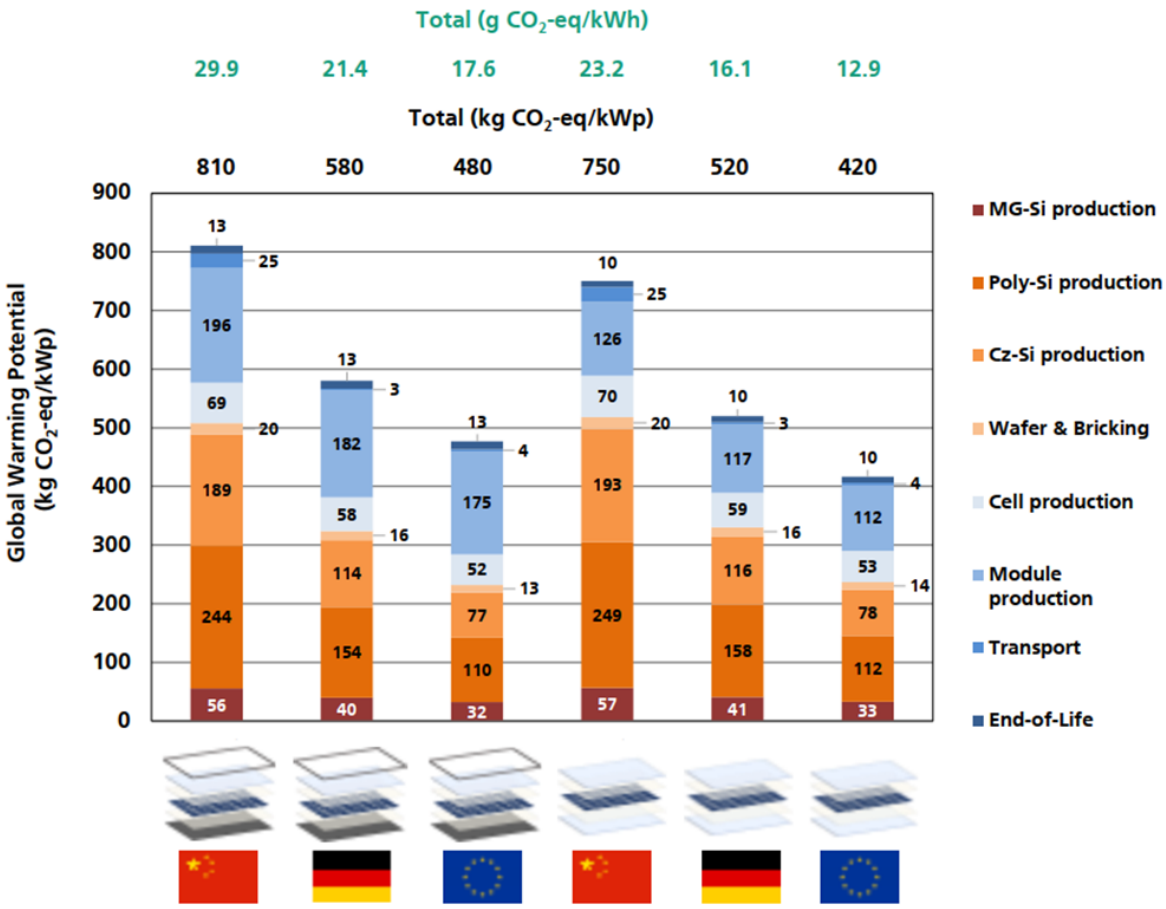


Source: JRC analysis based on (EurObserv'ER, 2022a)

3.3 Environmental and socio-economic sustainability

PV modules produced in China have a higher carbon footprint than those in the EU. PV modules manufactured in the EU produce 40 % less CO_2 than PV modules manufactured in China (Fraunhofer ISE, 2021). This is mainly attributed to the polysilicon (poly-Si) and the monocrystalline Czochralski silicon (Cz-Si) production. Regarding the different PV module configurations, the glass-glass PV modules have a slightly lower carbon footprint compared to the traditional backsheet and framed PV modules (Figure 41).

Figure 41. Carbon footprint of different PV module configurations in different countries.



Source: (ETIP-PV, 2023)

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

Additional information, also for the carbon footprint of the different PV technologies and systems as a whole, can be found in Annex 6.

3.4 Role of EU Companies

The analysis of the EU companies in the PV value chain is performed based on the structure presented in Figure 42.

Figure 42. Value chain structure.

Source: JRC 2023

The EU PV manufacturing status is presented in Figure 43 and the announced EU PV manufacturing facilities that are planned until 2025 (latest update June 2023) are presented in Figure 44. In June 2023, Norwegian Crystals, the mono c-Si ingot producer has declared bankruptcy, weakening the efforts for rebuilding the EU PV supply chain (Bernreuter Research, 2023a). In addition, in September 2023, NorSun announced a temporary suspension of its production, and ultimately also related employee layoffs, as a result of the pressure from the module oversupply in Europe (PV Magazine, 2023a). At global level, some of the major announcements are presented in Table 6.

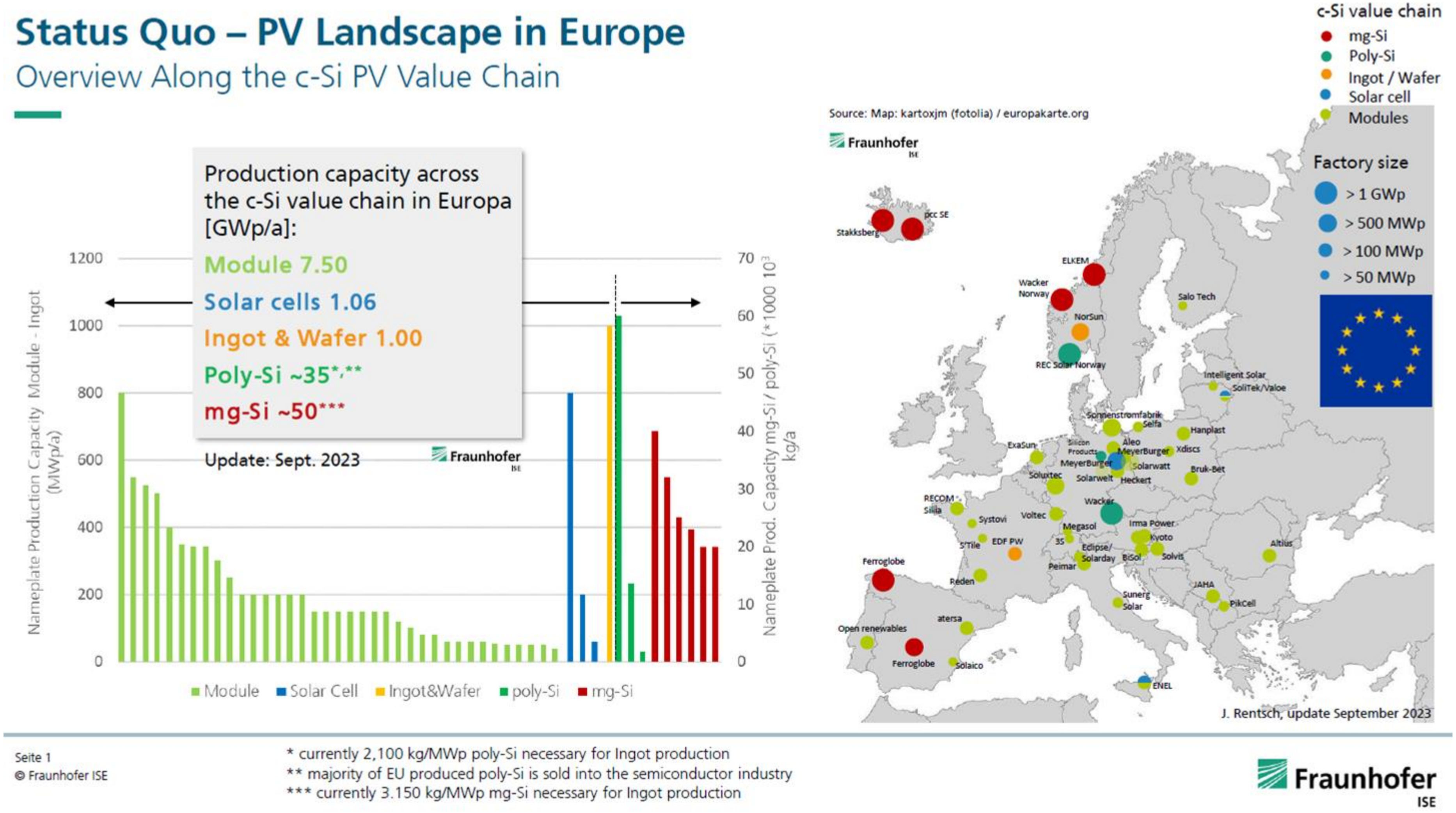
Regarding the raw materials of PV manufacturing the EU leading company in polysilicon is Wacker Chemie, while the main companies for solar glass are Interfloat Corporation (Germany), ENF Ltd. (Germany), Euroglas GmbH (Germany), Saint-Gobain (France) and Alliaverre (France). Endurans (the Netherlands),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

Furthermore to the metallurgical grade silicon (mg-Si), polysilicon, ingot and wafer, cell and module status quo in the EU in Figure 43, Annex 7 presents the main EU companies for production equipment for polysilicon, ingot, wafer, cell and module as well as for module components, tracking systems and inverters. The information has been obtained from SolarPower Europe (SolarPower Europe, 2023b).

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

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

Figure 43. PV manufacturing capacities in the EU in September 2023.



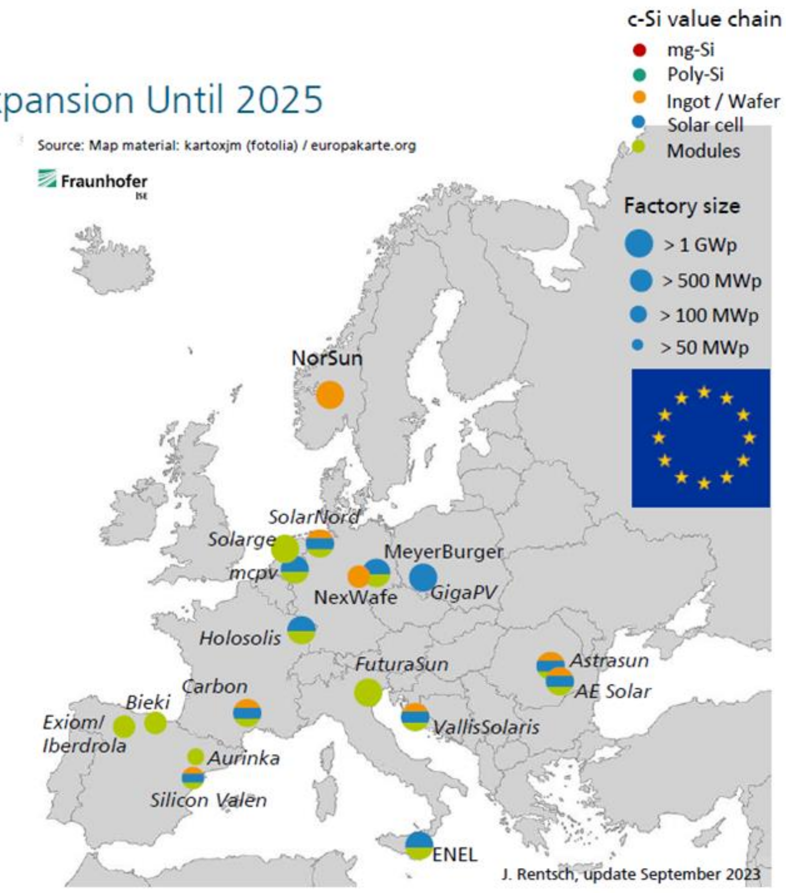
Source: Fraunhofer ISE

Figure 44. PV manufacturing capacity expansions until 2025.

Europe is on the Move …

Public Announcements for Capacity Development and Expansion Until 2025

	Ingot	Wafer	Cell	Modules
NorSun[1]	**0.5** (+4)	**0.5** (+4)		
MeyerBurger[2]			**0.4** (+ 3)	**0.4** (+ 1.6)
ENEL[3]			**0.2** (+ 3)	**0.2** (+ 3)
NexWafe[4]		+0.5		
Carbon[5]	+5	+5	+5	+3.5
VallisSolaris[6]	+2	+2	+2	+2
Exiom/Iberdrola [7,16]				+0.5/+1.6
GigaPV[8]			+1	
AstraSun[9]	+1.2	+1.2	+1	
mcpv[10]			+5	+5
FuturaSun[11]				+2
Bieki Solar Energy[12]			+2	+2
Solarge[13]				+0.5
Silicon Valen[14]	+5	+5	+5	+0.5 (+4.5)
AE Solar[15]	+2	+2	+2	+2
Holosolis[17]			+5	+5
SolarNord[18]	+5	+5	+5	+5



Source: Fraunhofer ISE

Table 6. Global PV manufacturing expansion announcements.

Country	Company	Component	New capacity
China	Lihao Semiconductor	Polysilicon	100 000 MT
China	Tongwei	High-purity crystalline silicon	120 000 MT
China	Runyang Yueda	High-purity crystalline silicon	30 000 MT
China	Shangji CNC	High-purity crystalline silicon	50 000 MT
China	Runxiang Quartz Mining	Polysilicon	260 000 MT
China	Hoshine Silicon	High-purity crystalline silicon	200 000 MT
China	LONGI Green Energy	Wafer	100 GW_p
China	TCL Zhonghuan	Wafer	35 GW_p
China	JA Solar	Wafer Crystal pulling	20 GW_p 20 GW_p
China	Jinko	Wafer	20 GW_p (first phase: 10 GW_p)
China	Canadian Solar	Wafer and cell	14 GW_p
China China	Huamin Daheng Energy	Wafer	41 GW_p
China	Shijing Technology	High efficiency n-type mono c-Si, TOPCon solar cells	34 GW_p
China	Mingpal Jewelry	TOPCon cells HJT cells	16 GW_p 4 GW_p
China	Anhui Haojing New Energy	TOPCon cells	-
China	Hongxi Energy	TOPCon and HJT cells	-
China	Maddle Technology	High-efficiency mono c-Si	9 GW_p
China	Shunfeng Electric	High-performance cells	10 GW_p
China	Zhengqi Holdings	High efficiency n-type cells	20 GW_p
China	Sunflower, Shaoxing Jicheng	TOPCon cells	10 GW_p
China	East China Heavy Machinery	High-efficiency cells	10 GW_p
China	Light Potential Energy	HJT laminated cells	10.8 GW_p
China	Hewang New Energy	High-efficiency cells	10 GW_p
China	Qingyuan Energy Group	TOPCon cells	10 GW_p
China	Yonghe Intelligent Control	Ultra-efficient n-type cells	10 GW_p
China	Tianchen Shares	High-efficiency cells	20 GW_p
China	Youhua Technology	High-efficiency cells	20 GW_p
China	Ju Neng Power	HJT cells	10 GW_p
China	Zhengxin Optoelectronics	Cells	10 GW_p

Country	Company	Component	New capacity
India	Reliance New Energy	Integrated PV	4 GW_p
India	Adani Infrastructure	Integrated PV	737 MW_p
India	Shirdi Sai	Integrated PV	4 GW_p
United States	REC Silicon	Polysilicon	20 000 MT
United States	SPI Energy	Wafers/ingots	1.5 GW_p
United States	First Solar	Thin-film modules	3.5 GW_p
United States	Q Cells	Integrated c-Si modules	9 GW_p
United States	Fuyao Group	Glass	-
United States	Toledo Solar	Thin-film modules	2.7 GW_p
United States	Meyer Burger	Modules	1.5 GW_p
United States	PV Hardware	Trackers	6 GW_p
United States	Endurans Solar	Backsheets	-
United States	Q Cells	Modules	1.4 GW_p
United States	GameChange Solar	Trackers	6 GW_p
United States	Mission Solar	Modules	700 MW_p
United States	3Sun (Enel)	Modules/cells	3.0 GW_p

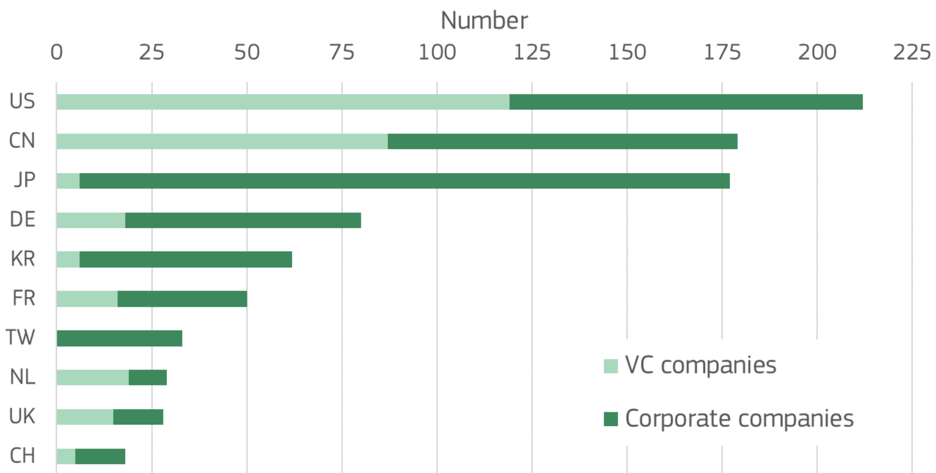
Source: (IEA, 2022c; Mercom Clean Energy Insights, 2023)

Ten countries host almost 85 % of identified innovators globally (Figure 45). The United States concurs the first position with 21 % of the world's innovating companies, followed by China with a share of 18 %. Three EU countries are included in the top ten countries of innovating companies: Germany (4th), France (6th) and the Netherlands (8th).

The United States (1st) and China (2nd) have a very strong base of venture capital companies while most of the innovators in Japan (3rd), Germany (4th) and South Korea (5th) are corporate innovators (Figure 45).

Within the EU (hosting 22 % of the globally identified innovating companies), the Netherlands and Sweden report a stronger share of venture capital companies.

Figure 45. Innovating companies in the period 2017-2022.



Source: JRC analysis based on compilation of sources

3.5 Employment

Employment in the PV sector is another parameter reflecting its market growth. Employment data differ significantly based on the data source as can be seen in Box 2. The discrepancies encountered in the different sources are a result of different methodological approaches in estimating the employment, both at EU as well as global level. From the 648 000 PV jobs in the EU in 2022, SPE estimates that 281 000 were direct. IEA-PVPS's estimation for the direct jobs created in 2022 is 330 000. IRENA reports direct and indirect jobs and estimates the EU PV jobs in 2022 to have amounted to 517 000, a number of more than 100 000 jobs lower than the 648 000 jobs SPE estimation. Taking these differences into consideration, caution is needed when evaluating the data. The present analysis uses data from EurObserv'ER and IEA-PVPS and completes where necessary with data from IRENA, namely for the global numbers. For the EU jobs of the different segments in the PV value chain, SPE data was used.

Box 2. Differences in EU and global PV employment data.

EU

	2020	2021	2022
SolarPower Europe:	357 000 PV jobs	466 000 PV jobs	648 000 PV jobs
EurObserv'ER:	166 000 PV jobs	223 000 PV jobs	Not available yet
IEA-PVPS:	185 000 PV jobs	185 000 PV jobs	330 000 PV jobs
IRENA:	166 000 PV jobs	236 000 PV jobs	517 000 PV jobs

World

	2020	2021	2022
IRENA:	3 980 000 PV jobs	4 290 000 PV jobs	4 900 000 PV jobs
IEA-PVPS:	3 980 000 PV jobs	4 290 000 PV jobs	5 800 000 PV jobs

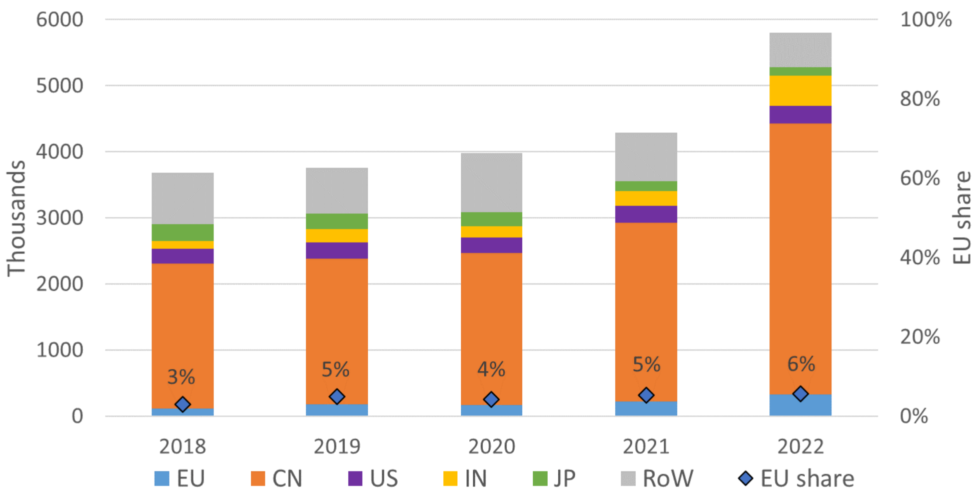
Source: (IRENA and ILO, 2021; SolarPower Europe, 2021a; IRENA and ILO, 2022; SolarPower Europe, 2022b; EurObserv'ER, 2022a; IRENA and ILO, 2023; SolarPower Europe, 2023a; IEA-PVPS, 2023b)

Between 2008 and 2016, the PV sector suffered a dramatic decrease in jobs. The compound decrease in total PV jobs in the EU was 15 %. This decrease reflected a decrease of 8 % for rooftop and 23 % for ground-mounted applications. This is in part due to base effects, owing to the sudden increase in the number of PV jobs in 2008 in Spain for the installation of around 3 000 MW of ground-mounted systems that were not maintained afterwards (EY, 2017).

Globally, PV jobs reached 5.8 million at the end of 2022 (IEA-PVPS, 2023b), from 4.3 million in 2021 (IRENA and ILO, 2023). EU's PV jobs represented 6 % of the global PV jobs in 2022. EU's position in the world for the number of total PV jobs between 2018 and 2022 is depicted in Figure 46. According to IEA-PVPS, China, that has the largest PV market in the world, accounted for 71 % of the world PV jobs in 2022 (4.1 million jobs) (IEA-PVPS, 2023b). In 2020, the EU was in the 5th place globally, after China, the United States, Japan and India. However, in 2022, the EU conquered the 3rd position behind China and India.

In 2021, of the 4.3 million PV jobs globally, 28 % are estimated to have been in the upstream sector (i.e production) and the remaining 72 % in the downstream sector (i.e. installation) (IEA-PVPS, 2022). This is in accordance with previous research conducted in 2016 stating that 25 % of EU employment supported by the PV industry was upstream and 75 % downstream (Dodd *et al.*, 2020). In 2022, the share of jobs in the upstream segment was increased to 33 % (vs. 67 % share of jobs in the downstream activities) (IEA-PVPS 2023). A 2022 report from Fraunhofer ISE (Fraunhofer ISE, 2022a) suggests that 7 500 full-time equivalents (FTEs) are needed for the production of 10 GW_p of PV generation assets from silicon ingot via wafer and cell to module, whereas the installation of 10 GW_p of PV requires 46 500 FTEs, suggesting a standard ratio of 14 % for upstream versus 86 % for downstream activities (Fraunhofer ISE, 2022a). In general, small scale PV generates more jobs than utility-scale PV (IEA-PVPS, 2023b).

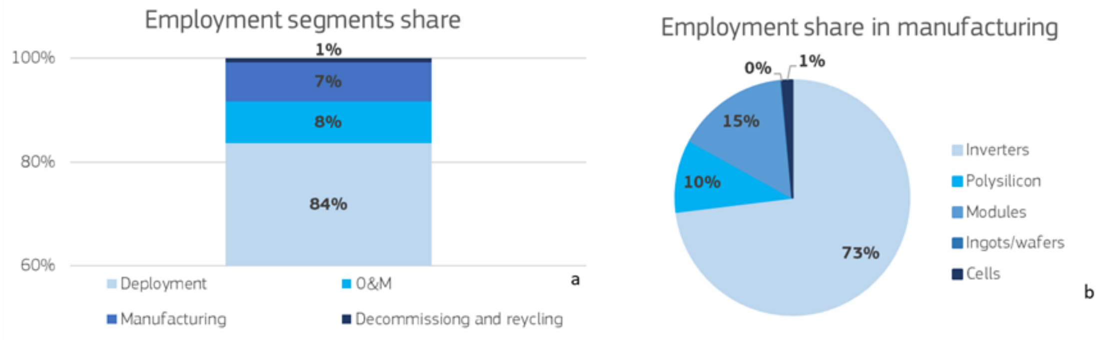
Figure 46. Global direct and indirect PV jobs and EU share between 2018 and 2022.



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

According to Figure 47a, in 2022 most PV jobs in the EU were related to deployment activities (84 % versus 79 % in 2021). Of those, a bit less than two thirds were identified as indirect jobs. O&M activities represented 7 % of total PV jobs (9 % in 2021) and of these half were direct and half indirect jobs. Jobs related to manufacturing activities account for 7 % (9 % in 2021) and are mostly direct jobs (SolarPower Europe, 2023a). The manufacturing activities are further divided into the manufacturing of inverters representing 73 % of PV jobs in 2022, up from a 70 % share in 2021 and a 46 % share in 2020 (SolarPower Europe, 2023a). On the contrary, the share of PV jobs in the polysilicon production and module production activities appear to have decreased between 2020 and 2022 from 29 % to 10 % for the former and from 22.5 % to 15 % for the latter (SolarPower Europe, 2023a). PV jobs in the inverter, polysilicon and modules sectors accounted for 98 % of the total manufacturing jobs (Figure 47b). In the polysilicon production sector, half of the jobs are direct and half indirect, whereas, in the rest of the sectors, jobs are mostly direct.

Figure 47. (a) Employment in PV value chain segments and (b) employment in manufacturing segment share in 2022.



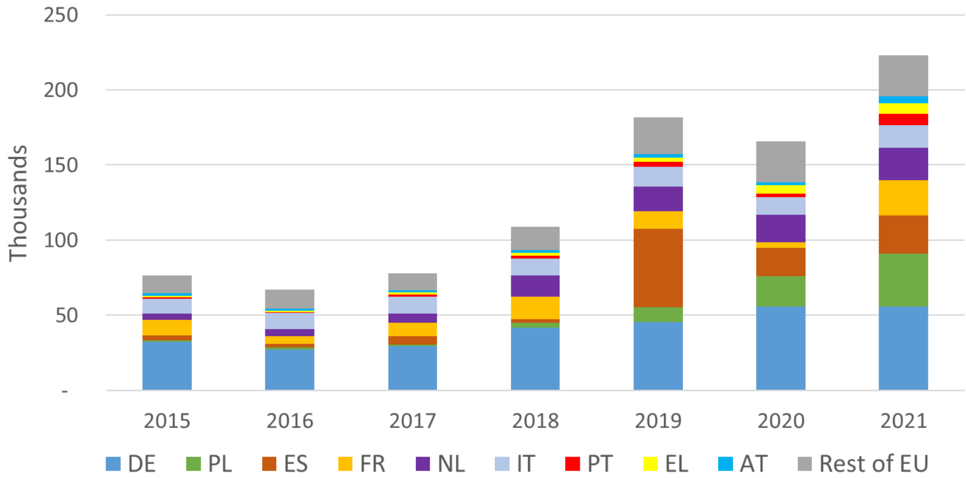
Source: JRC analysis based on (SolarPower Europe, 2023a)

As far as PV jobs with relation to applications are concerned, in 2021, 73 % of the jobs in the EU were for rooftop and 27 % for utility applications. The country with the highest, but decreasing over the years, proportion of jobs (72 % in 2020, 56 % in 2021 and 50 % in 2022) for utility applications was Spain. For rooftop applications, the highest proportion of jobs can be found in Poland and Italy (close to 90 %) (SolarPower Europe, 2023a).

As depicted in last year's report (Chatzipanagi, Jaeger-Waldau, *et al.*, 2022), there was a decrease in EU PV jobs between 2019 and 2020, mainly due to the significant respective decreases which took place in Spain and France. The 2017 auction in Spain required that all installations be realised before the next one in 2019. For this reason, the number of PV-related jobs increased notably until 2019 but decreased again afterwards as the annual power installed decreased from about 5 GW_p in 2019 to 3 GW_p in 2020. As the annual PV installations increased between 2020 and 2021 by 4.5 GW_p, so did the related jobs by 33 %. Of course, it has to be noted that 2020 was the year when Covid19 occurred and disruptions took place both in the upstream as well as the downstream activities. This report presents the EU employment data acquired from EurObserv'ER (Figure 48). Most PV jobs have been created in Germany, the country with the biggest PV market and the largest installed PV power in the EU. For 2021, in Germany, the total number of jobs, according to EurObserv'ER was 56 000, increased by only 1 % compared to 2020. Germany is followed by Poland, which was the 6th country in PV installed capacity in the EU in 2021 creating around 35 200 jobs (74 % increase compared to 2020). Spain and Netherlands had a bit more than 20 000 jobs in 2021 (Figure 48). For the period between 2015 and 2021, Germany's PV employment sector was on an upward trend with a compound annual growth rate (CAGR) of 10 %. Poland and Spain exhibit CAGRs of 76 % and 43 % respectively. High CAGRs in PV employment for the period 2015-2021 occur also in Portugal (44 %), Greece (34 %) and the Netherlands (31 %). On the contrary, Italy appears to be on a much flatter trajectory. It ranks 3rd in the EU as far as cumulative installed PV capacity is concerned but exhibits a low CAGR in employment (7 %) between 2015 and 2021 due to the fact that the country has not installed more than 800 MW_p annually these past eight years.

It has to be noted that apart from the total EU number of PV employment, SPE reports differences also at EU level (SolarPower Europe, 2023a). More in particular, according to SPE, Poland has exceeded Germany's PV-related jobs already since 2020 and Spain's PV jobs surpassed Germany's in 2022. Poland, Germany and Spain together accounted for half of the EU's PV jobs in 2022, with Poland being the fastest-growing PV jobs market in the recent years, surpassing Germany. PV jobs in Spain and Italy presented a CAGR of 50 % between 2020 and 2022. Italy is re-emerging regarding PV jobs in 2022 in the 5th position.

Figure 48. EU direct and indirect PV jobs between 2015 and 2021.



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

Regarding projections for 2027, SPE devised 3 different scenarios. These are the low, medium and high scenarios that are based on the non-, partial- and full-accomplishment of the targets of the European Solar Industry Alliance (ESIA)[20] respectively. Growth projections by 2027 range between 39 % (903 000 jobs for the low scenario) and 153 % (1 600 000 jobs for the high scenario) with a moderate increase of 86 % (1 200 000 jobs) for the medium scenario (SolarPower Europe, 2023a). The number of deployment jobs in the EU in 2027 may increase by approximately 79 % according to SPE's above-mentioned medium scenario while the number of O&M-related jobs may increase by 141 % according to the same scenario. Manufacturing-related jobs are expected to grow between 28 % (low scenario) and 168 % (high scenario). The medium scenario foresees a 104 % growth in manufacturing employment, with module and inverter manufacturing accounting for three fourths of the total manufacturing in all scenarios. Decommissioning and recycling jobs are projected to grow by 153 % based on the medium scenario as many PV systems are approaching their end of operating lifetime (SolarPower Europe, 2023a). SPE also projects that the portion of rooftop-related jobs will decrease from 73 % in 2022 to 63 %. 60 % and that of utility-scale related jobs will increase to 40 % (SolarPower Europe, 2023a).

[20] The European Solar PV Industry Alliance (ESIA) aims to accelerate solar PV deployment in the EU by scaling-up to 30 GW of annual solar PV manufacturing capacity in Europe by 2025 (https://solaralliance.eu/).

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

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

Reskilling and upskilling workers in the PV sector will be essential in the near future, if not already now, as many workers are shortly going into retirement. At the same time, the needs for workers will continue to grow along with the planned manufacturing expansions as well as the planned installations in the next years.

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

3.6 Energy intensity and labour productivity

3.6.1 Energy intensity

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

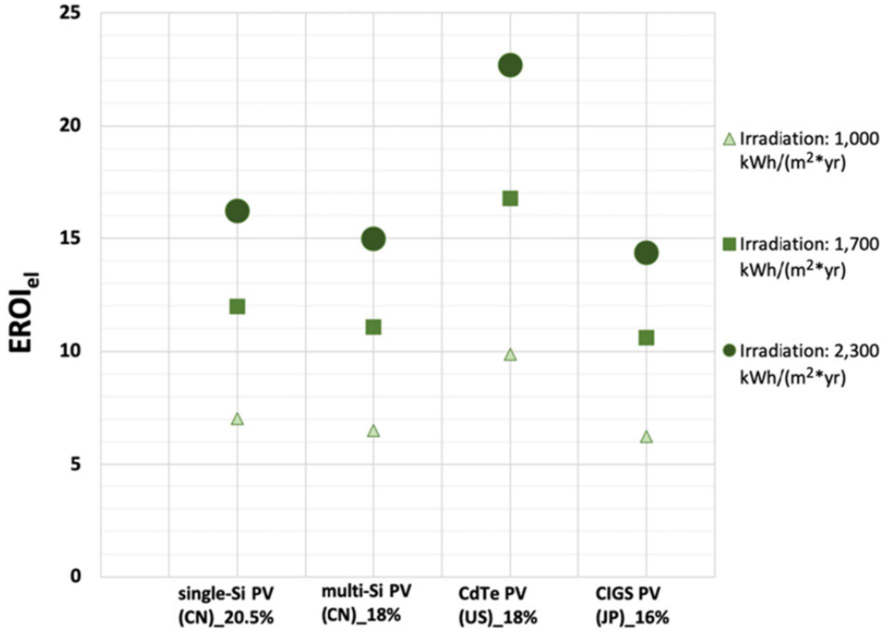
According to Fraunhofer ISE, in the past 24 years, the Energy Payback Time (EPBT) of PV has experienced a decrease of 12.8 %. Depending on the location and the technology used for the PV system, its EPBT can be as low as 0.9 years (South Europe), while in the Northern European countries it slightly exceeds the one year (Fraunhofer ISE, 2023).

Figure 50 shows presents an EPBT comparison between different PV technologies at different irradiation levels in different global locations.

EPBT for PV systems produced in Europe is shorter than for those produced in China because of better grid efficiency[21] in Europe." (Fraunhofer ISE, 2023). Additional information can be found in Annex 6.

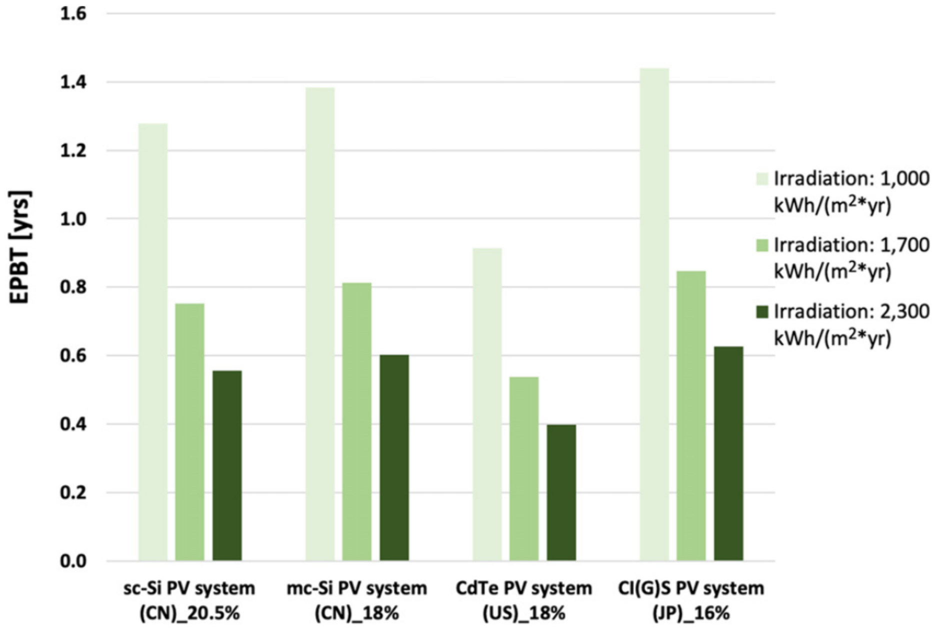
[21] The higher, the better in countries where upstream production is located; (better energy mix to generate electrical power; less losses in the electrical transmission network). At downstream (where PV is installed) a low grid efficiency reduces the EPBT (Fraunhofer ISE, 2023).

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



Source: (Fthenakis and Leccisi, 2022)

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

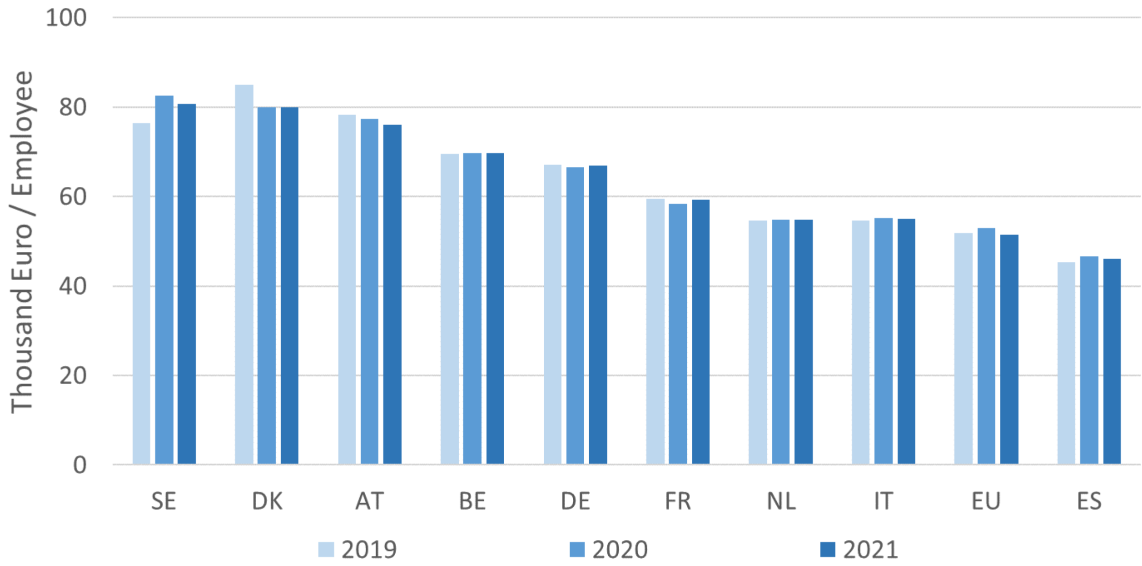


Source: (Fthenakis and Leccisi, 2022)

3.6.2 Labour productivity

The labour productivity of the entire PV value chain for the years 2019, 2020 and 2021 is presented in Figure 51. The most job-intensive segments along the upstream PV supply chain are module and cell manufacturing. Over the last decade, however, the use of automation and automated guided vehicles has increased labour productivity, thereby reducing labour intensity (IEA, 2022b).

Figure 51. PV labour productivity in the EU in 2019, 2020 and 2021.



Source: JRC analysis based on EurObserv'ER

3.7 EU Production Data

No production codes are explicitly associated with photovoltaics. The selected Prodcom codes, "PRODuction COMmunautaire" (Community Production), (Table 7) correspond to vague product groups that include solar cells, semiconductor devices and photovoltaic cells. However, they can be used as a proxy for understanding the trends.

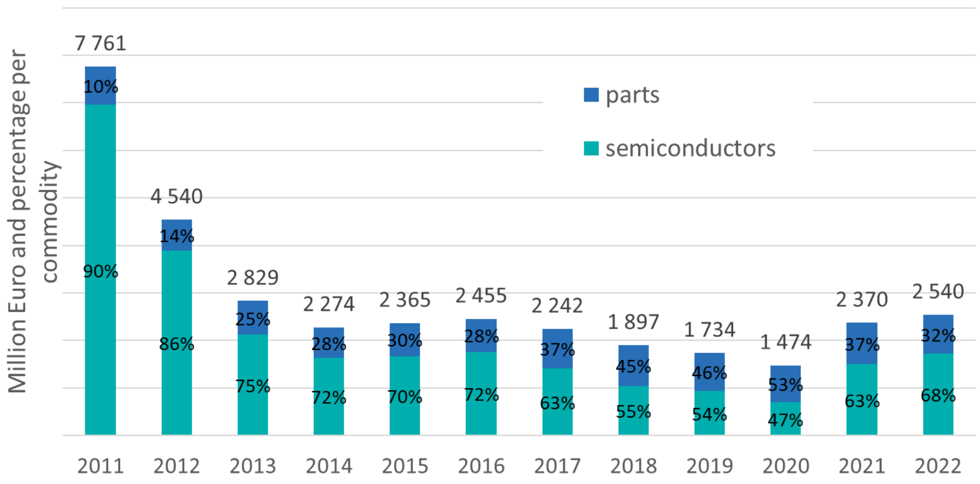
Table 7. Prodcom codes as a proxy for PV production.

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

Source: JRC analysis based on PRODCOM

Figure 52 shows the EU production in value. Over the past ten years (2013-2022), the overall production value shrunk by 10 % with an annual compound growth of -1 % and an average value of EUR 2.2 billion. In 2022, the total value had a 7 % increase compared to the previous year, reaching EUR 2.5 billion. Semiconductors occupy the biggest share of the EU production value, while the production value of parts has increased after 2018.

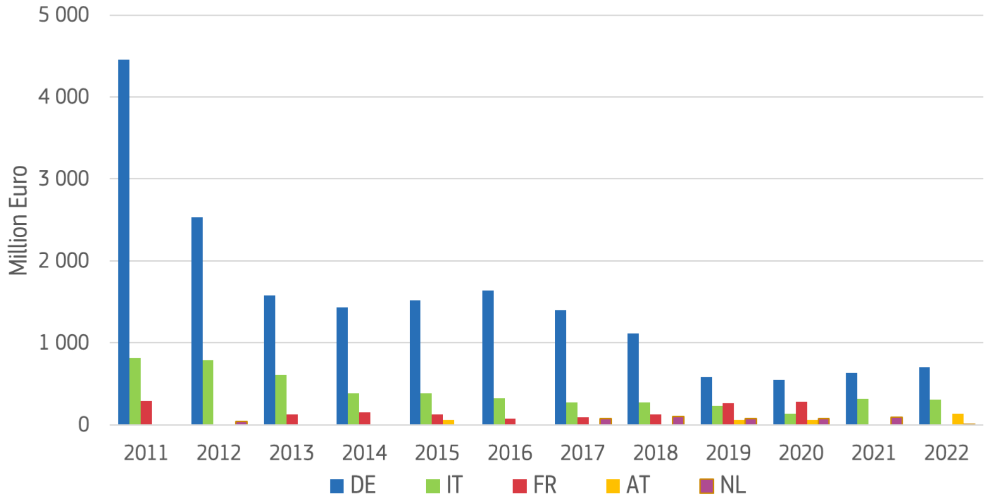
Figure 52. EU production value per commodity for the period 2011-2022.



Source: JRC analysis based on PRODCOM

Germany and Italy were the top EU producers (Figure 53) holding 50 % and 14 % of the total EU production respectively (ten-year average). Germany had a balanced production of both commodities, while the 90 % of Italy's production was about semiconductors. Not all Member States keep disclose their production data and this is why some years have no boxes for France, Austria and Netherlands.

Figure 53. Top five EU PV producers for the period 2011-2022.



Source: JRC analysis based on PRODCOM

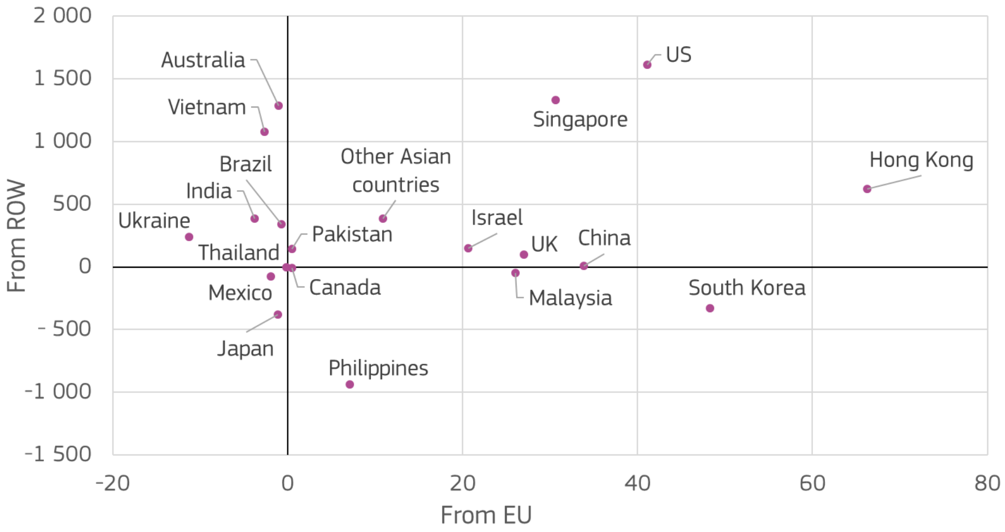
4 EU Market Position and Global Competitiveness

4.1 Global & EU market leaders

Figure 54 demonstrates EU's position in different markets for the period 2019-2021. The horizontal axis shows the 2-year average of net import change from the EU and the vertical axis shows the 2-year average of the net import change from the rest of the world. Countries in quadrant I (above the horizontal axis and right of the vertical axis) are considered to have a growing market (increase of imports). Countries in quadrant III (below the horizontal axis and left of the vertical axis) have less imports.

China's market is experiencing rapid growth as it is the most cost-competitive location for the manufacturing of all PV components throughout the entire supply chain (IEA, 2022b). It is reported that costs in China are 10 % lower than in India, 20 % lower than in the United States and 35 % lower than in Europe. This is due to China's lower energy, labour and investment costs (IEA, 2022b). In Europe, rising energy prices following the geopolitical circumstances of years 2021-2022 widened the cost gap with China. In 2022, EU industrial energy prices are more than triple those of China, India and the United States (IEA, 2022a).

Figure 54. EU positioning in different markets with 2-year average (2019-2020 and 2020-2021) of change in import from the EU and ROW.



Source: JRC based on UN Comtrade data

In 2015 China accounted for 65 % and 69 % of the global PV cell and module (crystalline and thin-film) production respectively (Survey report of Selected IEA Countries between 1992 and 2015 – IEA-PVPS). In 2022, the country increased its share to 84 % and 78 % for cell and module production respectively while Europe accounted for only 0.2 % and 0.6 % respectively (Trends in photovoltaic applications 2023 – IEA-PVPS). Vietnam and Malaysia hold a significant and increasing share in cell and module manufacturing as countries in which major Chinese solar cell manufacturers have built production lines in an attempt to overcome the barrier of the USA antidumping duties and countervailing duties imposed on Chinese products (Trends in photovoltaic applications 2023 – IEA-PVPS).

The global leaders in cell and module (crystalline and thin-film) manufacturing in 2022 are presented in Table 8 (IEA-PVPS, 2023b). These leading companies are all based in China apart from Canadian Solar which is headquartered in Canada but has most of its factories in China. These top five companies accounted for 47 % and 52 % of the global cell and module (crystalline and thin-film) production in 2022 (IEA-PVPS, 2023b).

Table 8. Top five global manufacturers for cell and module manufacturing in 2022.

Cell production (GW_p)	Module production (GW_p)
Tongwei Solar (49.2)	LONGI Green Energy Technology (48.2)
LONGI Green Energy Technology (36.2)	Trina Solar (45.4)
Aiko Solar (33.7)	JA Solar Technology (43.9)
Trina Solar (33.6)	Jinko Solar (40)
JA Solar Technologies (32.7)	Canadian Solar (21.1)

Source: (IEA-PVPS, 2023b)

Other major companies in the sector are Hanwha Q CELLS (South Korea), First Solar (United States), BrightSource Energy, Inc. (U.S.), SunPower Corporation (U.S.)[22], Yingli Solar (China), Wuxi Suntech Power Co. Ltd. (China), Waaree Group (India), AccionaEnergia S.A. (Spain), Nextera Energy Sources LLC (U.S.), Vivaan Solar (India), eSolar Inc. (U.S.), Tata PowerSolar Systems Ltd. (India) and Abengoa (Spain) (Fortune Business Insights, 2022).

Module shipments from 2019 until 2022 for the five leading companies are presented in Table 9.

Table 9. Top five global manufacturers for module shipments from 2019 until 2022.

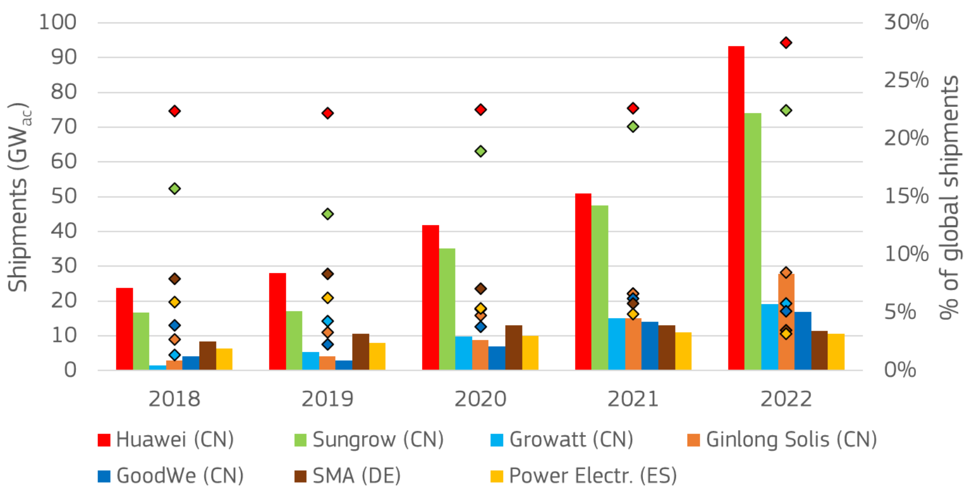
Companies	Module shipments (GW_p)			
	2019	2020	2021	2022
LONGI Green Energy Technology	8.4	24.5	38.5	46.8
Jinko Solar	14.3	18.8	22.2	44.5
Trina Solar	10.0	15.9	24.8	43.1
JA Solar Technology	10.3	15.0	25.5	39.8
Canadian Solar	8.6	11.3	14.5	21.1

Source: (IEA-PVPS, 2023b)

The inverter market has also seen a tremendous market expansion as a result of the extended PV deployment activities. Revenues for inverters manufacturing companies have increased over the years. Global inverter shipments grew from 98.5 GW_{AC} in 2017 to 330 GW_{AC} in 2022, a compound growth of 27 % (PV Magazine, 2018, 2019, 2020, 2022, 2023b, 2023c; CDS Solar, 2022). Huawei is the leading inverter supplier for the past seventeen years. After a consecutive three-year period (2018-2020) of ranking in the 3rd and 4th position, the two European suppliers SMA (Germany) and Power Electronics (Spain) have been surpassed by three Chinese companies (Growatt, Ginlong Solis and GoodWe) and are placed in the 6th and 7th position respectively based on their shipments growth in 2022 (Figure 55) (CDS Solar, 2022; PV Magazine, 2022, 2023c).

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

Figure 55. Global inverter shipments for the period 2018-2022.



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

Between 2019 and 2022 inverter shipments exhibited a 38 % increase in compound growth from approximately 127 GW_{AC} (2019) to 330 GW_{AC} (2022). In the same period, the compound growths of the two major inverter manufacturers Huawei and Sungrow were 49 % and 63 % respectively. Growatt, Ginlong Solis and GoodWe have increased their shipments by 52 %, 88 % and 81 % (compound growth) and completed the top five inverter manufacturers list. SMA and Power Electronics have exhibited a 3 % and 10 % compound growth in 2022 and hence have been shifted outside the top five global leading manufacturers (already since 2021).

In 2022, half of the global inverter shipments were destined for the Asia-Pacific market (the largest market) and China accounted for 78 % of the market. Europe and the United States had a 28 % and 13 % share of global shipments in 2022 (PV Magazine, 2023b). Despite the decrease of the European inverter companies' shipments shares, Europe exhibited its highest shipment growth in 2022 (82 %) (PV Magazine, 2023b).

EU's position in the upstream and downstream value chain segments is distinctively different. The EU holds a considerable share in the equipment and inverter manufacturing segments of the PV value chain. However, it lags as far as large-scale production of polysilicon, wafers, cells and modules is concerned. The high labour, energy, materials and equipment costs for the large-scale production segment are the main reason why countries like China, where these costs are lower, dominate these segments of the value chain. The difference in the costs is as high as 74 % (ETIP-PV, 2023). However, it has to be noted that the increasing automation in manufacturing render energy costs a more influencing parameter.

Even though the EU is a technology leader in polysilicon, in the past years cannot compete with the large-scale production facilities developed in China. Wacker Chemie in Germany and MEMC Merano in Italy have been in the top ten of polysilicon manufacturer in 2004. In fact, in 2004, Wacker Chemie had the second highest manufacturing capacity after Hemlock Semiconductor in the United States. Wacker Chemie was also the largest polysilicon manufacturer between 2016 and 2019. In 2020, the situation has changed and the company held the third position in the global market with 84 000 MT (18 % share of the total global production) after the Chinese company Tongwei with 96 000 MT (20.5 % share of the total global production) and the Hong-Kong based GCL-Poly with 90 000 MT (19 % share of the total global production). The fourth, fifth and sixth position held again Chinese companies (Bernreuter Research, 2023b).

Between 2019 and 2022, the EU domestically produced PV modules could not compete with the Chinese ones. Despite the announcement of several energy policies, such as the Green Deal Industrial Plan (GDIP) and the Net Zero Industry Act (NZIA), that aim to boost the domestic manufacturing and decrease dependency on China, the EU imported from China a 87 GW_p capacity of PV modules between 2021 and 2022 (112 % increase of imports) but managed to install less than half, remaining therefore with 47 GW_p of PV module stacked in warehouses. The projections for 2023 show that the imports will reach 120 GW_p of which almost 60 GW_p will be kept unused (RystadEnergy, 2023). Bloomberg draws attention to the fact that, despite the accelerating pace of PV installations, the manufacturing boom in China (Table 6) will further lower the costs, decrease the profit margins and create an overcapacity that may put at risk of bankruptcy several Chinese companies (Bloomberg, 2023). At the same time, the created oversupply and continuous lowering prices of Chinese PV modules threaten the coveted European re-build of PV manufacturing. Concerns regarding the potential bankruptcies following that of Norwegian Crystal due to the intensification of the competition from China have risen significantly lately. In September 2023, the European Solar PV Alliance released a document with recommendations regarding the financial mechanisms to fill the cost gap and restore the PV industry in Europe (ESMC, 2023b).

China is the leader in the polysilicon, ingot, wafer, cell and module manufacturing segments of the value chain with a share of 63 %, 95 %, 97 % (96 % in 2021), 79 % and 71 % (78 % in 2021) of these global markets respectively (IRENA and ILO, 2022). The EU was a leader in equipment and inverter manufacturing as it is more knowledge-intensive and the EU has a highly skilled workforce and research infrastructure (Bolscher *et al.*, 2017). In 2015, the EU's share in turnover related to equipment manufacturing was 63 % and related to inverter manufacturing it was 20 % of the global turnover. Its share in the other value chain segments was less than 10 % (Bolscher *et al.*, 2017). However, in more recent years, the situation has changed as one of the strongest EU-based inverter manufacturer, SMA (Germany), has gradually seen its market share being reduced (from 8 % in 2018 to 3 % in 2022) while China-based companies increased their share in the segment. The 2nd European inverter manufacturing company in the global top ten inverter shipments is Power Electronics (Spain) which has also seen its market share decrease from 6 % in 2018 to 3 % in 2022. Apart from SMA and Power Electronics, other important EU inverter manufacturers at global level are Fronius, Ingeteam and Fimer. In other BoS activities, Soltec is a strong global competitor in the field of trackers. EU companies are also strong competitors in downstream activities (EPC, O&M and recycling).

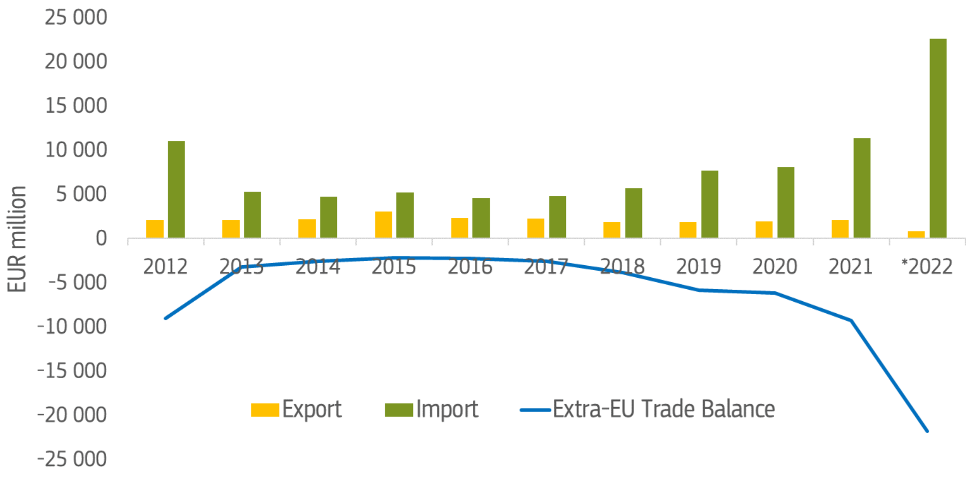
The value chain disruptions experienced in the previous years as well as the concentration of supply in China has led major economies to adopt manufacturing policies in an effort to diversify their supply chain and boost their domestic manufacturing capabilities. The United States' Inflation Reduction Act (IRA), India's Product Linked Incentive (PLI) Scheme and EU's Net Zero Industrial Act (NZIA) are expected to increase PV production capabilities outside China and reduce PV production costs that will render manufacturing outside China (and Asia) competitive. In particular, because of these policies, it is expected that China's share will decrease from 80 % - 95 % (depending on the segment) to 75 % - 90 % (depending on the segment) by 2027 (IEA, 2022a). Additional trade-related policies supporting domestically and low carbon manufactured products can reduce China's share even more to 60 % - 75 % by 2027 (IEA, 2022a). An EMBER report projects that China's solar manufacturing capacity will reach 931 GW_p/year in 2023, while Europe's target for 2025 is 30 GW_P/year. In the United States, the IRA is bringing forward investments of 85 GW_P/year of PV manufacturing capacity and India, through PLI, aims to reach a manufacturing capacity of 110 GW_P/year by 2026 (Hawkins, 2023).

4.2 Trade (Import/export) and trade balance

International trade is monitored using six-digit codes of the Harmonised System (HS) classification. In 2022, the HS nomenclature was revised, and the codes used for photovoltaics (PV) are affected. More specifically, the previously used 854190 (Photosensitive semiconductor devices, incl. photovoltaic cells) has been restructured to "Parts, diodes, transistors", and the previously used 854140 (Photosensitive semiconductor devices, incl. photovoltaic cells whether or not assembled in modules or made up into panels; light emitting diodes (excl. photovoltaic generators)) was discontinued and substituted by four new codes: 854141 (Light-emitting diodes (LED)), 854142 (Photovoltaic cells not assembled in modules or made up into panels), 854143 (Photovoltaic cells not assembled in modules or made up into panels) and 854149 (Other). The new nomenclature is effective as of January 1st 2022, and does not apply to the previous years. For the purposes of this study, codes 854190 and 854140 are used until 2021 and 854142 and 854143 as of 2022. In some cases, 854149 could not be excluded from 2022 calculations. However, the data analysis showed that it had a consistently low share for both imports (1 %) and exports (7 %) in both versions of the nomenclature. When all new codes are considered, assembled PVs (854143) represented 28 % of the extra-EU exports and 87 % of the extra-EU imports, while non-assembled PV cells (854142) represented 1 % in both trade flows. Therefore, the new nomenclature allows the elimination of non-relevant products in the dataset as of 2022.

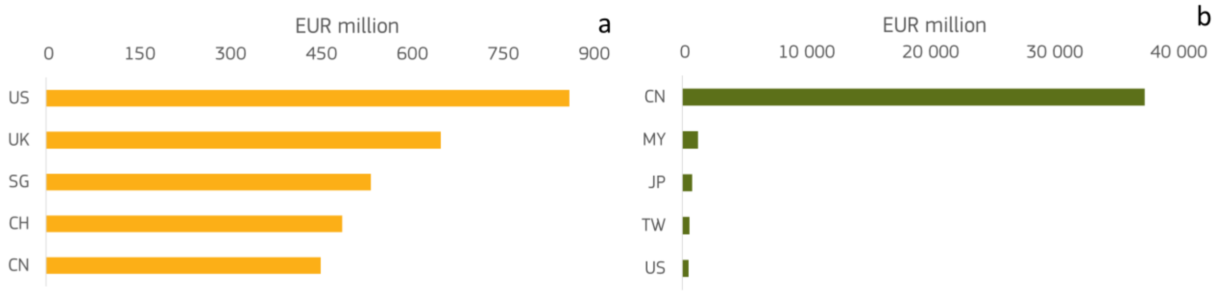
The EU presence as an importing partner in the global market is intensifying as, in 2022, imports almost doubled, and exports more than halved compared to the previous year, resulting in a trade deficit of almost EUR 22 billion (Figure 56). However, assuming that the new HS nomenclature allows for a filtering out of the non-relevant elements in previous years, we may say that extra-EU exports are almost stable, since LED were 25 % and semiconductors 40 % of the importing streams. 2022 includes only the new codes. The extra-EU share in global exports remained low (3 %) for 2020-2022.

Figure 56. Extra-EU trade for the period 2012-2022.



Source: JRC based on COMEXT data

Figure 57. Top countries (a) importing from and (b) exporting to the EU for the period 2020-2022.



Source: JRC based on COMEXT data

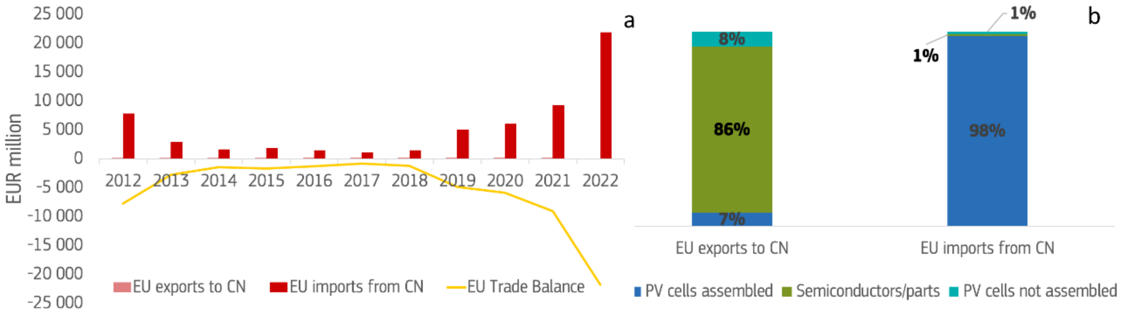
While importing flows from the other top exporters to the EU (seemingly) decreased in 2022, imports from China more than doubled, reaching almost EUR 22 billion with the main imported product being assembled PV cells (Figure 58a and b). According to an EMBER report, exports of solar modules from China increased by 34 % in the first half of 2023 compared to the same period last year (Hawkins, 2023).

The intra-EU imports remained at the same level (32 % in 2020-2022). China remained the main partner for EU imports holding 83 % of total extra-EU imports (

Figure **57**a and b), much higher than the 65 % limit set by NZIA[23]. Netherlands, Germany and Spain, the top EU importers for 2020-2022, imported respectively 84 %, 73 % and 97 % of their extra-EU imports from China. In 2022, the EU imports from Malaysia, Taiwan and the United States decreased by -54 %, -32 % and -56 % compared to the previous year, and the main imported product was assembled PV cells (97 %, 88 % and 76 % respectively). Imports from Japan shrunk by 94 %, and the main imported product was parts (64 %). However, given the HS distribution for 2022, LED and semiconductors must account for an important share of the previously observed imports.

[23] COM(2023) 161 final & SWD(2023) 68, 16th March 2023. Net Zero Industry Act

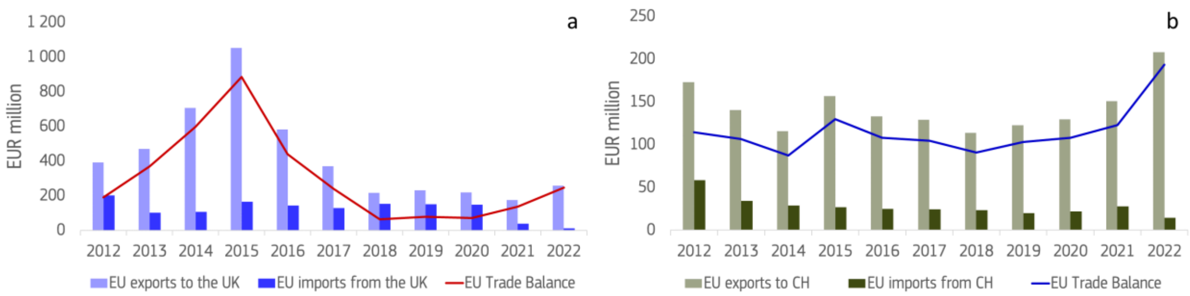
Figure 58. (a) EU trade and (b) share of traded goods with China for 2022.



Source: JRC based on COMEXT data

In 2022, EU exports fell to under EUR 0.8 billion, but the decrease is mainly due to fact that the new HS nomenclature has cleared the data from irrelevant LED and semiconductors. Netherlands, Germany and France were the top EU exporters for 2020-2022. More than half of the Netherlands' export flows (55 %) went to the UK and France's (50 %) to Singapore, while Germany had a more diversified portfolio of export customers. In 2022, EU exports to the UK and Switzerland increased by respectively 47 % and 38 % compared to the previous year (Figure 59a and b), and the main trading product was assembled PV cells. Exports to Singapore and China were minor and consisted mainly by parts. Exports to the United States dropped by -72 % and consisted of 51 % assembled PV cells and 44 % parts.

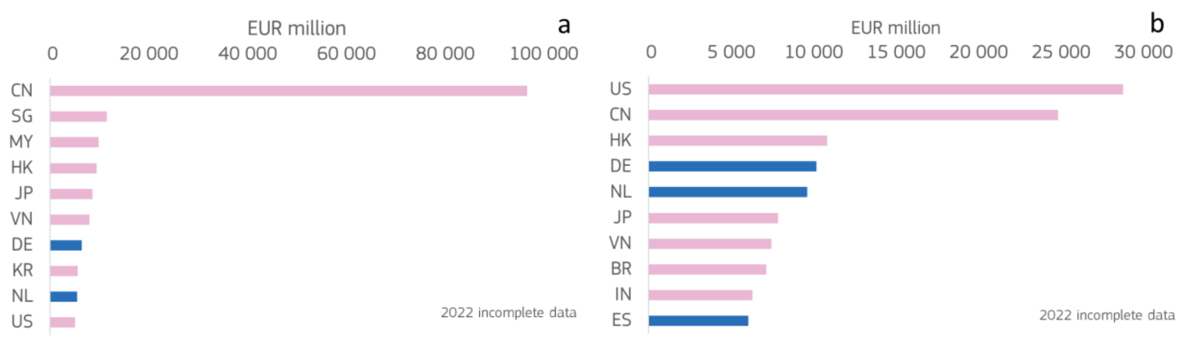
Figure 59. EU trade with (a) the UK and (b) Switzerland.



Source: JRC based on COMEXT data

The EU maintained its presence amongst the top ten global exporters and importers (Figure 60a and b). Germany fell two ranks among the top exporters but kept its position in the top importers ranking. The Netherlands advanced one position among the top exporters and two among the top importers. Spain also appeared among the top global importers.

Figure 60. Top global (a) importers and (b) exporters for the period 2020-2022.



Source: JRC based on COMEXT and COMTRADE data

Among non-EU growing markets in terms of their imports[24] during 2019-2021[25], EU companies managed significant exports only to the UK, with a 36 % share of imports in this country coming from the EU (Table 10).

Table 10. Non-EU growing markets based on a 2-year average of net import change.

Country	Total import (2019-2021) [EUR Million]	% import from the EU	2-year average of net import change
United States	25 645	4 %	1 654
Singapore	6 248	13 %	1 362
Australia	3 634	1 %	1 288
Vietnam	10 714	0 %	1 074
Hong Kong	14 049	3 %	689
Other Asia, nes	2 788	6 %	396
India	7 107	1 %	381
Brazil	4 368	1 %	340
Ukraine	1 564	2 %	230
Israel	864	14 %	169
Pakistan	1 096	0 %	146
United Kingdom	1212	36 %	128
China	29 671	7 %	44

Source: JRC based on COMTRADE data

An interesting result from the analysis is that the Netherlands, Spain, Germany, Poland, France, Greece and Italy appear to be concentration points of the extra-EU imports and re-distributing points for the intra-EU trade. Italy has exporting relation with Africa, while Sweden, Denmark and Greece with South America (ESMC, 2023a).

4.3 Resource efficiency and dependence in relation to EU competitiveness

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

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

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

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

24 Calculated as $net\ import\ change = [(import_{2020} - import_{2019}) + (import_{2021} - import_{2020})]/2$

25 Latest year data (2022) may be incomplete for COMTRADE, because it does not provide estimates for the missing values as COMEXT does.

film technologies. The components segment is characterised by the highest supply risk and in fact, the EU is importing over 90 % of the main components of solar modules, mainly wafers and solar cells (PVEurope, 2022). The final assembly is characterised by higher risk for the crystalline silicon than for the thin-film modules (Carrara *et al.*, 2023).

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

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

As far as the future consumption of raw primary materials is concerned, the projections for 2050 show a variation between the different materials depending on the scenarios (low and high demand) and the market share of each technology. Taking into account that the crystalline technology will remain the dominant PV technology in the forthcoming years, the projections for 2030 report that the silicon and silver demand will increase 1.8 times compared to 2020. The increase in demand in 2050 (compared to 2020) will be 1.4 times for silicon and silver, reflecting the accomplished material efficiency (Carrara *et al.*, 2023). Copper demand will increase by 2 and 2.3 times compared to 2020 in the years 2030 and 2050 respectively. Other projections report that the demand for silicon, for the Net Zero emissions by 2050 scenario, will be 1.7 times the 2022 demand. For copper, the respective demand for 2050 will be 2.5 times the 2022 demand (IEA, 2023a).

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

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.

5 Conclusions

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

The global cumulative PV installed capacity exceeded 1 TW_p in March 2022 and estimations for 2023 are above 1.5 TW_p. The EU alone reached a cumulative installed PV capacity of over 211 GW_p at the end of 2022 and a cumulative electricity generation of 196 TWh from PV systems. According to projections, the EU capacity will increase to 328 GW_p in 2025, between 500 GW_p and 1 TW_p in 2030 and between 7 TW_p and 8.8 TW_p in 2050, whereas the projected global installed capacity will increase between 22 TW_p and 60 TW_p.

The average PV module efficiency has increased from 9.0 % in 1980 to 14.7 % in 2010 and 21.1 % in 2022. In the next few years, silicon-based PV technology will remain the predominant technology with module efficiencies reaching 24.0 % and over. As a possible future alternative to silicon, perovskite technology has developed rapidly and has the potential to achieve comparable costs (current module efficiency is 18.6 % while the record cell efficiency is 24.35 ± 0.5 %). Two of the most promising and efficient technologies are silicon-based tandems with III-V top material (currently at 32.65 ± 0.7 % module efficiency) and perovskite-silicon tandem devices (28.6 % module efficiency for large area cells as required for module production). The market's tendency towards the replacement of Passivated Emitter and Rear Contact (PERC) architecture (currently at ~21.0 % module efficiency with projections reaching 23 % in 2033) by the n-type Tunnel Oxide Passivated Contact (TOPCon) (currently at 22 % module efficiency with projections reaching 24.0 % in 2033) is bringing further efficiency increases towards 25.0 % in 2033. Continuous research and improvement are required to achieve such higher efficiencies, combined with lower material consumption and lower costs.

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

The Levelised Cost of Electricity (LCoE) from photovoltaics and electricity storage has decreased significantly in the past years. The global weighted-average LCoE for utility-scale projects fell by 88 % between 2010 and 2022 from USD 0.417/kWh to USD 0.045/kWh. Projections for the EU indicate that it will further decrease from the 2020 values of EUR 0.050/kWh (Northern Europe) and EUR 0.020/kWh (Southern Europe) to EUR 0.020/kWh (Northern Europe) and EUR 0.010/kWh (Southern Europe) in 2050, rendering PV technology as a competitive renewable energy technology.

EU PV companies are facing considerable competition, especially from China, which has a leading market in PV and exhibits minimal dependence on the EU. Most of the leading solar cell and module production companies are Chinese and they dominate the PV module shipments. In 2022, China accounted for over 84 % of the total global cell (crystalline and thin-film) production, whereas the top five cell (crystalline and thin-film) manufacturers (all Chinese companies) accounted for almost half of the global production. In module production China accounted for 78 % of the global production (crystalline and thin-film) with four of the top five companies being based in China and producing 52 % of the global PV modules. Vietnam and Malaysia (countries where Chinese companies have built manufacturing plants) accounted for 5 % each of the global PV cell production and 6.5 % and 2.8 % of the global PV module production respectively. Additionally, according to the IEA, the costs for PV manufacturing in China are considerably lower than in Europe. Costs in China are 10 % lower than in India, 20 % lower than in the United States, and 35 % lower than in Europe. EU's recent competitiveness regarding the inverter market has suffered a considerable hit in 2022 as more Chinese companies have entered the market and surpassed the European companies in market share. The top two European companies reduced their combined market share from 14 % in 2018 to 7 % in 2022. There are two important enablers for this development in China: first, better access to the capital needed for capacity expansions and second, faster permitting for new factories as well as faster construction and ramp-up times.

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

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

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

The current trend of the EU market shows that it is growing faster than required to reach the new PV system capacity installations between 2021 and 2030 as described in the recent EU European Solar Strategy communication. As the overall global demand for PV components is growing even faster than in the EU and trade frictions can occur, precaution has to be taken to avoid a fallout of international supply chain disruptions on the deployment of PV in the EU. To hedge such a risk, the EU value chain should be able to supply at least 25-35 % of the EU market. At the moment, this is possible for the production of polysilicon, backsheets, contact materials, inverters and balance of system components. Additional new capacities for wafers, cells and solar glass production are needed.

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

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List of definitions

General

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

LCoE	Levelised Cost of Electricity
MS	Member State
NREPBT	Non Renewable Energy Payback Time
NZIA	Net Zero Industry Act
O&M	Operation and Maintenance
OPEX	Operational Expenditure
Prodcom	Production Communautaire (Community Production)
PV	Photovoltaics
RED	Renewables Energy Directive
R&D	Research and Development
R&I	Research and Innovation
SET-Plan	Strategic Energy Technology Plan
SME	Small and medium-sized enterprise
SPE	SolarPower Europe
SRIA	Strategic Research and Innovation Agenda
SRM	Strategic Raw Material
STEM	Science, Technology, Engineering and Mathematics
TIM	Tools for Information Monitoring
TRL	Technology Readiness Level
TWG	Temporary Working Group
UN Comtrade	United Nations International Trade Statistics Database
VC	Venture Capital
WACC	Weighted Average Costs of Capital

Technical

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

Pks	Perovskites
poly c-Si	Poly-crystalline Silicon
TOPCon	Tunnel Oxide Passivated Contact
TW_p	Terra Watt peak
TWh	Terra Watt hour
W	Watt
W_{AC}	Watt alternating current
W_{DC}	Watt direct current
W_p	Watt peak
Wh	Watt hour

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Annexes

Annex 1 Summary Table of Data Sources for the CETO Indicators

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

Annex 2 Countries, regions and continents coding

EU		WORLD	
CODE	COUNTRY	CODE	COUNTRY
AT	Austria	BR	Brazil
BE	Belgium	CA	Canada
BG	Bulgaria	CN	China
HR	Croatia	CH	Switzerland
CY	Cyprus	EU	European Union
CZ	Czech Republic	HK	Hong Kong
DK	Denmark	IL	Israel
EE	Estonia	IN	India
FI	Finland	JP	Japan
FR	France	KR	South Korea
DE	Germany	MY	Malaysia
EL	Greece	RoW	Rest of World
HU	Hungary	SG	Singapore
IE	Ireland	TW	Taiwan
IT	Italy	UK	United Kingdom
LV	Latvia	US	United States of America
LT	Lithuania	VN	Vietnam
LU	Luxembourg		
MT	Malta		
NL	Netherlands		
PL	Poland		
PT	Portugal		
RO	Romania		
SK	Slovakia		
SI	Slovenia		
ES	Spain		
SE	Sweden		

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

This annex provides an overview of the energy system models and scenarios used in CETO to support the technology development assesment and the strategic oveview on clean energy technologies.

A3.1 POTEnCIA Model Overview

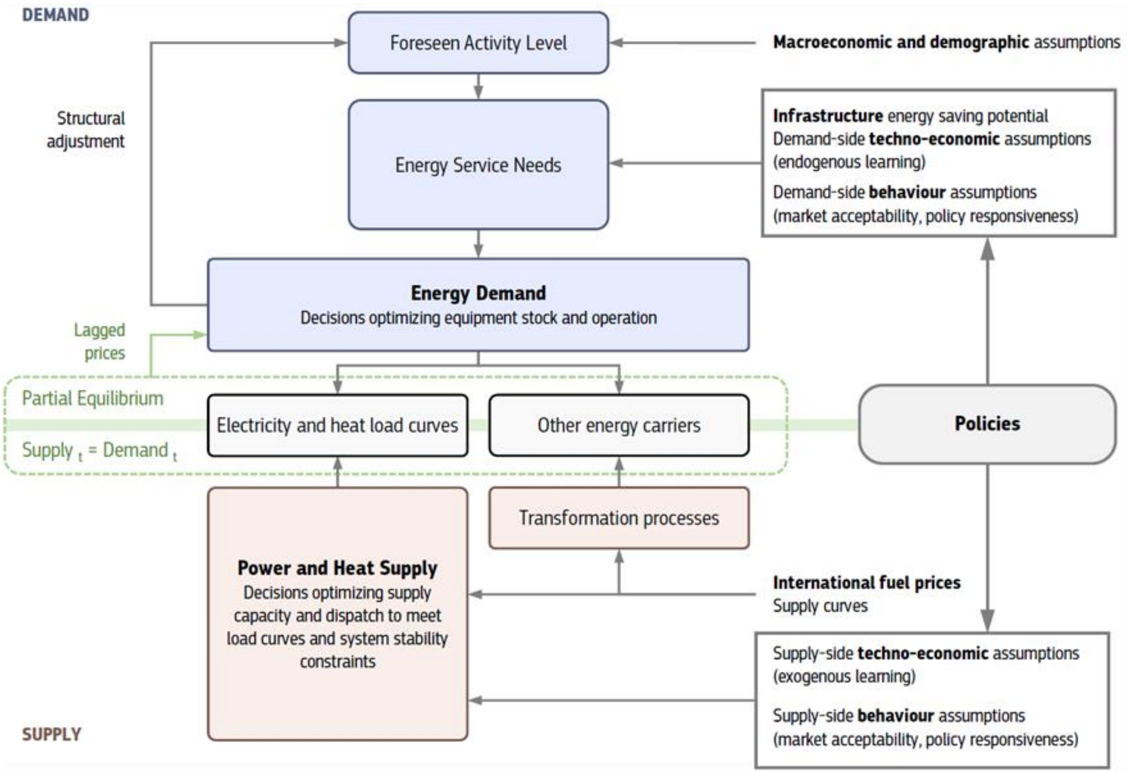
The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed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

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

The core modelling approach of POTEnCIA (Figure A3-1; detailed in the (Mantzos *et al*., 2017, 2019)) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method. As such, for each sector of energy supply and demand, this approach assumes a representative agent seeking to maximize its benefit or minimize its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies. This core modelling approach is tailored to each sector, for instance to represent different planning horizons and expectations about future technologies under imperfect foresight. In particular, power dispatch modelling uses a high time resolution with full-year hourly dispatch to suitably depict the increasing need for flexibility from storage and demand response, and the changing role of thermal generation in a power system dominated by variable renewable energy sources. Within this sector modelling framework, investment decisions of the representative agents are simulated with discrete-choice modelling. The model then finds an overall equilibrium across different sectors using price signals for resources such as traditional and renewable energy carriers while accounting for efficiency and environmental costs.

This core modelling approach is implemented individually for each EU Member State to capture differences in macroeconomic and energy system structures, technology assumptions, and resource constraints. The national model implementation is supported by spatially-explicit analyses to realistically define renewable energy potentials and infrastructure costs for hydrogen and CO_2 transport. Typical model output is provided in annual time steps over a horizon of 2000-2070; historical data (2000-2021) are calibrated to Eurostat and other official EU statistics to provide accurate initial conditions, using an updated version of the JRC Integrated Database of the European Energy System (JTRC-IDEES) (Mantzos *et al*., 2018). JRC-IDEES has been developed in parallel to POTEnCIA, and an updated release is planned in 2024 to ensure the transparency of POTEnCIA's base-year conditions and to support further research by external stakeholders.

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



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

A3.2 POTEnCIA CETO Climate Neutrality Scenario Overview

The technology projections provided by the POTEnCIA model are obtained under a Climate Neutrality Scenario aligned with the broad GHG reduction objectives of the European Green Deal. As such, this scenario reduces net EU GHG emissions by 55 % by 2030 versus 1990, and reaches the EU's climate neutrality by 2050 under general assumptions summarized in Table A3-1. To suitably model technology projections under these overarching GHG targets, the scenario includes a representation 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 deployment of bioenergy and renewable power generation technologies to 2030 is consistent with the EU's Renewable Energy Directive target (42.5 % share of renewables in gross final energy consumption by 2030). Similarly, the adoption of alternative powertrains and fuels in transport is also promoted by a representation of updated CO_2 emission standards in road transport and by targets of the ReFuelEU Aviation and FuelEU Maritime proposals.

Table A3-1. General assumptions of the POTEnCIA CETO Climate Neutrality Scenario.

General scenario assumptions	Modelled scenario and policy assumptions
GDP growth by Member State	GDP projections based on EU Reference Scenario 2020, with updates to 2024 from DG ECFIN Autumn Forecast 2022.
Population by Member State	Population projections based on EU Reference Scenario 2020, with updates to 2032 from EUROPOP 2019.
International energy markets	Natural gas import projections consistent with REPowerEU targets for supply diversification and demand reduction. International fuel price projections to 2050 aligned with REPowerEU.

Source: JRC

A3.3 POLES-JRC Model

POLES-JRC (Prospective Outlook for the Long term Energy System) is a global energy model well suited to evaluate the evolution of energy demand and supply in the main world economies with a representation of international energy markets. POLES-JRC is hosted at the JRC and is particularly adapted to assess climate and energy policies.

POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables etc.) to transformation (power, biofuels, hydrogen) and final sectoral demand (Figure A3-2). International markets and prices of energy fuels are simulated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global framework: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2050 and is updated yearly with recent data and model updates.

The POLES-JRC model is used to assess the impact of European and international energy and climate policies on energy markets and GHG emissions, by DG CLIMA in the context of international climate policy negotiations and by DG ENER in the context of the EU Energy Union.

POLES-JRC has also been applied for the analyses of various Impact Assessments in the field of climate change and energy, among them: the "*Proposal for a revised energy efficiency Directive*" (COM(2016) 0761 final) and "*The Paris Protocol – A blueprint for tackling global climate change beyond 2020*" (COM(2015) 81 final/2).

Moreover, POLES-JRC provided the global context to the *EU Long-Term Strategy* (COM(2018) 773) and formed the energy/GHG basis for the baseline to the CGE model JRC-GEM-E3.

POLES-JRC forms part of the *Integrated Assessment Modelling Consortium* (IAMC) and participates in inter-model comparison exercises with scenarios that feed into the IPCC Assessment Reports process.

POLES-JRC results are published within the series of yearly publications "*Global Climate and Energy Outlooks – GECO*". The GECO reports along with detailed country energy and GHG balances and an on-line visualisation interface can be found at (European Commission, 2022g).

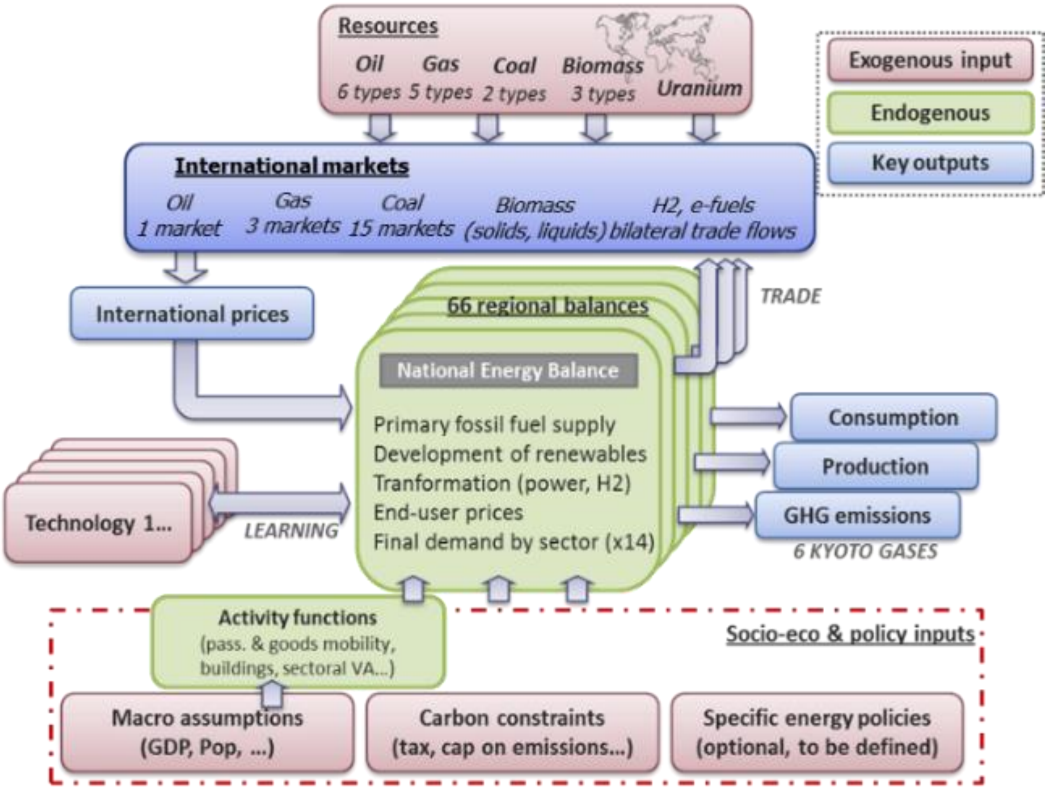
A3.3.1 Power system

POLES-JRC considers 37 power generating technologies, covering existing technologies as well as emerging technologies. Each technology is characterised by its installed capacity, cost parameters (overnight investment cost, variable & fixed operating and maintenance cost), learning rate and other techno-economic parameters (e.g. efficiencies). The cost evolution over time is taken into account by technology learning driven by accumulated capacity.

For renewable technologies maximum resource potentials are taken into account. Similarly, the deployment of carbon capture and storage (CCS) technologies is linked to region-specific geological storage potential. In addition to these technical and economic characteristics, non-cost factors are applied to capture the historical relative attractiveness of each technology, in terms of investments and of operational dispatch.

With regard to the clean energy technologies covered by CETO, the model includes power generation using photovoltaics (utility and residential), concentrated solar power (CSP), on-shore and off-shore wind , ocean energy, biomass gasification and steam turbines fuelled by biomass, geothermal energy as well as hydropower. CCS-equipped combustion power technologies are considered as well. Moreover, electricity storage technologies such as pumped hydropower storage and batteries are also included.

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



Source: JRC

A3.3.2 Electricity demand

The total electricity demand is computed by adding the electricity demand from each sector (i.e. residential, services, transport, industry and agriculture). The evolution over time of the sectoral electricity demand is driven by the activity of each sector and competition between prices for electricity and other fuels.

POLES-JRC uses a set of representative days with an hourly time-step in order to capture load variations as well as to take into account the intermittency of solar and wind generation. The usage of representative days also allows to capture hourly profiles by sector and end-uses.

With a view to other CETO technologies influencing electricity consumption, the model includes heat pumps in the residential and service sector, batteries for electric vehicles and electrolysers.

A3.3.3 Power system operation and planning

The power system operation assigns the generation by technology to each hour of each representative day. The supplying technologies and storage technologies must meet the overall demand.

The capacity planning considers the existing structure of the power mix (vintage technology), the expected evolution of the demand, and the production cost of technologies.

A3.3.4 Hydrogen

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

Hydrogen can used as fuel in all sectors. Moreover, hydrogen is used to produce fertilisers as well as to produce fuels used in the transport sector (i.e. gaseous and liquid synfuels and ammonia). POLES-JRC models global hydrogen trade and considers various means of hydrogen transport (pipeline, ship, truck, refuelling station).

A3.3.5 Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM model[26]. This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass potential, production cost and carbon value. Moreover, the emissions from land use and forestry (CO_2) as well as agriculture (CH_4 and N_2O) are derived from GLOBIOM.

Power generating technologies using biomass are biomass gasification (with and without CCS) and biomass fuelled steam turbines.

Hydrogen can be produced from biomass via gasification and pyrolysis. Moreover, the production of 1st and 2nd generation biofuels for gasoline and diesel is considered.

A3.3.6 Carbon Capture Utilisation and Storage (CCUS)

POLES-JRC takes into account CCUS technologies for:

- Power generation: advanced coal using CCS, coal and biomass gasification with CCS, and gas combined cycle with CCS;
- Hydrogen production: Steam reforming with CCS, coal and biomass gasification with CCS, and coal and biomass pyrolysis;
- Direct air capture (DAC) where the CO_2 is stored or used to produce synfuels (gaseous or liquid);
- CO_2 storage in geological sites.

A3.3.7 Model documentation and publications

A detailed documentation of the POLES-JRC model and publications can be found at:

- https://publications.jrc.ec.europa.eu/repository/handle/JRC113757
- https://ec.europa.eu/jrc/en/poles

A3.4 POLES-JRC CETO Global 2°C Scenario

The global scenario data presented in this CETO technology report refers to a 2 °C scenario modelled with the POLES-JRC model. The 2 °C scenario assumes a global GHG trajectory consistent with a likely chance of meeting the long-term goal of limiting the temperature rise over pre-industrial period to 2 °C in 2100.

The 2 °C scenario was designed with a global carbon budget over 2023-2100 (cumulated net CO_2 emissions) of approximately 1 150 $GtCO_2$, resulting in a 50 % probability of not exceeding the 2 °C temperature limit in 2100. A single global carbon price for all regions is used in this scenario, starting immediately (2023) and strongly increasing. The 2 °C scenario is therefore a stylised representation of an economically-efficient pathway to the temperature targets, as the uniform global carbon price ensures that emissions are reduced where abatement costs are lowest. This scenario does not consider financial transfers between countries to implement mitigation measures.

The POLES-JRC model has been updated with the latest technologies costs from recent literature. Most of the historic data used in the 2 °C scenario refers to data used in the GECO 2022 scenarios (energy balances, energy prices, capacities) (European Commission, 2022f).

[26] Global Biosphere Management Model (GLOBIOM) model description. International Institute for Applied Statistical Analysis, Laxenburg, Austria. http://www.globiom.org

Annex 4 PV topics in Horizon Europe Work Programmes (WP) 2021-2022 and 2023-2024, the ongoing projects of the 2021-2022 PV calls and ongoing Innovation Fund projects

WP 2021-2022

HORIZON-CL5-2021-D3-02-04: Novel tandem, high efficiency Photovoltaic technologies targeting low cost production with earth abundant materials

HORIZON-CL5-2021-D3-03-07: Stable high-performance Perovskite Photovoltaics

HORIZON-CL5-2021-D3-03-10: Innovative foundations, floating substructures and connection systems for floating PV and ocean energy devices

HORIZON-CL5-2021-D3-03-13: Demonstration pilot lines for alternative and innovative PV technologies (Novel c-Si tandem, thin film tandem, bifacial, CPV, etc.)

HORIZON-CL5-2022-D3-01-03: Advanced manufacturing of Integrated PV

HORIZON-CL5-2022-D3-01-06: Novel Agro-Photovoltaic systems

HORIZON-CL5-2022-D3-03-05: Novel Thin Film (TF) technologies targeting high efficiencies

HORIZON-CL5-2022-D3-03-09: Recycling end of life PV modules

WP 2023-2024

HORIZON-CL5-2023-D3-01-02: PV integration in buildings and in infrastructure

HORIZON-CL5-2023-D3-01-03: Floating PV Systems

HORIZON-CL5-2023-D3-01-04: Solar Systems for Industrial Process Heat and Power

HORIZON-CL5-2023-D3-02-11: Advanced concepts for crystalline Silicon technology

HORIZON-CL5-2023-D3-02-12: Large Area Perovskite solar cells and modules

HORIZON-CL5-2023-D3-02-13: Operation, Performance and Maintenance of PV Systems

HORIZON-CL5-2024-D3-01-01: Alternative equipment and processes for advanced manufacturing of PV technologies

HORIZON-CL5-2024-D3-01-02: Low-power PV

HORIZON-CL5-2024-D3-02-05: PV-integrated electric mobility applications

HORIZON-CL5-2024-D3-02-06: Innovative, Community-Integrated PV systems

HORIZON-CL5-2024-D3-02-07: Resource Efficiency of PV in Production, Use and Disposal

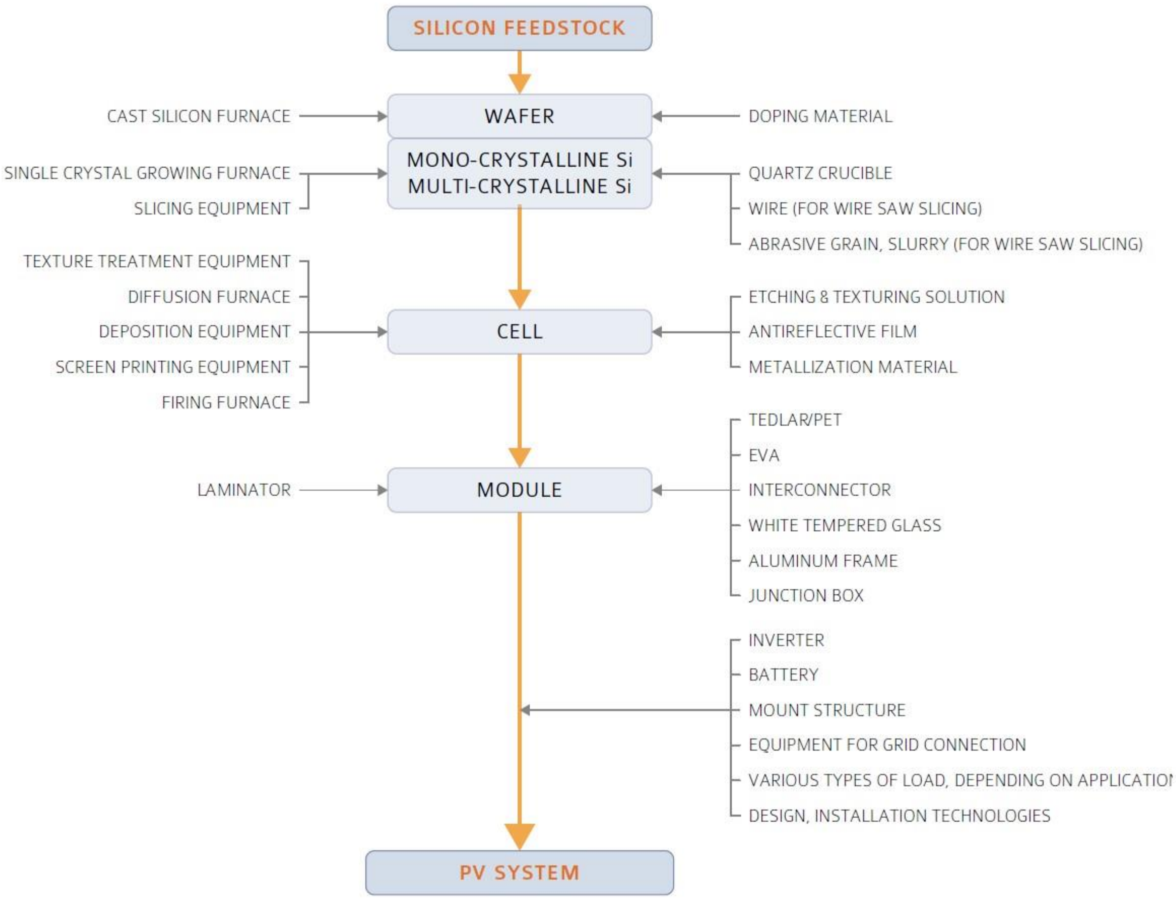
Ongoing projects of the 2021-2022 PV calls	
NEXUS	NEXUS
SuPerTandem	Sustainable materials and manufacturing processes for the development of high efficiency, flexible, all-Perovskite Tandem photovoltaic modules with low CO2 footprint
SITA	Stable Inorganic TAndem solar cell with superior device efficiency and increased durability
TRIUMPH	Triple junction solar modules based on perovskites and silicon for high performance, low-cost and small environmental footprint
VALHALLA	Perovskite solar cells with enhanced stability and applicability
SUREWAVE	STRUCTURAL RELIABLE OFFSHORE FLOATING PV SOLUTION INTEGRATING CIRCULAR CONCRETE FLOATING BREAKWATER
PLOTEC	PLOCAN Tested Optimised Floating Ocean Thermal Eenergy Conversion Platform
PILATUS	Digitalised pilot lines for silicon heterojunction tunnel interdigitated back contact solar cells and modules
DIAMOND	Ultra-stable, highly efficient, low-cost perovskite photovoltaics with minimised environmental impact
PEPPERONI	Pilot line for European Production of PEROvskite-Silicon taNdem modules on Industrial scale
IBC4EU	Piloting novel cost-competitive bifacial IBC technology for vertical integrated European GW scale PV production value chain
NATURSEA-PV	NOVEL ECO-CEMENTITIOUS MATERIALS AND COMPONENTS FOR DURABLE, COMPETITIVE, AND BIO-INSPIRED OFFSHORE FLOATING PV SUBSTRUCTURES
SUNREY	Boosting SUstaiNability, Reliability and EfficiencY of perovskite PV through novel materials and process engineering.
REGACE	Crop Responsive Greenhouse Agrivoltaics System with CO2 Enrichment for Higher Yields
SEAMLESS-PV	Development of advanced manufacturing equipment and processes aimed at the seamless integration of multifunctional PV solutions, enabling the deployment of IPV sectors
MC2.0	Mass customization 2.0 for Integrated PV
SYMBIOSYST	Create a Symbiosis where PV and agriculture can have a mutually beneficial relationship
PV4Plants	AgriPV system with climate, water and light spectrum control for safe, healthier and improved crops production
Flex2Energy	Automated Manufacturing Production Line for Integrated Printed Organic Photovoltaics

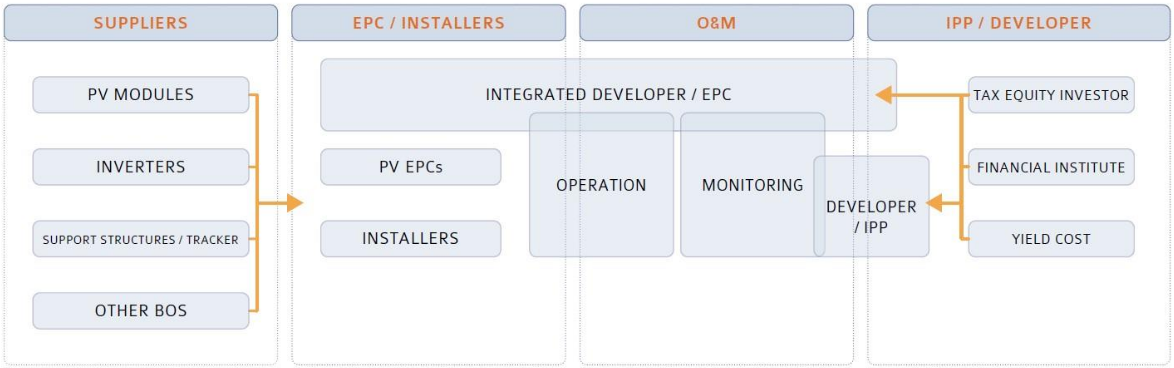
Innovation Fund	
SUN2HY	*First Small-Scale Deployment of a Pre-Commercial Plant Based on Photoelectrocatalytic Technology for Hydrogen Production* *Location: Puertollano (ES)* *Coordinator: SUN2HY* *Start date: 1 January 2022* *Expected entry into operation date: 1 April 2025* *Summary* *The aim of the SUN2HY project is to design, implement and validate a pre-commercial stage production plant to generate green hydrogen via photoelectrocatalysis (PEC), an innovative technology which directly converts solar energy to chemical energy by splitting water into hydrogen and oxygen with no external energy input. The produced hydrogen will supply refuelling stations serving the transport sector (i.e. freight buses, trucks and light duty vehicles (LDVs)). The project has the potential to reduce greenhouse gas (GHG) emissions by 94% compared to conventional electricity production.* *Status of implementation* *The project is progressing according to schedule. The consortium has carried out the front-end engineering studies and it is in the process of obtaining the relevant permits from the authorities to reach financial close.* *The main key achievements up to date* *The project is still in its early phases of implementation and has not achieved/delivered significant milestones/results yet.*
CO2-FrAMed	*Free Agriculture for the Mediterranean region* *Location: Ebro River Valley (ES)* *Coordinator: Acciona Generacion Renovable S.A.* *Start date: 1 January 2022* *Expected entry into operation date: 1 July 2024* *Summary* *The CO2-FrAMed project will build approximately 12 stand-alone large-power photovoltaic irrigation systems (PVI) that do not require back-up batteries and significantly reduce risks related to the integrity of the water distribution infrastructure. This solution is a suitable alternative to conventional electric and diesel-based pumping systems. It brings environmental benefits in terms of CO2 emission reduction and economic benefits in terms of lower costs for farmers. Overall, the project will reduce Greenhouse gas (GHG) emissions compared to a conventional technology by 100% and farmers will benefit from zero carbon irrigation at a competitive price.* *Status of implementation* *The project has not achieved significant milestones yet.* *The main key achievements up to date* *The project is still in its early phases of implementation and has not achieved/delivered significant milestones/results yet*
HELEXIO Line	*Demonstrating the manufacture of innovative building integrated photovoltaics roof components* *Location: Contrisson (FR)* *Coordinator: ArcelorMittal Construction* *Start date: 1 October 2021* *Expected entry into operation date: 1 November 2024*

	Summary *The objective of the Helexio® line project is to develop the first full-scale plant to manufacture a 'ready to plug-in' Building Integrated-Photovoltaic roofing steel envelope for the European non-residential buildings market. This unique technology combining in one component steel roof + photovoltaic (PV) solutions brings lightweight, flexible and easy-to-implement solutions adaptable to all types of roof, there by addressing key market barriers in this sector, while being economically viable. These innovative components once implemented in buildings will replace significant grid electricity by solar electricity, leading to significant reduction of greenhouse gas (GHG) emissions.* *Status of implementation* *The project is progressing according to schedule, with the pre front end engineering and design analysis finalised.* *The main key achievements up to date* *The project is still in its early phases of implementation and has not achieved/delivered significant milestones/results yet.*
DMC	*Renewable heat for large-scale decarbonisation of the malt production process in Croatia* *Location: BOORTMALT's malting site in Nova Gradiska (HR)* *Coordinator: NEWHEAT* *Start date: 1 December 2021* *Expected entry into operation date: 1 December 2024* *Summary* *The DECARBOMALT project will build a solar thermal heating plant, heat pumps and a storage facility to provide renewable heat to an energy-intensive malt production process in Croatia. The flagship industrial project will bring existing technologies together for the first time at such a scale so as to deliver more than 50% of the total process heat needs of the site at a competitive price.* *Status of implementation* *The project is in the phase of obtaining the relevant permits from the Croatian authorities. The consortium is constantly working on mitigating the impacts of the price increase on raw materials and the high costs required for connecting to the electrical grid.* *The main key achievements up to date* *The project is still in its early phases of implementation and has not achieved/delivered significant milestones/results yet.*
TANGO	*ITaliAN PV Giga factory* *Location: Catania (IT)* *Coordinator: 3SUN S.R.L.* *Start date: 1 January 2021* *Expected entry into operation date: 1 September 2023* *Summary* *The TANGO project will develop an industrial-scale pilot line in the South of Italy for the manufacture of innovative, high-performance photovoltaic (PV) modules, increasing production capacity by 15 times, from 200 MW to 3 GW per year. Production will include bifacial heterojunction (B-HJT) PV cells, which offer a very important effective efficiency improvement of up to 20%, relative to current state-of-the-art cells, and an innovative module design called "Tandem" structure. The modules produced in one year (3 GW) will have the potential to generate 5 445 GWh of renewable electricity per year. Once installed, all the modules produced over the first ten years of operation have the potential to avoid up to 25 Mt CO2eq emissions. The main innovation lies in scaling up production of these cells to a gigawatt scale – a key goal for the European PV industry. The gigawatt-scale*

	factory will foster European technology leadership in the manufacture of next-generation PV modules, thereby contributing to the reduction of energy dependency in Europe and improving European competitiveness in PV manufacturing. *Status of implementation* *The project has reached Financial Close in January 2023. The construction of the factory is progressing according to schedule, with the aim to enter into operation in September 2023. Moreover, the coordinator has changed to a newly created entity, 3SUN S.r.l. (3Sun). 3Sun has received the TANGO activities from ENEL Green Power Italia including the construction and operation of the gigafactory under development.* *The main key achievements up to date* *The project has reached the first milestone of Financial Close with the Final Investment Decision taken by Enel Green Power Italia.*
AGRIVOLTAIC CANOPY	*The Brounchy Agrivoltaic Canopy – An acceleration toward energy transition* *Location: Somme (FR)* *Coordinator: TSE* *Start date: 1 September 2022* *Expected entry into operation date: 1 January 2024* *Summary* *The Brouchy project will be an innovative agrivoltaic canopy to answer the critical dual need of the agricultural and energy sectors. The project aims to enhance agricultural production and develop new renewable energy capacities. Its breakthrough technical feature is a 5-metre-high shade house structure on steel cables, held in place by poles with a width of 27 metres, making it suitable for large field crops. The canopy's versatility will expand the market potential of agrivoltaics at a large scale, contributing to the decarbonisation of the energy mix and improve food security as it delivers 100% relative greenhouse gas emission reduction compared to the reference scenario.* *Status of implementation* *The consortium is in the phase of obtaining the relevant permits from the authorities. In parallel, the installation of the photovoltaic panels at the project's site has started.* *The main key achievements up to date* *The project is still in its early phases of implementation and has not achieved/delivered significant milestones/results yet.*

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





Source: (IEA-PVPS, 2023b)

Annex 6 Sustainability Assessment Framework

Parameter/Indicator	*Input*
Environmental	
LCA standards, PEFCR or best practice, LCI databases	• At international level the IEA PVPS Task 12 group issued methodology guidelines on PV-specific parameters used as inputs in LCA (Frischknecht et al., 2016). • 'Product Environmental Footprint category rules' for PV power systems27, developed by the European Commission in the framework of the Product Environmental Footprint initiative pilot phase. The results for all the 16 impact categories based on the Environmental Footprint method are available in the PEFCR document (European Commission, 2019). • Italy's LCA legislation Promotion of the Green Economy - Legislation fully based on the Environmental Footprint methods. Voluntary "Made Green in Italy" label. • France's public tenders for utility-scale PV plants - ADEME guidelines. • Country-specific Product Category Rules (Italy, France, Norway, Finland, Netherlands) based on EN 15804. • NSF/ANSI 457 Sustainability Leadership Standard for PV Modules and PV Inverters.
GHG emissions	PV systems *A recent study from IEA PVPS indicates that, through their lifetime, mono c-Si systems emit 42.5 gCO_2/kWh, poly c-Si systems emit 42.3 gCO_2/kWh, CIS systems emit 36.3 gCO_2/kWh and CdTe systems emit 26.5 gCO_2/kWh* (Frischknecht and Krebs, 2021)[28]. PV modules *In terms of technologies, thin-film modules have the lowest emissions, followed by poly c-Si and then mono c-Si. There is considerable scope to reduce these values, and projections for 2050 indicate that life cycle emissions for PV can drop to 10 gCO_2eq/kWh and below* (Pehl *et al.*, 2017). *Carbon footprint values corresponding to the Climate Change impact category, calculated as per the PEFCR* (European Commission, 2019)*:*

PV technologies	Life cycle excl. use stage Climate change (g$CO_2$$e_q$/kWh)	Use stage Climate change (gCO_2eq/kWh)
Representative (virtual) product	59.3	0.0105
CdTe	19.9	0.0107
CIGS	35.9	0.0139
Micromorphous silicon	43.0	0.0150
Polycrystalline silicon	48.8	0.0102
Monocrystalline silicon	80.4	0.0099

The partial adjustment of some technical parameters for PV modelling based on LCI and LCA outdated datasets leads to significant overestimation of the environmental impacts of PV technologies. For this reason a careful and in depth examination and update is crucial to obtain realistic results. The amount of silicon use in the production of c-Si modules, the wafer thickness and the kerf play a significant role. A moderate wafer thickness reduction from 180 μm in 2010 to approximately 170 μm in 2021 and a notable silicon usage reduction from 7 g/Wp in 2010 to 2.5 g/Wp in 2021, contributed to a lower carbon footprint (Fraunhofer ISE, 2022a). *New approaches indicate that the carbon*

[27] https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_PV_electricity_v1.1.pdf
[28] Average residential PV system: 1 kWh AC energy, produced with a 3 kW_p roof-mounted PV system in Europe (included PV panel, cabling, mounting structure, inverter and system installation), 975 kWh/kW_p annual production, linear degradation 0.7% per year, service life: panel 30 years, inverter 15 years. Module efficiencies assumed: mono c-Si: 19.5 %, poly c-Si: 18 %, CIS: 16 % and CdTe: 18 %.

<table>
<tr><td></td><td>footprint of crystalline technology may be notably lower and between 13 and 30 gCO_2eq/kWh (Müller et al., 2021).</td></tr>
<tr><td>Energy balance</td><td>The Energy Payback Time of PV systems is dependent on the geographical location: PV systems in Northern Europe need around 1.2 years to balance the input energy, while PV systems in the South equal their energy input after 1 year and less, depending on the technology installed and the grid efficiency (Fraunhofer ISE, 2022b).
According to the IEA PVPS Task 12, the Non Renewable Energy Payback Time (NREPBT)[29] for mono c-Si, poly c-Si, CIS and CdTe technology PV system is 1.2, 1.2, 1.3 and 0.9 years respectively (Frischknecht and Krebs, 2021).
For low irradiation locations (1 000 kWh/m^2/year), mono c-Si module installations have an EPBT of 1.3 years and poly c-Si module installations of 1.5 years. For high irradiation locations, the EPBT is 0.6 years (Fthenakis and Leccisi, 2021).</td></tr>
<tr><td>Ecosystem and biodiversity impact</td><td>The European Commission has published a report on the potential impacts of PV applications on the ecosystem and the biodiversity (Lammerant, Laureysens and Driesen, 2020).
The EU biodiversity strategy specifically mentions solar-panel farms providing biodiversity-friendly soil cover as a win-win solution for energy and biodiversity. Any intervention on water bodies must respect the conditions set out in the Water Framework Directive and the Marine Strategy Framework Directive (European Commission, 2020a).</td></tr>
<tr><td>Water use</td><td><u>PV modules</u>
The available reported water consumption of PV module technologies in studies is considered outdated due to the rapid technological advancements of PV. Therefore, the reported values of water consumption must be used with caution. Results for the impact category water use are available also in the PEFCR for PV panels (European Commission, 2019):
<table>
<tr><th>PV technologies</th><th>Life cycle excl. use stage
Water use
(l world$_{eq}$/kWh)</th><th>Use stage
Water use
(l world$_{eq}$/kWh)</th></tr>
<tr><td>Representative (virtual) product</td><td>22.8</td><td>0.158</td></tr>
<tr><td>CdTe</td><td>4.30</td><td>0.161</td></tr>
<tr><td>CIGS</td><td>6.27</td><td>0.209</td></tr>
<tr><td>Micromorphous silicon</td><td>11.2</td><td>0.226</td></tr>
<tr><td>Polycrystalline silicon</td><td>19.6</td><td>0.154</td></tr>
<tr><td>Monocrystalline silicon</td><td>31.7</td><td>0.150</td></tr>
</table>
A 2017 IEA PVPS report, based on LCIs from 2010 and 2013, reports that the share of consumptive water use during the life cycle of mono c-Si and CdTe rooftop systems, defined as the amount of water consumed divided by the volume of water withdrawn, is 20 % and 34 % respectively (Stolz et al., 2017).
According to the most recent IEA PVPS report on water use of PV module systems over their lifetime, systems with mono c-Si modules consume 7.49 l/kWh, systems with poly c-Si modules consume 6.71 l/kWh while systems with CIS modules consume 6.27 l/kWh and systems with CdTe modules 3.08 l/kWh (Frischknecht and Krebs, 2021)[30].
<u>PV system operation</u>
Water consumption for the operation of PV systems has been reported to be 0.08 l/kWh for utility-scale PV installations and 3.3 l/kWh for Concentrated Solar Power (CSP) installation in the US (Solar Energy Industries Association, 2022).
PV systems withdraw and consume between 2 % and 15 % of the water consumed by coal or nuclear plants for 1 MWh of generated electricity (Lohrmann et al., 2019).</td></tr>
</table>

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

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

Air quality	*In the case of thin film PV module technologies, there are some hazards that need to be taken into consideration. These hazards include the toxicity and explosiveness of specific gases. Health issues for workers (and public health in extreme cases) from accidents or elusive air emissions may arise if proper measures are not taken. However, the proper manufacturing procedures together with the use of less toxic materials ensure the avoidance of accidental releases of toxic gases and vapors that may potentially put in danger the health of humans and the air quality* (Tchognia Nkuissi *et al.*, 2019).
Land use	*1.9 hectares/MW* (IRENA, 2020c). *1-2 hectares/MW$_p$* (IFC, 2015).
Soil health	*Soil health may be influenced in a negative way by manual and automated cleaning that uses mostly water to remove debris that accumulates on the surface of the PV panels* (Tawalbeh *et al.*, 2021).
Hazardous materials	*There are materials used in the manufacturing procedure covered by dispositions under the REACH regulation (lead in c-Si and perovskites, cadmium in CdTe, etc.)* (Tchognia Nkuissi *et al.*, 2019; Gebhardt *et al.*, 2022). *Also, chemicals and solvents are used throughout the manufacturing processes of different PV technologies* (Tawalbeh *et al.*, 2021). *The back-sheet layer of the PV panel may contain halogenated plastic layer that can pose potential waste management problems* (Latunussa *et al.*, 2016; Ardente, Latunussa and Blengini, 2019).
Economic	
LCC standards or best practices	
Cost of energy	*See 2.3 Technology Cost – Present and Potential Future Trends*
Critical raw materials	*Some of the raw materials used to manufacture solar cells are critical, such as borates, silicon metal, germanium, indium, and gallium* (Bobba *et al.*, 2020). *These materials are characterized as CRMs for the EU* (Dodd *et al.*, 2020). *Copper, cadmium, selenium, silver and tellurium are raw materials used in the PV industry with a low supply risk (Bobba et al., 2020).* *Other studies suggest that also boron, molybdenum, phosphorus, tin and zinc are raw materials that should be closely monitored* (European Commission, 2022d).
Resource efficiency and recycling	*In the EU, the treatment of end-of-life PV modules must comply with the WEEE Directive since 2012. Several organisations have developed recycling processes. Several sustainability aspects are being addressed in the framework Ecodesign* (European Commission, 2022c). *The assessment of the resource efficiency and related environmental benefits and burdens of a pilot PV waste recycling processes showed the advantages of an innovative PV recycling process, compared to current recycling processes. The benefits are even more evident with regard to the recovery of silver and silicon (critical raw materials). Overall, recycling processes with high efficiency can recycle up to 83 % of the waste panel* (Ardente, Latunussa and Blengini, 2019). *An ongoing EU-funded project called PHOTORAMA*[31] *is currently working to improve the recycling of Photovoltaic (PV) panels and recovery of Raw Materials (RM). This project is implemented by a consortium of 13 organisations in the period 2021-2024.*
Industry viability and expansion potential	*For market data see section 4.1*
Trade impacts	*For trade data see section 4.2*
Market demand	*For market data see section 4.1*
Technology lock-in/innovation lock-out	

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

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

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

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

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

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

Source: SolarPower Europe

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