ETIP Photovoltaics

ETIP PV Industry Working Group White Paper

PV Manufacturing in Europe: understanding the value chain for a successful industrial policy

The European Technology and Innovation Platform for Photovoltaics

etip-pv.eu

The European Technology & Innovation Platforms (ETIPs) have been created by the European Commission in the framework of the new Integrated Roadmap Strategic Energy Technology Plan (SET Plan) by bringing together EU countries, industry, and researchers in key areas. They promote the market uptake of key energy technologies by pooling funding, skills, and research facilities. The European Technology and Innovation Platform for Photovoltaics (ETIP PV) mobilizes all stakeholders sharing a long-term European vision for PV, helping to ensure that Europe maintains and improves its industrial position, in order to achieve a leadership position within the global PV market.

The experts of the ETIP PV Working Group on PV Industry jointly contributed to this publication. They represent leading European research institutes and industrial actors in the PV community, and work to further the objective of an efficient, highly innovative European PV industry with a positive environmental and social impact.

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Executive Summary

The European PV industry has been the focus of much policy attention in the past years, from the inception of debates to define the European climate and energy policy framework to 2030. This culminated at the end of 2022 with the launch of a European Solar PV Industry Alliance, which aims to deliver European PV targets of 600 GW of PV in the European electricity system by 2030 and 30 GW of domestic manufacturing capacity for the PV supply chain in Europe by 2025. Both objectives suppose a crucial shift in the investment trends of the PV industry, as well as a profound transformation of today's European industry. This white paper explores how these objectives could be pursued considering the state of the European PV value chain. This white paper will notably assess how research and innovation, an area where the EU retains competitiveness and even global leadership in several areas, can be cornerstones of a successful European PV industrial strategy.

The PV sector is dominated by crystalline silicon technologies, which define the overwhelming majority of the global PV supply chain. The production of polysilicon, ingots and wafers is a crucial segment of PV manufacturing, and an area where the EU is lagging behind in terms of production capacity. Although several actors – most notably Wacker – continue to be active in Europe and provide competitive and qualitative products to the European and PV market, the EU is clearly lacking sufficient industrial capacity and investments to meet the ambitions of a domestic integrated value chain. This vulnerability is also present in other segments of the PV value chain, although with potentially fewer barriers to rapid manufacturing capacity expansion. Beyond technical, financial and permitting barriers to rapid capacity production expansion for PV manufacturing in Europe, the question of available skills to manufacture and operate the equipment required by this industrial sector is one that will need to be answered. The relative deindustrialisation of the European PV industry over the past decade has led to a loss of expertise in several parts of the value chain.

The chief threat to the cost competitiveness of PV manufacturing in Europe is the cost of energy, which weighs heavily in the competitive advantage of other global PV production markets. To solve this challenge, the EU PV industrial policy will likely need to address the operational challenges of several segments of PV production, from raw materials production to module assembly. Investments in R&I to accelerate the adoption of production technologies with higher energy efficiency and better throughput will also have an impact. Moreover, European manufacturers face competitiveness issues due to a lack of value chain integration on the continent, requiring a specific focus on ensuring the availability of production capacity throughout the entire PV value chain.

Although the EU maintained a relative leadership in several areas of PV research and innovation (most notably new cells technologies such as heterojunction and perovskite tandem), there is a rapid growth of R&I investments by the public and private sectors of other regions, inducing a rapid catch up if not overtake. The EU will need to expand R&I investments in accordance with its renewed ambitions for PV manufacturing, considering the crucial role of positive R&I/industry interconnections in the successful growth of PV manufacturing.

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1. Identification of EU goals for PV manufacturing:

PV manufacturing is emerging as a core priority of the European Union, as it is looking to achieve its ambitious renewable and climate targets for 2030 and 2050, while strengthening the independence of the European economy from external supply shock disruption as a consequence of the COVID-19 pandemic and, more importantly, the invasion of Ukraine by Russia and the ensuing energy crisis that shook the European economy and society. The European Union is therefore looking to produce 42.5-45% of its energy from renewable sources by 2030, envisioning a fully decarbonized economy by 2050, with some member states having more ambitious goals. PV stands at the center of this energy transition story, with an expected contribution of 400 GW (320 GWac) to the European electricity system by 2025, and 750 GW (600 GWac) by 2030. These represent a doubling and nearly a quadrupling of the 160 GW of PV capacity available in Europe in 2021, respectively. In order to achieve the set targets, the EU needs to significantly expand its PV production capacity along the entire value chain and needs to make investments into building new PV factories, equipment, and research and development to improve the efficiency and affordability of PV technologies.

In December 2022 the European Commission launched the EU Solar Industry Alliance (ESIA). Through ESIA the EU aims to achieve the goal of 30 GW production across the whole PV value chain in Europe by 2025. The main priorities of the alliance entail research and development to strengthen the advancements of novel and more efficient PV technologies, establishing a favourable regulatory environment, supporting the growth of the entire PV value chain as well the needed financial means to achieve such growths. Through addressing these priorities, ESIA aims to support the EU's goal of becoming climate neutral with a net-zero economy by 2050 while reinforcing the independence of the European economy from external supply chain disruptions.

Increasing the European PV manufacturing capacity aligns with the targets of the ETIP PV which is emphasized in the Strategic Research and Innovation Agenda (SRIA), published early in 2022. More particularly, ETIP PV aims for achieving 100 GWp silicon-based cell and module manufacturing capacity by 2030 and reducing the overall carbon impact of PV manufacturing. To achieve this manufacturing capacity in Europe it will be vital to purchase materials from European manufacturers and bring the PV supply chain back to Europe. Therefore, the platform also identified the target to increase the production of ingot and wafers to 20% and silver to 30% in Europe. These targets will not only counterbalance the dominance of China in the PV supply chain, notably ingots and wafers where China currently represents 95-98% but also strengthen the domestic supply chain and reduce dependence on external sources. Overall, achieving the ETIP PV targets for both materials acquisition and manufacturing capacity will demand substantial investment, collaboration, and innovation from all players involved in the PV industry.

1. Current global supply chain

As one of the cheapest sources of electricity, PV has largely been deployed globally. This growth - coupled with the supply chain disruption due to COVID - 19 - made increasingly aware of the fact that the supply chain is geographically concentrated in China and involves a complex and diverse nature of the materials, components and manufacturing processes. During the past decade, we could observe a shift in the global solar PV manufacturing capacity from the US, Japan and Europe to being predominant in China. This also is a result of massive Chinese investment programmes (more than USD 50 billion) for building new PV supply capacity which has led to having over 80 percent of the market share in all stages of the PV supply chain, including solar panel manufacturing, including polysilicon, ingots, wafers, cells, and modules.

The two main technologies dominating global solar PV production are crystalline silicon (c-Si) modules, which account for over 98% of the production globally and cadmium telluride (CdTe) thin-film PV technology representing the remainder. Accordingly, this publication will focus primarily on the c-Si supply chain, as the widespread deployment will provide a comprehensive understanding of the current state of the solar PV market. This publication will also put a significant emphasis on the manufacturing of PV cells and modules while focusing less on other key components of the PV value chain because they are not to the same extent the focus of current industrial policy discussions.

- **Polysilicon**

One of the crucial components of c-SI solar modules is Polysilicon. China currently obtains a global polysilicon production of 80% which makes it the leading producer followed by South Korea, the US and Europe. The polysilicon market experienced tightness over the past few years due to incidents related to fires in manufacturing plants and supply chain disruption. In addition, the rapid increase in global PV installation has led to the quadrupling of polysilicon prices to around USD 35/kg in the last quarter of 2021. The prices have remained high throughout 2022, and currently remain around USD 37/kg (as of April 2023). The volatility of the polysilicon market, however, will most probably not affect the polysilicon production demand in the coming years, as the demand for renewable energies and therefore PV systems will increase steadily.

- **Wafers**

In 2021, the global production capacity for silicon wafers exceeded 360 GW which was nearly double the estimated demand. Despite overcapacity, wafer prices have risen significantly since the start of 2021 due to higher polysilicon prices. Technological advancements have enabled wafer production costs to decrease steadily, and the introduction of the diamond wire saw has further improved material and energy efficiency. The shift to monocrystalline wafer production has facilitated cost-effective large-scale manufacturing of high-efficiency cells, which has reduced the per-watt cost of solar PV modules. China dominates the wafer market with a 97% share of global manufacturing capacity, and the Asia-Pacific region accounts for almost all remaining capacity. China's rapid growth in wafer production has prevented other market participants from gaining significant market shares.

- **Cells**

The global solar cell-manufacturing capacity has significantly increased in recent years, reaching almost 410 GW at the end of 2021. China currently dominates this segment of the PV value chain by producing over 70% of the world's supply (2021). This can be attributed to factors such as low labor costs, access to raw materials, and the fact that Chinese manufacturers are able to receive easy and cheap access to capital through government support. China's leading PV cell market share is followed by Southeast Asia and Korea with an 18% share, while the rest of the world only represents 2% of production. Next to China, Southeast Asia and Korea have an 18% share of the global PV cell market while the rest of the world only represents 2% of production. R&D spending has led to improvements in energy conversion efficiency from solar irradiation to electricity and reduced manufacturing costs. The gradual replacement of multi-crystalline silicon back surface field technology with more efficient Passivated Emitter and Rear Cell (PERC) cells, along with improvements in the manufacturing process and shift to monocrystalline wafer production, has enabled rapid cost reductions and made the more efficient PERC cell the dominant technology. More advanced cell designs, such as heterojunction, TOPCon, and back contact, are expected to gain greater market share in the upcoming years, promising further efficiency gains. The technology cycle in cell technologies is relatively short, with new solutions reaching important market shares in a few years[1], requiring manufacturers to keep pace with innovation.

- **Modules**

In 2021, Solar PV module production capacity accounted for 460 GW, including 98% of crystalline silicon technology assembly and the rest by the manufacture of thin-film modules. Assembly of modules has the highest production capacity, but the lowest asset utilisation level, due to the low investment requirements and limited need for technological knowledge. Although 38 countries have module assembly facilities, China is still responsible for about 70% of production, with other important module assembly countries being Vietnam, Malaysia, Korea and Thailand. Large solar PV demand centres in the United States, India and Europe depend strongly on imports for main solar module components.

[1] For instance, TopCon is expected to reach a 17% market share in 2023 (ITRPV), compared with 8% in 2020, being introduced as a concept by Fraunhofer ISE in 2014 only.

2. Overview of costs structure for PV manufacturing

PV largely is a commodified product. Business models of PV project developers, and incentives schemes put a strong emphasis on the reduction of the cost of a PV panel on a EUR/Wp basis. Even small differences in manufacturing costs for PV modules lead to major competitiveness issues when it comes to deploying hundreds or thousands of GW of solar PV. Over the past decades, this has led to a transformation of the global PV industry with the emergence of China as the main actor in the PV sector – driven by a comprehensive industrial strategy to achieve leadership in that area. As Europe is looking to invest in the upscaling of its manufacturing capacity it is crucial to understand the cost structure of PV manufacturing, and the economic forces that govern competitiveness in the PV sector.

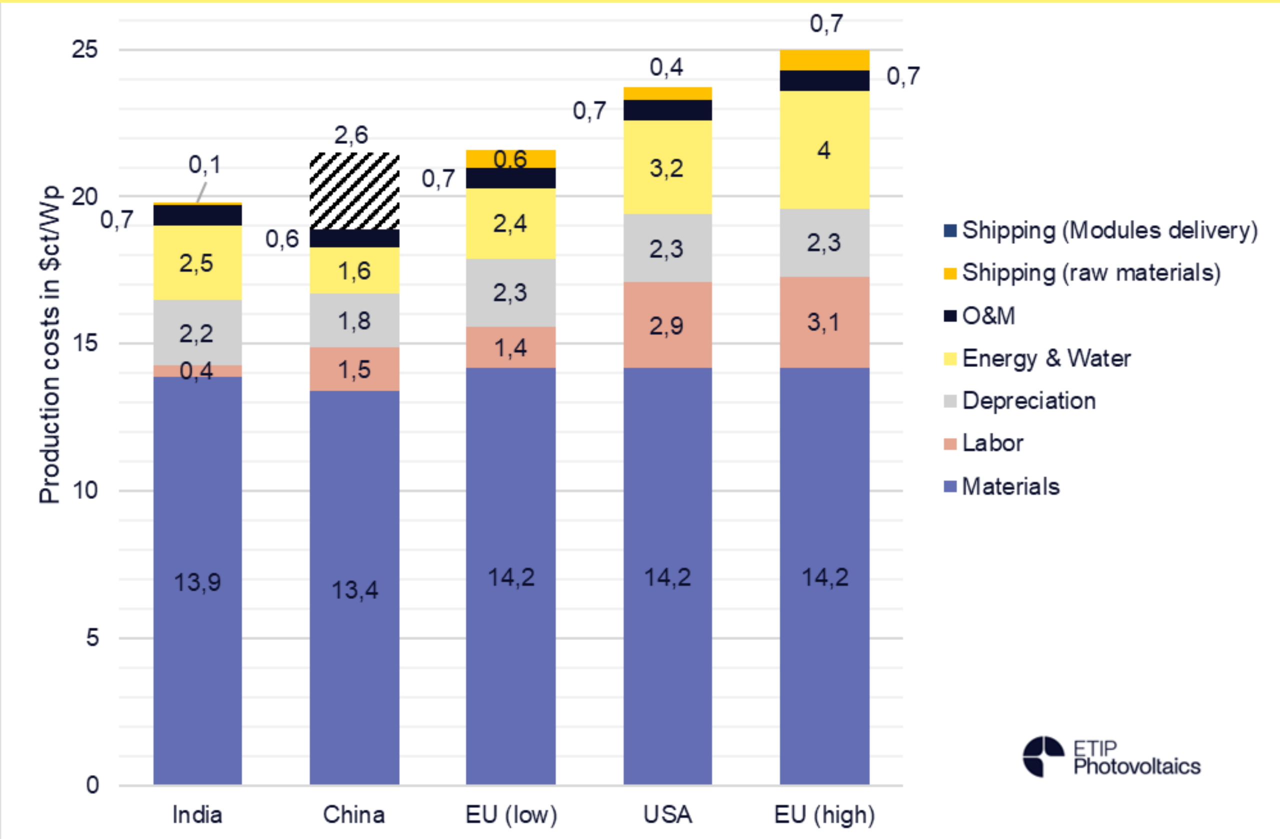


Figure 1. Breakdown of cost components per region for PV modules deployed in Europe (electricity, labour and CAPEX) (Source: RCT Solutions)

As highlighted by Figure 1 above, the cost of a PV module is largely determined by a few factors. Materials represent most of the cost of a unit, and their costs are also very similar across regions because polysilicon, wafers, glass and so on are also easy to transport on a global market. Nonetheless, PV module manufacturers can be expected to pay a premium of 6% compared to Chinese companies when sourcing materials and components for their products – due to the important concentration of the supply chain in China and the strong integration of the value chain in the country. However, this premium is marginal, and largely offset by the cost of transporting the manufactured panels from China to Europe. The main factors explaining the total production cost discrepancy from one production region to another are the costs of energy and of labour which explain 74% of the difference in production costs in the high estimate for European manufacturing with Chinese panels while ignoring transport costs. Energy and water costs by themselves explain nearly 69% of the cost disparities between these two cases when accounting for transport. It therefore appears clear that energy is a core condition of the competitiveness of PV manufacturing on the global market.

Overall, the costs of producing a panel in Europe can be estimated to be 15-33% more expensive than one produced in China. When accounting for the cost of transporting manufactured panels to Europe, the spread falls to 16% in the "High European production costs" scenario.

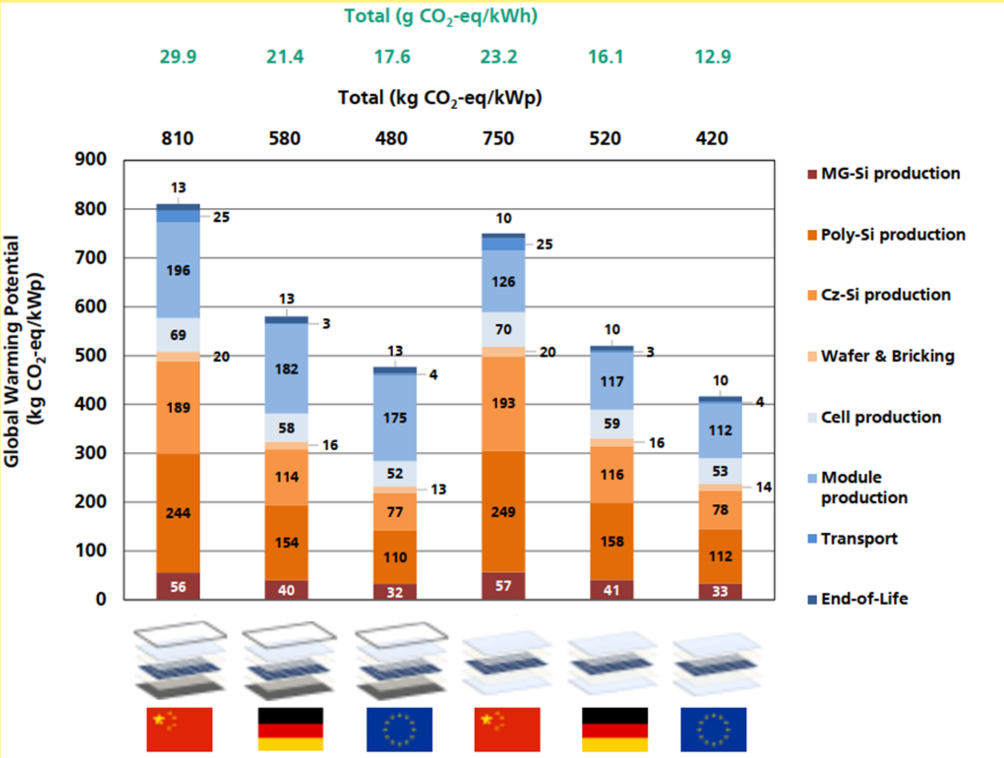


Figure 2. Comparison carbon footprint and other factors in production: while EU modules are more expensive to manufacture, a more advanced decarbonisation of the power sector also means they have a lower environmental impact (Source: Fraunhofer ISE)

The weight of energy costs in PV manufacturing's cost structure is important for module manufacturing, but even more so for several key raw materials such as polysilicon, wafers or solar glass. However, while energy is more expensive in Europe, it also is much more decarbonised than in many global markets. This is one feature that makes European panel manufacturers much more competitive when it comes to the carbon footprint of their products.

Interestingly, looking at estimates for the cost of manufacturing PV in different regions also point to a relatively small spread from one global manufacturing region to another, with low estimates for PV module manufacturing costs in Europe only 2 EUR/kWp higher than those for China when accounting for transport. For a typical 500W panel, European PV is 1-17.5 EUR more expensive than a Chinese one. For a 10kW domestic installation, this is a 20-350 EUR spread. For a utility-scale 300 MW project, developers might need to invest up to EUR 10.5 million more to source panels from the EU. Small discrepancies in production costs can lead to major differences for project developers and investors. A successful European PV industrial policy would therefore need to bring European PV panel manufacturing costs in a range comparable to that of its global competitors. Such a policy would therefore also consider the different factors that contribute to the competitiveness of a PV industry, from the cost of inputs such as energy and raw materials to the establishment of a reliable value chain and reaping economies of scale.

3. The European PV supply chain

- **Raw materials**

Key raw material of the PV value chain	European production capacity	Potential production expansion to meet future EU PV industry needs
Polysilicon	80,000 MT	
Ingots		
Wafers		
Glass	100,000-120,000 metric tonnes	
Silver Paste	3,000 tonnes	
Aluminium	4,000,000 tonnes	
Process gases (indium, gallium…)		

Polysilicon: The leading producer of polysilicon in Europe is Wacker. As a main component of solar cells, it is crucial that polysilicon is available and affordable in Europe. The production process entails chemical purification of metallurgical-grade silicon, which is extracted from quartzite or quartz. The specific consumption of polysilicon is between 2,000 and 3,000 tons per (GW) of installed capacity for the production of PV cells. Hence, the production of 20 GW PV capacity will require 40,000 - 60,000 tons per GW. The costs estimated for a 20 GW PV factory are approximately EUR 4 billion with a construction process of several years. Wacker's expansion plans for the production of polysilicon are critical to the growth of the PV industry in Europe, particularly regarding the EU's ambition to increase PV deployment by 30 GW production across the whole PV value chain in Europe by 2025. This will increase the demand for polysilicon, notably for ingots and wafers production. Therefore, investments in European polysilicon production today will be important to avoid bottlenecks in the future.

Solar Glass: The main European producers of solar glass are Interfloat (Borosil IN), Sisecam, and Alliaverre. The characteristics of solar glass allow for maximising the power of PV modules by minimising the amount of reflection and absorption of sunlight by the glass itself. It also can protect the PV panel from external environmental impacts. Interfloat (Borosil IN) currently has the highest production capacity in Europe of 6 GW, followed by Sisecam with a capacity of 3+ GW and an extension plan of an additional 5 GW. Alliaverre current solar glass production capacity entails 0.6 GW. Solar glass obtains a specific consumption for solar panel production of around 4,000 tons per gigawatt (GW) of installed capacity. Due to the increasing demand for renewable energies and hence solar PV, the production capacity is expected to increase in the coming years. The market demand has led solar glass suppliers like AGC and NSG to announce interest in increasing their production capacities.

Backsheets and Foils: Endurans, Coveme, Dunmore, Krempl, and Aluminium Feron are the primary producers of backsheets and foils in Europe. Backsheets consist of polymer material and are used to protect the backside of the PV panel by providing insulation, preventing moisture from leaking into the panel and generally protecting from environmental influences. Increasingly, the trend towards bifacial panels means that backsheets are made up of glass instead of polymer. Several materials are available and mature to manufacture backsheets, and manufacturers are exploring different formats, looking to provide better quality insurance and performance for module efficiency. Foils on the other hand should possess a high chemical inertness and a high barrier for oxygen and moisture. This needs to come with durable optical performance

over the module lifetime. It also needs to show degradation resistance to PID, UV radiation and thermal oxidation. They are part of the laminated layers of a panel between the backsheet and the cells and are a crucial component in ensuring the quality and reliability of PV modules, however, the PV sector is not facing a raw material vulnerability regarding aluminium, considering it is only a marginal component of global demand. The specific consumption of backsheets and foils is determined by the type of PV panel and the manufacturers' equipment. Compared to solar glass and polysilicon the production is more flexible as it can be used for products beyond solar panels. Accordingly, capacity expansion plans are adjusted depending on market demand. The production capacity of backsheets and foils in Europe is therefore sufficient to meet the current demand for PV panels.

Encapsulants: Encapsulants are a key component of a PV module, providing protection, insulation and robustness to PV modules. Encapsulants are for instance crucial to protect the cells and other components from water ingress and oxidation. The encapsulant market for PV is dominated by EVA (dominating for PERC modules) and POE (notably for TOPcon front side, with some worries about supply considering TOP con growth globally), with the emergence of EPE formulas (notably used for TOPcon backside and HJT). Key manufacturers are mostly located outside Europe, including notably Hangzhou First, Sveck or Crown in China, Enrich or Renewsys in India, Dow and Dupont in the USA. In Europe, Borealis based in Austria is contributing to encapsulant production.

Silver Paste: There are few producers of silver paste in Europe, and although Heraeus, DuPont, and Dycotec Materials had significant production across Europe, most of their silver paste production has moved overseas over the past decades. Silver paste is needed as a conductive material which is applied on the top of the PV cell. It transfers the electricity generated by the solar cells to the electrical circuits in the solar panel and can therefore highly affect the efficiency of the cell depending on its quality and consistency. The specific consumption of the silver paste on PV cells differs depending on the type of PV cell it is needed for. For example, Passivated Emitter and Rear Cell (PERC) solar cells require approximately 12 tons of silver paste per GW whereas Heterojunction solar cells need around 22 tons of silver paste per GW.

- ## Machine tools

The EU, led by Germany, is a global leader in the production of machine tools for various industries. In the PV sector however, the collapse of the European industry and the rapid evolution of the PV manufacturing technologies as annual production capacity boomed globally in the past decade has also led to a relative loss of expertise in the production of machine tools in Europe. Currently, while the European PV Machine tools industry is quite robust for the “downstream” components of PV module manufacturing, such as cell manufacturing and module assembly equipment, we see major gaps in production capacity and even expertise in key equipment of the “upstream” section of PV modules, notably wafering and for materials. In the short term, the EU is currently falling short in its capacity to upscale equipment manufacturing for ingot pulling and diamond wire saws, as well as for producing key inputs to the PV manufacturing process such as crucibles and diamond wire (key consumables in the ingot production and wafering processes).

Table: equipment and materials for the availability in the EU for PV manufacturing

Legend: Orange means basic knowledge of the technology and innovation processes is still available in Europe,

Yellow means that there is a need to expand the production.

Green means that this equipment and technology is available in Europe, although expansion and new investments in production capacity may remain necessary, depend on yearly installation / production necessary.

Key equipment Wafering	Availability in EU	Scale up capacity in EU
Ingot Puller	✓	Lack of available expertise and capacity to rapidly expand manufacturing for these investments without significant investments.
Cropping - Squaring - Polishing	✓✓	
Diamond Wire Saws	✓	
Separation and cleaning	✓✓	
Testing and Sorting	✓✓✓	
Fab Automation	✓✓	

Key equipment Cell Manufacturing	Availability in EU	Scale up capacity in EU
Wet Chemical tools (texture, etching, etc.)	✓✓✓	Manufacturing capacity for this equipment could be significantly expanded, though requiring investments and market visibility.
Thermal tools (diffusion, CVD, firing, etc.)	✓✓✓	
Laser tools	✓✓✓	
Printing	✓✓✓	
IV Sorting, Insitu Quality Control	✓✓✓	
Equipment + Fab Automation	✓✓✓	
PERC, TOPCon, HJT, New technologies	✓✓✓	

Key equipment Module Manufacturing	Availability in EU	Scale up capacity in EU
Laser cutter	✓✓✓	Manufacturing capacity for this equipment could be significantly expanded, though requiring investments and market visibility.
Stringer	✓✓✓	
Laminator	✓✓✓	
IV Measuring – Inline Quality Controll	✓✓✓	
Automation	✓✓✓	

Material for Wafering, Cell & Module production	Availability in EU	Scale up capacity in EU
Polysilicon	✓✓	Lack of a defined industrial framework for midstream material production towards consumption in the PV manufacturing process in Europe. To expand capacity and drive investment, guarantees as to investment trends in PV in Europe are necessary, as is the definition of added value of European production, notably linked to supply chain circularity.
Crucibles	✓	
Diamond wire	✓	
Chemicals + Gases	✓✓✓	
Ag pastes	✓✓	
Al pastes	✓✓	
Printing screens	✓✓	
Glass (front and rear)	✓✓	

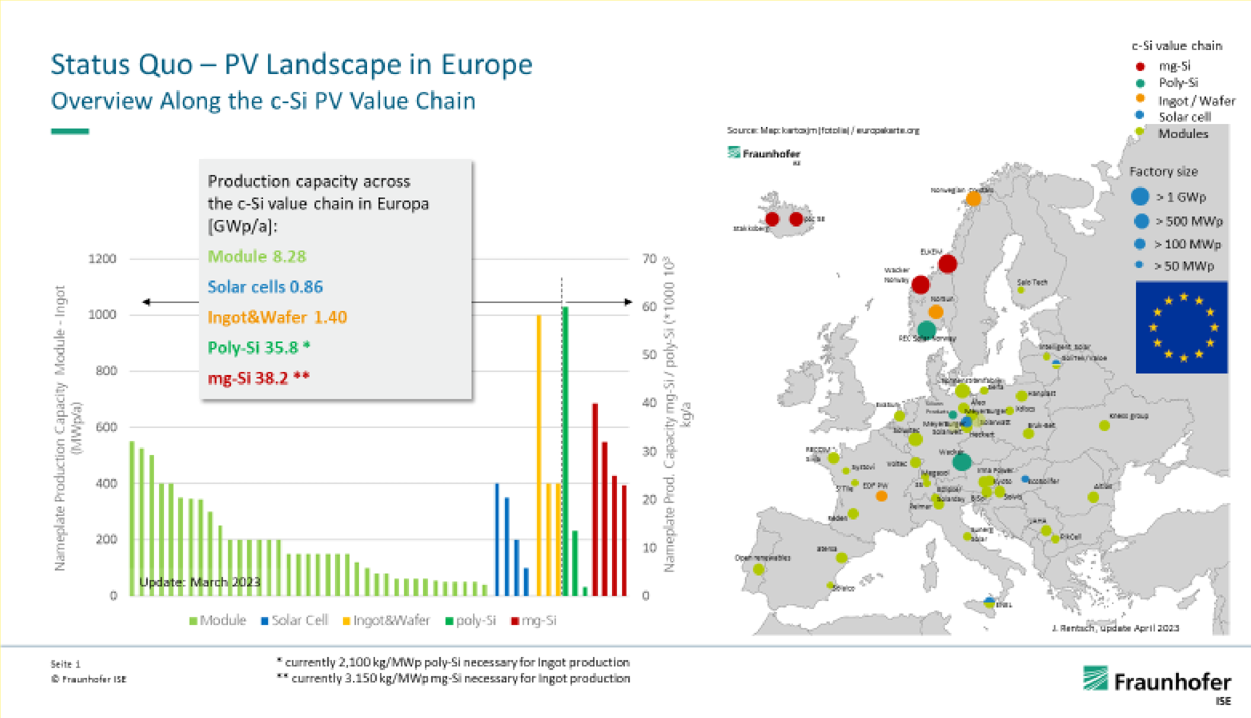
Encapsulants	✓✓	
Frame	✓✓✓	
Ribbon	✓✓	
Junction Box	✓✓	

The capacity of the EU to rapidly recover the expertise and expand its PV equipment manufacturing capacity will be a central challenge towards achieving European domestic PV manufacturing targets. Many investments currently consider the need to rely on Chinese equipment considering the longer lead time for European machines. Moreover, for many European equipment manufacturers, additional investments in PV equipment production face competition from the semiconductor sector which is also undergoing important investments towards the expansion of its value chain in Europe and the USA.

Moreover, despite the initial lead of European manufacturers for producing PV production equipment, the rapid transformation of the industry over the past decade and the relative deindustrialisation of the EU PV sector for specific components (most strikingly wafering) has led to a loss of expertise in the capacity to produce relevant, cutting equipment, but also a lack of experienced workers, engineers and technicians trained with the operation of said machines. Here again, the skills challenge is an important condition of the success of European industrial policies.

- **Manufacturing**

The EU's PV manufacturing capacity currently is not aligned with the European objectives of 30 GW of manufacturing capacity across the entire value chain. The SolarPower Europe Manufacturing Map identifies several areas that are far from these objectives with 9.4 GW of module manufacturing capacity, 1.4 GW of cell manufacturing capacity and 1.7 GW of ingot and wafers manufacturing capacity. On the other hand, the European inverter manufacturing industry has remained strong and has an annual production capacity of nearly 70 GW, while the European polysilicon industry remains strong with over 23 GW of annual manufacturing capacity.



Picture: Mapping of existing PV manufacturing projects in Europe throughout the PV value chain (Source: Fraunhofer ISE).

In light of the RepowerEU initiative, in reaction to global supply chain disruptions linked to COVID and the war started by Russia against Ukraine, many companies have been announcing investments into production capacity for various segments of the European supply chain, closing the gap in the 30 GW objective announced by the European Solar PV Industry Alliance. Currently, there are:

- Over 30 GW by 2030 of additional module manufacturing capacity as announced or planned investments across Europe for at least 8 projects. Projects in the pipeline include 8 GW of manufacturing capacity for modules (much less for other segments of the value chain, see figure below) by 2025, a far cry from the 30 GW of domestic PV manufacturing capacity throughout the value chain. Projects are announced at various stages of technology and industrial maturity, with a trend towards the design of projects that aim at the manufacturing of conventional panels for the first time, with an increasing degree of innovation as the manufacturing capacity grows and the investment consolidates (shingling, TopCon and or silicon HJT towards tandem perovskite for instance).
- For cells, ongoing projects represent a projected addition of 24 GW of new production capacity, notably driven by new investments in integrated PV manufacturing plants, where cells and modules are both manufactured.
- Thus far, around 20 GW of new wafering capacity by 2030 is announced in Europe, going a long way towards bringing the European supply chain gap in that area.
- For ingots, announced investments represent nearly 10 GW of new capacity in Europe.

Figure: Announced PV manufacturing projects, including capacity per segment of the value chain (Source: J. Rensch, Fraunhofer ISE, 2023)

Europe is on the Move …

Public Announcements for Capacity Development and Expansion Until 2025

Company	Ingot	Wafer	Cell	Modules
	1 (+18)	0.5 (+15)	0.6 (+26)	8.3 (+23)
Norwegian Crystal[1]	**0.5** (+3.6)			
NorSun[2]	**0.5** (+4)	**0.5** (+4)		
MeyerBurger[3]			**0.4** (+ 2)	**0.4** (+ 1.6)
ENEL[4]			**0.2** (+ 3)	**0.2** (+ 3)
NexWafe[5]		+0.5		
Carbon[6]			+5	+3.5
VallisSolaris[7]	+2	+2	+2	+2
Exiom/Iberdrola[8,16]				+0.5/+1.6
GigaPV[9]			+1	
AstraSun[10]	+1.2	+1.2	+1	
mcpv[11]			+5	+5
FuturaSun[12]				+2
Aurinka[13]				+0.3
Silicon Valen[14]	+5	+5	+5	+0.5 (+4.5)
AE Solar[15]	+2	+2	+2	+2

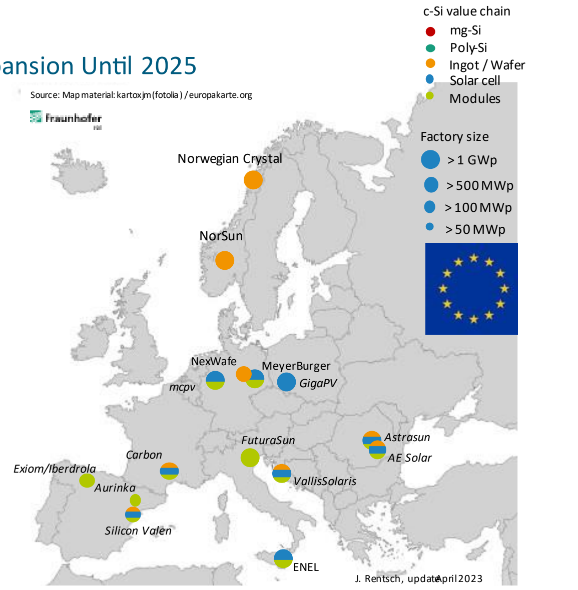


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Figure 3: Planned investments in PV manufacturing capacity across the value chain (Source: Fraunhofer ISE)

The PV supply chain is very dynamic and reactive to new investments. Factories for module assembly can be built in 2-3 years (permitting process aside), moreover, factories can relatively easily be adapted to contribute to the value chain of different PV technologies. Plants can also be developed on a wide range of scales, from production lines with a few hundred MW to gigafactories for several 10 GW annual outputs as are increasingly frequent in China. Scale of investments, outputs and value chains are crucial factors for competitiveness in PV. For modules with niche applications (e.g. BIPV) production with volumes in the range of a few 100 MWp/a might be economically viable. However, for cell and wafer manufacturing, facilities with such small scale certainly are not likely to become competitive due to the “commoditised” nature of these segments of the PV value chain, cells and wafers being essentially interchangeable from one supplier to another from a module manufacturing perspective. In the cells and wafer segment, to achieve a substantial degree of product differentiation, it would be necessary to propose products with performances that go far beyond the market baseline such as 10+%rel higher efficiency, 20+% higher lifetime, 50% smaller LCA footprint, 50+% more regional production or similar. If this is not the case, a smaller scale is a fundamental disadvantage. While the downstream of the PV value chain is relatively flexible, it is much more complex to rapidly scale up the manufacturing capacity of upstream components of the PV value chain. The European PV value chain is therefore looking for a stable investment landscape that allows for the development of new projects in a predictable timeframe.

- **Innovation**

The European Union has demonstrated a strong commitment to advancing energy research and innovation in the last decade, recognizing the crucial role that sustainable energy sources play in addressing climate change and ensuring the long-term viability of energy systems. In the previous multiannual financial framework (2014-2020), the EU invested EUR 4.99 billion towards research and innovation for projects related to the priority “Secure Clean and Efficient Energy” of the programme Horizon2020. Around EUR 490 million were invested towards PV-related research projects. Horizon Europe, the programme for the 2021-2027 period, enhanced the investment amount to at least EUR 15 billion towards “Climate, Energy and Mobility”. Estimates from Eurobserv’ER point to national public support to R&I in PV amounting to around EUR 250 million/year on top of the European Commission’s support. The EU's substantial investment in

research and innovation has provided significant support for specialized PV research institutes in several countries across Europe. Solar manufacturers can rely on these institutes, such as IMEC in Belgium, Fraunhofer ISE & CSP, FZ Jülich, HZB, ISC, ISFH, and ZSW in Germany, CEA-INES and IPVF in France, TNO in the Netherlands, and CSEM in Switzerland, among others, to provide cutting-edge research and development in the photovoltaic industry.

Which photovoltaic innovation did profit?

Throughout the past decades, the EU has been a leader in PV innovation. Many key innovations that contribute to the competitiveness of PV today were developed by European companies and research centres. As a result, this R&I effort has contributed to making PV the fastest-growing and cheapest energy source globally. The currently dominating half-cell PERC technology has been developed based on a number of innovations from European research institutes, solar cells and modules in the period 2000-2014, before being adopted by Asian manufacturers. Another recent example of European innovation that is rapidly growing in the market today is the TOPCon technology, developed in Germany by Fraunhofer, but industrialised in China. In the coming decade, we can expect other key innovative technologies developed within Europe to reach the market and transform the PV sector, for instance with cells combining silicon and perovskite for greater efficiency.

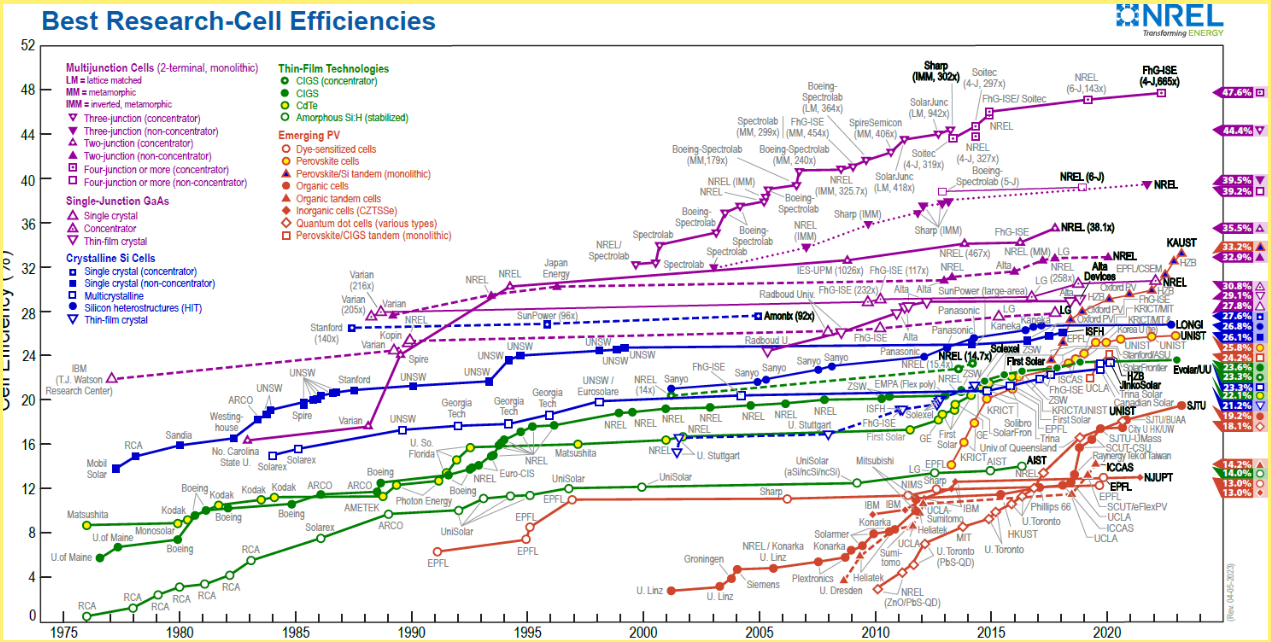

Figure 4: NREL Best Research Cell Efficiencies (NREL, 2023)

European research centres are still leading in the development of innovative technologies for PV, including at the level of fundamental research into new materials for cells. Fraunhofer for instance holds the absolute efficiency record for a PV cell with a multijunction cell at 47.66%. HZB and Oxford PV are among the organisations with the highest recorded efficiency for a Perovskite tandem PV cell[2], while ISFH recorded the highest efficiency for a homojunction silicon cell at 26.1%. This continued innovation in cell technologies is complemented by a capacity to innovate across the PV value chain, e.g. direct wafering with minimal kerf loss or Fraunhofer's Matrix shingling technology.

[2] HZB has only seen its efficiency record for a perovskite tandem cell at 32.5% beaten weeks before the publication of this publication by KSAUT at 33.2%, highlighting how fast the field is moving globally.

The European PV Research community has also been able to develop several innovations to meet specific challenges that emerged as PV penetration rates increased: integrating photovoltaics seamlessly in buildings and developing PV systems that do not negatively compete with agricultural uses of lands.

Where are Gaps and Weaknesses?

The successes of Europe's specialised PV research centres are always aligned with the research interest of Europe's PV industry. For example, in the last ten years innovation in cell and module technology was driven by specialised tool manufacturers and their strategy to offer new tools and processes against a backdrop of certified record efficiencies utilising their tools and processes. As the PV manufacturing value chain moved out of Europe however, and as technology innovation in PV manufacturing continued and accelerated globally, there has been a loss of expertise in several key segments of the PV R&I landscape. In the supply chain segment of ingots and wafers, Europe has seen a notable loss of expertise in research and innovation, but also in the capacity to manufacture specialised tools. This knowledge and innovation gap needs to be closed fast to achieve the ambitions put forward by the European Commission.

How much is Europe investing compared to the world for PV R&I?

Despite the European Union's commitment to renewable energy research, as embodied by the Horizon2020 and Horizon Europe programmes, Europe's technological leadership is rapidly eroding in the face of rapidly accelerating investments across global markets in PV R&I. The biggest PV wafer, cell and module producers in China such as LONGi, Trina Solar, Jinko, JA Solar or Tongwei are operating profitably and are investing hundreds of millions of USD each year in research and indeed in their own specialised research centres. For example, LONGi reported an R&D spending of USD 689 million in 2021, Trina Solar reported spending roughly USD 370 million in 2021 and Tongwei reported spending USD 300 million in 2021, amounting to 2% to 4% of their budget. It is worth noting that the amount spent by just one leading Chinese PV manufacturing company on R&I in a single year is in the same order of magnitude (or far greater) than the total public EU spending on PV R&I for the 2014-2020 period under the Horizon 2020 programme. This highlights the importance of a robust industry to sustain R&I efforts, but also the need to intensify investments in Europe to avoid stalling behind on R&I performance.

European PV companies across the value chain are also investing in R&I. Due to EurObservER, private R&D investments in EU-27 on 'Solar Energy' amounted to EUR 767 million in 2019. However, due to the smaller size of European PV companies, individual research budgets are smaller. For example, for a solar cell manufacturer with a production capacity of 2 GW it is much more challenging to run an R&D line with 500 MW capacity than for a manufacturer with 40 GW production capacity. This has an impact in the capacity of European manufacturers to industrialise innovative technologies, and keep up with global competitors. Fortunately, European governments are willing to support the rebuilding of cell and module manufacturing in Europe by supporting such R&D lines.

Continuous innovation is key to further reducing the costs of PV-generated electricity and material consumption, increasing the recyclability of materials and ensuring the sustainability of the multi-TW market. Non-price criteria in public tenders are an example of a demand-side tool to support such innovations.

Although they constitute the foundation of the PV industry, it also is crucial to not focus efforts to support R&I in the PV sector on cell technologies or even modules only. Many other components of the PV value chain have tremendous potential for improved efficiency, delivering additional energy services and value, from the development of integrated PV technologies to produce energy in more diverse situations (from building facades to offshore at sea), to the improvement of the capacities of inverters to operate PV installations reliably while exploiting synergies with flexibility providers such as storage or demand response on the grid. Besides, the drive towards increasing manufacturing capacity in Europe – as well as the continued market uptake of innovative PV technologies – requires improving the capacity of the industry to guarantee the quality and reliability of cells, modules and systems. Moreover, many additional R&I efforts will be required for a successful industrial PV policy in Europe to guarantee that new investments also integrate the establishment of a circular PV value chain, that manages end of life of systems, and aims to close the loop on material uses.

- ## Skills

The solar industry has grown significantly in recent years due to the increased awareness of the need to transition to renewable energy sources. This growth has led to the creation of numerous jobs, with a focus on manufacturing and deployment. The companies will need to find and integrate talent with a wide range of skills to guide them through the energy transition and help build new, greener businesses.

Job Creation

The solar industry has the potential creating jobs through both manufacturing and construction. Manufacturing and installation jobs have different impacts on the economy and local communities, with manufacturing jobs being typically more stable. However, jobs created during construction can be a benefit to local communities, as they provide employment opportunities and can boost the local economy. Besides, innovation and technological advancements, will create new job opportunities in areas such as research and development, engineering, and design.

The number of jobs in construction depends on the project capacity, its location and the country. The number of jobs for manufacturing per GW is shown in the table below. The given ranges depend on the equipment's design and the level of automation.

Table: Estimates of Full Time Equivalent needs per employee categories for different steps of the PV manufacturing process for a model integrated 10 GW TOPCon manufacturing plant (Source: RCT Solutions)

	mgSi	Polysilicon	Ingot & Brick	Wafer	Cell	Module
Net capacity	39 MTY	30 MTY	10 GW	10 GW	10 GW	10 GW
Operator	106	520	1047	1531	1052	3014
Technician	28	76	209	156	389	129
Engineer	10	176	459	121	134	36

Job Status and Perspectives in Europe

The solar industry in Europe has seen significant growth in recent years, with Germany, Spain, Poland, Netherlands, and France leading the way in solar panel installation. According to Solar Power Europe, the European solar sector employed 466,000 full-time employees in 2021, among which 205,000 were employed directly. It is a 30% increase from 2020. The great majority of jobs (79%) are associated with solar deployment activities. Operation & Maintenance jobs are 10% of the total. The remaining share belongs to Manufacturing, at 9%, and Decommissioning & Recycling, at 3%. Out of the total 44,000 jobs created by Manufacturing, inverter manufacturing provided the bulk with 31,000. With the nascent solar panel production capacities, it is expected that the number of jobs will increase significantly.

Future EU solar job creation will be influenced by the level of ambition in setting the new EU renewable energy target for 2030. With a 40% target, solar jobs would double compared to today's levels. Additionally, the European Union's goal of achieving carbon neutrality by 2050 will lead to further growth in the solar industry and the creation of more jobs.

Value Chain Jobs Distribution and skills

The solar industry has a diverse value chain that includes manufacturing, deployment, operation & maintenance, and decommissioning and recycling. Manufacturing jobs involve the production of solar panels and related equipment. Deployment jobs include the development, design and installation of solar panels. Operation and maintenance jobs involve the upkeep of solar panels and related equipment while decommissioning and recycling jobs focus on the removal and recycling of solar panels at the end of their lifespan.

To work in the solar PV manufacturing industry and power plant construction, you will need a combination of technical and soft skills. Here are some of the key skills required:

- *Skills requirements for solar panel manufacturing:*

Knowledge of solar technology: A strong understanding of the technology and science behind solar PV manufacturing is essential. This includes knowledge of semiconductor materials, photovoltaic cell design, solar panel assembly, and related concepts in physics.

Technical skills are essential for working in the solar manufacturing industry, as they require individuals who are skilled in electrical and mechanical engineering. This includes being familiar with complex solar panel manufacturing processes, troubleshooting systems, and performing maintenance on machinery and equipment.

Quality assurance is a critical component of the manufacturing process, and solar panel quality can impact the effectiveness and reliability of a solar power system. Individuals who work in the solar manufacturing industry must be skilled in inspection and testing to ensure that solar panels are meeting the required quality, performance standards and safety.

Managing manufacturing operations involves a wide range of skills, including **organisational and leadership skills**. Effective communication is necessary for ensuring that everyone is working in accordance with the company's values and goals. The solar manufacturing industry requires individuals who can supervise production teams, coordinate schedules, optimize processes, and create new innovative strategies to improve the manufacturing process.

Data analysis and statistical analysis are essential parts of quality assurance, testing, and inspection of making solar panels. To ensure that the products are meeting the desired quality, it is important to be able to analyse data and create insights from data. Individuals who work in the solar manufacturing industry must be skilled in data analysis to make better decisions, reduce costs and enhance production efficiency.

Safety awareness: Solar PV manufacturing involves working with potentially hazardous materials/products and equipment, so safety awareness is critical. You should be able to identify potential safety hazards and take appropriate precautions to prevent accidents.

- *Skills requirements for solar power plant construction:*

Knowledge of PV technology and installation: Individuals who work in solar power plant construction must be familiar with photovoltaic technology and installation processes. This includes knowledge of the electrical wiring and design of solar power systems.

Understanding of electricity and electrical systems: A strong understanding of electricity and electrical systems is essential for working in solar power plant construction. This includes knowledge of electrical safety standards and regulations, as well as the ability to read electrical diagrams and blueprints.

Project management: Managing solar power plant construction requires excellent project management skills. Individuals in this field must be skilled in coordinating teams, creating timelines, and ensuring that projects are completed on schedule and within budget.

Safety is a critical concern in solar power plant construction. Individuals working in this field must be knowledgeable about the safety procedures and regulations that apply to solar power systems and construction sites. They must also be able to identify potential safety hazards and take measures to prevent accidents from occurring.

Quality assurance is essential in ensuring the reliability and effectiveness of solar power systems. Individuals working in solar power plant construction must be skilled in inspection and testing to ensure that the systems are meeting safety and performance standards.

Overall, a combination of technical knowledge, problem-solving skills, attention to detail, teamwork, quality assurance, safety awareness, and a willingness to learn and adapt are essential to succeed in solar PV manufacturing and deployment.

<u>Filling the Gaps:</u> To fill the skills gaps in the solar industry, educational programs and training opportunities are essential. Educational programs can provide individuals with the necessary knowledge and skills to work in the solar industry. This can include vocational training, technical schools, and universities. The training opportunities can allow individuals to develop new skills and keep up to date with the latest technologies. Additionally, individuals with skills from other industries can often find synergies in the solar

industry, as many of the required skills are transferable. These programs can range from on-the-job training to formal apprenticeships and educational programs.

Overall, filling the skills gaps in the solar industry will require a collaborative effort between companies and educational institutions. By developing targeted training programs, partnerships, and recruitment strategies, the industry can attract and retain the skilled workers needed to support its growth and meet the demand for renewable energy.

Global Mobility: The solar industry is global, with solar projects and companies operating in multiple countries. This means that individuals with the necessary skills may have opportunities for global mobility, allowing them to work in different countries and gain valuable experience. Additionally, global mobility can help to fill skills gaps in areas with high demand for solar professionals.

In conclusion, the solar industry has the potential to provide significant employment opportunities and contribute to the growth of economies, while also helping to address the challenges of climate change. As the industry continues to grow, the demand for skilled professionals is likely to increase and educational programs and training opportunities will be essential to ensure the continued growth and success of the solar industry.

4. Global policy analysis

- ### Europe

The European PV industry is confronted with tough competition from established solar markets in China and the US as well as up-and-coming markets in India and Southeast Asia. Nonetheless, European Solar manufacturers currently obtain a few key advantages which could help them to compete globally in the future. These not only rely on producing high-quality products but also being the frontrunner in developing innovative PV solutions that incorporate advanced materials. By leveraging these strengths, European manufacturers can differentiate themselves from their competitors. However, in order to exploit these advantages, supportive European regulatory frameworks are crucial. The Green Deal Industrial Plan serves as an example of the need for such frameworks. The plan is a key complement to the European Green Deal fostering the goal of achieving a carbon-neutral Europe by 2050. As such, the industry plan aims to create a streamlined, efficient, and reliable regulatory framework that ensures sufficient supplies of Critical Raw Materials (CRMs) and allows users to benefit from the cost advantages of renewable energy. Two initiatives within the plan are critical to enhancing green industrial competitiveness in Europe: The Net-Zero Industry Act and the Critical Raw Material Act. These initiatives aim to streamline the regulatory framework, secure a reliable supply of raw materials, and promote the use of renewable energy to drive down costs and make European industries more competitive in the global market. Although Europe has better maintained its competitiveness for PV innovation compared to other segments of the PV value chain, other regions are fast catching up and overtaking the EU. Chinese researchers are now developing some of the most cutting-edge new technologies in the PV sector, and the robust industrial environment around innovation allows them to rapidly test and operationalise R&D results. A successful European industrial policy around PV will need to maintain and strengthen the performance of PV R&D in the region, while improving the linkages between the emerging manufacturing sector and the PV research community. Strong innovation policies will be needed, for instance on the model of a co-programmed partnership or similar mechanism to accelerate and scale up funding for R&I in PV.

The Net-Zero Industry Act (NZIA) is expected to play a crucial role in boosting the European PV industry. One of the objectives of NZIA is to advance strategic net-zero technology presently available in commercial markets or expected to enter the market in the near future and have the potential for being widely adopted. Moreover, the act seeks to simplify regulations around net-zero technology, particularly PV technologies. Thereby, it will help EU-based manufacturers to maintain their competitiveness by using novel production methods to manufacture innovative PV technologies. Alongside NZIA, the European Critical Raw Materials Act seeks to ensure reliable support of Critical Raw Materials (CRMs) for the European Union with a particular emphasis on CRMs relevant to energy technologies. Hence, the act will help to reduce any risks incurred as a result of CRM shortages or supply chain disruptions. Moreover, it will promote sustainable and environmentally sound mining practices in the EU which will ultimately contribute to the overall sustainability of the solar industry. As a result, the European Critical Raw Materials Act could considerably enhance the competitiveness and growth of PV manufacturers in the EU as it will ensure reliable access to the CRMs needed to manufacture solar technologies.

- **China**

China is the leading country in PV manufacturing boasting the majority of the market share in all segments of PV manufacturing, from polysilicon refining to module assembly, including ingot & wafer productions where the country holds a near monopolistic position, cell production, or solar glass. China has comprehensive leadership across the PV value chain that is the result of a consistent industrial and energy policy toward this goal. The Chinese PV industry emerged with a focus on exporting PV panels to European markets defined by a strong level of operational subsidies for PV electricity generation in the late 2000s. Rapidly gaining market share thanks to the important role of local and central governments in supporting the Chinese industry, the country became the global leader of the PV value chain by the mid-2010s, continuously consolidating its position since then despite international trade tensions.
China's PV industry benefits from strong support from local governments, and a favourable framework to support investments in industrialisation. PV is for instance one of China's identified priorities for strategic emerging industry as of 2010, and features prominently in the 11th, 12th and 13th Five Years Plans with clear development principles and goals. The 12th five-year plan[3], from 2011 to 2015 focuses on planning & supporting leading enterprises (identifying specific targets for companies with a given turnover, capacity and size across the value chain), supporting R&I (notably via the establishment of national laboratories and better industry/innovation linkages) to reduce production costs, all while expanding the PV market (via domestic RES generation incentives for instance). The 13th five-year plan sets a 105 GW target for PV in China with a 50% cost reduction compared to 2015, emphasizing the deployment of distributed PV and PV integration (agriculture, buildings, floating)[4]. The 14th plan, implemented between 2021 and 2025, adds ambitious deployment objectives and investments toward putting PV and other renewables at the heart of the Chinese energy system, while maintaining the rank of the Chinese PV industry.

- **India**

India is a country with a major potential to exploit the benefits of PV electricity, and one that is only beginning its industrial transformation towards renewable energy technologies such as photovoltaics. The country adopted a 100 GW objective of installed PV capacity by the end of 2022 which was not quite met with 79 GW of capacity installed. India also has an objective of 450 GW of PV installed by 2030 within reach, a target that has not yet been achieved despite a significant acceleration of the market. To complement this installed capacity target, India has more recently adopted an objective of 65 GW of domestic manufacturing capacity along the PV value chain by 2027. To achieve this objective, India is implementing a production-linked incentive that dedicates USD 2.4 billion to supporting the installation of PV manufacturing plants to incentivise the production of PV panels in India by eligible companies (i.e. a production subsidy). The Indian incentives framework to invest in PV manufacturing capacity also includes a CAPEX subsidy ranging from 20-25%, a domestic content requirement for PV projects benefiting from renewable energy generation subsidies from the Indian government, as well as a basic customs duty on the import of PV cells and modules.

- **USA**

The Inflations Reduction Act allocates $369 billion to the effort of decarbonizing the US economy. Among other targets, the legislation aims to reduce CO2 emission by up to 40 percent nationwide in 2030, promoting particularly energy savings for US households. The solar industry will play a central role in achieving these targets as the IRA aims to deploy 950 million solar panels resulting in offsetting 747 million metric tons (MMT) of CO2 emissions over the next decade (compared to a non-IRA implementation scenario). The act will also incentivize investments in renewable energy sources (RES) by extending investment tax credits (ITC) for RES and production tax credits (PTC) for solar energy. More specifically, the ITC has received an extension for a period of ten years with a tax credit equal to 30 % of the cost of the installed equipment for the named period. The credit will be reduced consistently to 26% in 2033 and 22% in 2034. Furthermore, the Act entails a 10% surcharge on the ITC for domestically produced content and an additional 10% for projects that are implemented in designated energy communities.

[3] https://policy.asiapacificenergy.org/sites/default/files/chinas-five-year-plan-for-solar-translation.pdf
[4] https://www.iea.org/policies/6275-china-13th-solar-energy-development-five-year-plan-2016-2020

For the first time, PTC will also be available for PV projects, receiving a tax credit of $0.003 per kilowatt-hour generated. The IRA also aims to promote research and development for RES with a substantial amount of 2 billion, supporting the Department of Energy's Office of Science and national laboratories. A significant amount of $1.55 billion is earmarked for improving the national laboratory infrastructure, including the improvement of scientific facilities, upgrading infrastructure and eliminating deferred maintenance projects. A further amount of $150 million will be assigned to upgrade laboratory infrastructure at the National Renewable Energy Laboratory (NREL). These funds represent one of the largest investments in national laboratory infrastructure ever made and are intended to support research and innovation by the nation's top scientists.

5. Recommendations and conclusions:

- **Financing needs to be adequate throughout the PV value chain:** the bottom line of PV industrialisation in Europe is access to financing. The conditions for access to financing across the PV value chain are generally not in line with the ambitions for the deployment of PV manufacturing in a short timespan throughout Europe. At the European level, many solutions can be implemented to accelerate financing and implement a framework on par with those available globally to accompany investments in PV. These could notably include a relaxation of the Temporary Crisis and Transition Framework to accelerate the channelling of funding towards projects. EU funding programmes, beyond issues related to the clarity of the financing framework and the volume of funding available, projects are often faced with lengthy and complex procedures that are not aligned with the requirements of private project investments in terms of delays and financial risk mitigation.
  A solar bank could be a relevant solution to accompany investments in PV manufacturing in Europe, especially as a vehicle to channel OPEX support to projects.
- **Overall, the EU needs a streamlined framework for permitting and application processes for PV manufacturing projects.** The framework introduced by the Net Zero Industry Act is a step in the right direction towards a better framework for supporting such projects, however, it is insufficient in delivering clear timelines and risk reduction.
- **Consider the Solar PV Supply chain in its entirety: European** policy making around the PV supply chain cannot only focus on crystalline silicon PV modules. However, there are many other components of the PV value chain that are required for a successful energy transition. Inverters are an area where the EU notably maintains an important domestic manufacturing capacity and degree of innovation. All these components also need to be at the centre of the European PV industrial strategy.
- **Maintain and intensify investments in research and innovation:** the European PV R&I sector managed to maintain its leadership over the past decade, however, it would be unwise to assume that the situation will remain without additional efforts. The structural transformation of PV manufacturing globally over the past decade has led to an important loss of expertise in some key segments of the supply chain, and other regions are now able to match or exceed the EU’s research and innovation capacity in many areas of the PV value chain, thanks to important public and private R&I spending. Along with the renewed investments in PV manufacturing capacity, the EU needs to invest in the industrialisation of the results of its R&I efforts, as well as strengthen its investments towards developing the next generation of PV technologies.

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