The current state of the EU photovoltaic industry

An in-depth look at the ingot-wafer supply chain

Final report summarizing the findings of interviews conducted for the supply chain gap study.

January 2024
Contributors:
Fraunhofer-Institut für Solare Energiesysteme ISE
Oscar Rodolfo Ortega Alvarado, Estelle Gervais, Sebastian Nold
European Solar Manufacturing Council
Johan Lindahl

I. Introduction of the Report

With nearly 97% of the world's production capacity, the manufacturing of silicon wafers, used to make photovoltaic (PV) cells, is highly concentrated in China (ETIP Photovoltaics, 2023; IEA, 2022). The entire industrial ecosystem for ingot-wafer production, including materials, equipment, and consumables is also located there. The Chinese Ministry of Commerce (MOFCOM) and the Ministry of Science and Technology (MOST) latest communication of the "Catalogue of Technologies Prohibited or Restricted from Export" (Chinese Ministry of Commerce, 2022) includes "large scale solar wafer technologies, ultra-high efficient ingot casting mono/multi crystalline technology, black silicon preparation technology and „others", which implies a potential restriction on exporting three technologies related to the PV manufacturing industry: wafers, black silicon, and ingot casting. If the three categories are added to the restrictions list, manufacturers will need technology export licenses from the respective provincial departments to export such products (pv magazine International, 2023) to support non-Chinese manufacturing industries.

As part of the efforts to strengthen the European Union's (EU) energy security after the global energy market disruption caused by Russia's invasion of Ukraine, the European Commission (EC) created the European Solar PV Industry Alliance (ESIA) (EU Solar Energy Strategy, 2022) and set a goal to reach 30 GW of annual PV manufacturing capacity along the value chain by 2025 (European Solar PV Industry Alliance, 2023). Furthermore, the EC launched the Net-Zero Industry Act (NZIA) which aims to facilitate a rapid transition to climate neutrality by expanding the EU's manufacturing capacity for net-zero technologies. The main objective of the NZIA related to solar PV is to ensure that by 2030, the manufacturing capacity of solar PV in the EU approaches or reaches at least 40% of the Union's annual deployment needs (Net Zero Industry Act, 2023). The mentioned export restriction announced by China raises concerns about reaching these goals.

Ingot and wafer manufacturing is the most vulnerable stage in the PV supply chain in terms of dependency and difficulty to re-shore (ETIP Photovoltaics, 2023). To provide a clear overview of this significant phase, this report delves into the ingot-wafer manufacturing value chain, as illustrated in Figure 1. The purpose of the report is to identity and understand who the main industry players outside China are, and particularly within Europe for: Ingot and wafer manufacturing companies, and their main suppliers of materials, consumables, and equipment.

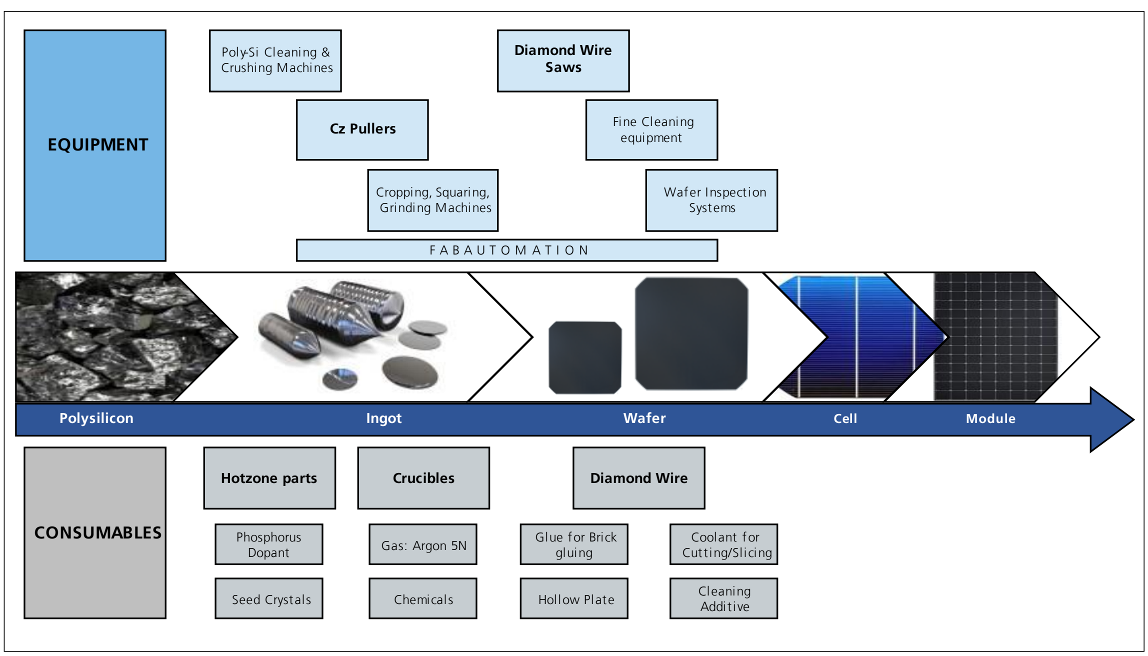

Fig 1. PV Ingot-Wafer manufacturing value chain

II. Semi-structured Interviews

Publicly accessible data on ingot and wafer manufacturing is scarce. To enhance the knowledge in this part of the value chain, interviews with professionals from various organizations were carried out. The interviews were conducted between September and December 2023. Several experts from different companies were approached and shared their views and information about the situation in the European ingot and wafer industry.

1. Interview results: Industry ecosystem analysis

As the list of important industry players shows, this study gathers information from a wide range of European companies, not only ingot and wafer manufacturers, but also their suppliers of equipment and consumables. In addition, companies in the semiconductor sector are studied, as well as former companies in the sector and new upcoming projects.

Role within the PV supply chain	Country HQ	Component	Company name	Annual Production Capacity (Current / Planned)
Polysilicon producer	Germany	**Poly-Si**	*Wacker*	Total: 80k Tons ~32 GW, Undisclosed % for Solar
Polysilicon producer	USA		*Hemlock (HSC)*	Total: 30-35k Tons ~14 GW, with 60-65% for Solar
Polysilicon producer	Netherlands		*Resi BV*	Planned Initial Capacity 12.5k Tons ~6 GW & Full production of 25k Tons ~12 GW
Polysilicon producer	Sweden		*Green14*	Planned: 25k Tons ~10 GW Manufacturing plant using green hydrogen plasma.
Supplier of Crystal growing equipment	USA/China	**Cz Pullers**	*Linton Crystal Technologies*	Total: ~6500 Cz pullers ~100 GW
Supplier of Crystal growing equipment	France		*ECM Greentech*	-
Supplier of Crystal growing equipment	Germany		*PVA TePla CGS*	Total: 50 - 70 Cz pullers ~0.7 - 1 GW (Focused on capacity for Semi-pullers which are not necessarily 1:1 to Solar GW)
Ingot and Wafer producers	Norway	**Ingots and Wafers**	*Norwegian Crystals*	(Formerly) Total: 0.25 - 0.5 GW
Ingot and Wafer producers	Norway		*NorSun*	Total: 1 GW Planned: +3 GW (Norway) +5 GW (US)
Wafer producers	Germany	**Wafers**	*Nexwafe*	Planned: 0.25 GW
Potential Crucible supplier	France	**Crucibles**	*Saint-Gobain*	-
Potential Crucible supplier	Norway		*DIGLOO AS*	Planned 4 furnaces, able to produce: 25,000 crucibles of 37 inch diameter ~15 GW
Supplier of high purity Quartz	Norway	**High purity Quartz used in Crucibles**	*The Quartz Corp*	Undisclosed current capacity, but enough to keep pace with the PV market, which in 2023 was near to 405GW or ~73K - 81kTons
Graphite supplier	France	**Hot Zone parts (Graphite)**	*Mersen*	-
Graphite supplier	Germany		*SGL Carbon*	Total: ~10K Tons of Isostatic graphite
Silicon Ingot Grinding and Automation Equipment supplier	Germany	**Grinding machines**	*Arnold Gruppe*	-
Lapping, Cutting and Polishing machines supplier	Germany	**Diamond Wire Saws**	*Lapmaster Wolters*	Planned: 80 -100 Diamond Wire Saws ~ 1.1-1.4GW
Additives for Wafer cutting supplier	Germany	**Additives for Wafer cutting**	*Evonik*	Market leader in wetting agents within formulations of PV wafer cutting, Undisclosed production capacity
Potential Diamond Wire supplier	Belgium	**Diamond Wire**	*Bekaert*	-
Bricks, Wafers, and Solar Modules producers	France	**Bricks, Wafers, Solar Modules**	*Photowatt*	Total: 0.20 GW
Ingot, Wafers, Solar Cells and Modules producers	Türkiye	**Ingots, Wafer, Cells and Modules**	*Kalyon*	Total: 2 GW
Ingot, Wafers, Solar Cells and Modules producers	France	**Ingots, Wafer, Cells and Modules**	*Carbon*	Planned: 5 GW
Solar Cells and Modules producers	France	**Solar Cells and Modules**	*Holosolis*	Planned: 5 GW

Table 1. Companies considered for the study.

2. Mapping the Supply Chain: Key components for production

2.1. Equipment for Ingot-wafer production

As illustrated in Figure 2, key equipment within the ingot-wafer manufacturing process includes *Solar Czochralski (Cz) pullers* and *Diamond wire saws* for slicing of bricks. Furthermore, *cleaning, packing, and inspection machines* also play essential roles in the process. Factory automation, or *fab automation*, is a crucial factor in the current solar production scene to increase productivity and reduce costs.

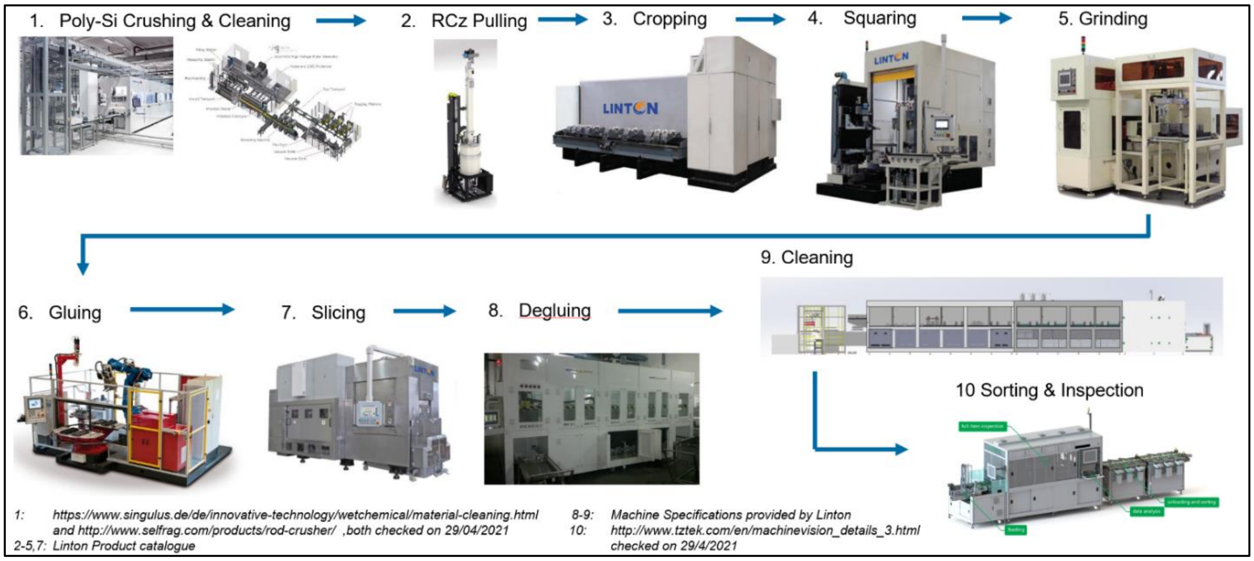

Fig 2. Process Flow for Ingot and Wafer (main equipment)

Now the report will then delve into the key equipment needed for the production of ingots and wafers. This section presents the findings from the interviews conducted with experts, outlining the current supply state of each component in Europe and the challenges faced by these sub-sectors.

2.1.1 Solar Cz pullers

Current state

- The supply of Cz pullers is the most crucial component for the ingot production process. However, there is a lack of the necessary industrial capacity and knowledge in Europe for manufacturing the required pullers for the PV industry. Moreover, there are seemingly no companies intending to start production for the PV ingot value chain without political backing and required funding.
- Expertise at the R&D level is present in research institutes as the Fraunhofer Center for Silicon Photovoltaics (Fraunhofer CSP). However, the industrial know-how is currently unavailable in Europe.
- *RCT Solutions*, a consulting and engineering company from Germany has acquired process knowledge through the installation of Chinese Cz pullers in India. This means that the consultancy can use their experience with technology implementation overseas to provide the knowledge needed for ramping up PV Cz puller operations in Europe.

- Setting up an ingot production plant without relying on Chinese suppliers for Cz pullers is practically impossible. Currently, Chinese suppliers dominate the market, providing the most advanced technology, the best quality, and the lowest prices.

Importance and challenges of Cz pullers

- The Cz puller is the most expensive piece of equipment in the whole value chain leading up to the wafer, the Cz puller accounts between 40 - 50% of the production equipment costs, and an estimated 25% of the overall capital expenditure (CapEx) in a manufacturing plant (PV manufacturing consultant, personal communication, September 04, 2023).
- In addition to incurring high CapEx costs, Cz pullers, as other equipment used for PV fabrication, experience rapid technological advancements and a short lifespan.
- To remain competitive, the modern ingot pulling process requires large and efficient Cz pullers capable of producing a high ingot output per cycle, the current estimate is between 15 to 17 MWp of ingots per Cz puller.

Relevant criteria for sourcing Cz pullers

- Given a CapEx share of over 40%, it is highly valuable for ingot-wafer companies to prioritize selecting the best supplier rather than focusing on the specific Cz puller.
- Beyond price, the level of service and support is one of the primary criteria for selecting an equipment supplier. Ingot-wafer companies need well-structured service agreements with service aspects such as assistance with installation and troubleshooting.
- While prices remain a key consideration, the focus on service would favor European suppliers who, being closer to the customer, could offer easier maintenance, consistent upgrade proposals and overall flexibility.
- Potential challenges when considering Chinese equipment include delays in bringing workers from certain regions due to visa approvals and other bureaucratic procedures.

Trends in wafer sizes and Cz pullers replacement

- Over the past few years, there has been a swift transition in wafer sizes, from M6 to M10, and now G12 within the global PV industry.
- Chinese equipment suppliers estimate that Cz pullers need to be replaced approximately every two years. As retrofitting is difficult, new generations of pullers would have to be implemented to increase production capacity. This replacement rate is considered very fast and demanding by European ingot manufacturers.
- However, the current industrial limit for ingot diameter is 450mm. Beyond this limit, sophisticated microelectronics equipment is needed. If there is a need to increase the ingot diameter, it may require advanced equipment, which could potentially slow down the replacement process.

Other Cz pullers equipment suppliers outside China

- *Linton Crystal Technologies (LCT)* could be a possible '*western*' supplier. Although Chinese-owned, it still possesses engineering, design, and process knowledge, and retains the capability to operate in the US.
- *LCT* has an approved plan for a new ingot equipment manufacturing plant in the US, but it is currently on hold due to geopolitical factors between the US and China.
- *RE:Build Manufacturing*, a company based in Massachusetts, US, announced the release of their own Solar Cz puller, which comes with its own hotzone. The company plans to deliver the ingot maker by the end of 2024.

Semiconductor Cz pullers equipment manufacturers

- *PVA Tepla*, *ECM* and other equipment manufacturers that supply Cz pullers to the semiconductor industry could convert to supplying the PV industry based on their knowledge of similar (but not identical) technology.
- The shift from semiconductors to PV would involve significant changes in product development and production facilities to supply the PV market, including a significant increase in the number of pullers they could manufacture per year, and a technical adaptation to match requirements of solar PV manufacturing for e.g., an increase in the crystal diameter, length, and quality.
- The main factors for transitioning to the PV sector include product quality, product design and cost competitiveness. Such a transition would require a complete redesign of both the supply chain and production strategies.
- Semiconductor sector companies justify higher costs by offering superior quality compared to what’s readily available in China. However, this advantage doesn’t matter as much in the PV industry because wafers in this sector can tolerate higher levels of impurities than semiconductors.
- If the necessary measures are taken, European Cz puller manufacturers in the semiconductor industry may consider re-entering the PV sector. However, they would require assistance in bridging the technology and cost gaps. Financial investment in both the CapEx and the operating expenses (OpEx) of equipment production facilities would be necessary.

Challenges for the EU Industry

- Companies entering the EU PV industry must first upgrade their technology to be competitive. The challenge is matching the low equipment prices from China. Therefore, companies need help filling the technology and cost gaps before they can successfully enter the industry.
- Equipment manufacturers need to find ways to produce Cz pullers that are cost-competitive. Allowing ingot-wafer companies to produce at competitive prices.
- Expanding equipment manufacturing capacity requires a sizeable market. Current market conditions for equipment manufacturers in Europe are unfavorable due to the lack of sufficient ingot production in Europe.

2.1.2 Cropping, Squaring Grinding equipment

Current State

- Cropping, squaring, and grinding equipment availability is better than for Cz pullers, this equipment could be developed through well positioned European suppliers specialized in metal cutting.
- However. the supply not only in Europe but in the Western world is limited and, in most cases, not mature compared to global competition from China (lower prices, and superior quality).

2.1.3 Diamond wire saws

Current state

- There is sufficient knowledge/technical expertise for establishing diamond wire saw manufacturing in Europe. However, there is currently no industrial capacity in place.
- Although wire sawing equipment was originally developed in Europe, the Chinese diamond wire sawing technology is currently world leading and holds a significant competitive advantage.
- A *European saw manufacturer* is developing its own equipment and has scheduled the completion of its first prototypes for January 2024. Following a 2–3-month testing period, if everything goes according to plan, the prototypes will be ready for delivery by the end of June 2024.

Advancements in diamond wire slicing technology.

- The semiconductor sector has achieved notable success in wire slicing, which could potentially be applied to the PV sector. However, it is important to note that there are technical differences between the two industries. Technical differences, such as the thickness of PV wafers, which are getting smaller and also significantly thinner than in the semiconductor industry. This will have a significant impact on machine throughput and scrap rates. Therefore, there is still a gap that needs to be addressed in this area.
- The EU PV sector can adopt semiconductor practices to enhance competitiveness and efficiency, such as semiconductor industry's experience with artificial intelligence (AI).
- The European saw manufacturer is planning an initial production capacity of 80 to 100 diamond wire saws, with ongoing discussions with the German government regarding financial support for future capacity expansions.
- There is a positive outlook within the European PV sector regarding the capability of developing and adapting diamond wire slicing technology within 2-3 years. This would enable the industry to compete with the Chinese benchmark.

Challenges of wafer cutting in the EU

- Currently, there is no European manufacturer of diamond wire saws. The market is dominated by *Goace*, a Chinese company that provides a complete setup for ingot shaping, gluing, and wafering, along with interconnected automation. This setup includes integrated mechanical, electrical, and software interfaces. Its strength lies in its integrated approach. Making it difficult to integrate with European equipment at other stages.
- Although saws are being developed, no European player is currently visible within the diamond wire production sector, a segment that is also dominated by Chinese entities. This threatens the independence of the whole process.
- One of the main components in wafer cutting operations is the 'coolant', which primarily consists of water with chemical additives. Managing the resultant wastewater is expected to pose a notable challenge in Europe, given the need to comply with stringent environmental regulations.

2.1.3 Cleaning, Packing, and Inspection equipment & Fab Automation

Cleaning

- There are several different cleaning processes involved in the production of ingots and wafers. However, EU companies do not have a solution for the *'wafer singulation'* step on their own. They are cautious about promising a solution within the next few years.
- *RENA*, a cleaning equipment supplier in Germany, has been out of the PV market for some time. However, they are now keen to re-enter the industry and is judged to be able do so quickly.
- *SCHMID* is also a supplier that can provide the service, but they do not offer a standard *'off the shelf'* solution, but rather specific 'purpose made' solutions.
- The volume that Chinese suppliers are producing, primarily for their own market, is very extensive. For that reason, they have standardized automation solutions and well-developed control systems.

Packing

- Packing equipment is another capability available in Europe. There are multiple possible companies with the capacity for making packing equipment.

Inspection equipment

- Inspection is essential at various stages of production. Automated optical inspection (AOI) is required for inspection of wafers.
- Some suppliers of cleaning equipment integrate the AOI into their products, while others offer it as standalone equipment. There are suppliers capable of providing this in Europe and the US.

Fab Automation

- Automation equipment including automatically guided vehicles and conveyor belts are readily available in Europe and can be supplied by EU companies. Europe possess the necessary knowledge, ability, and capacity to build automation equipment for production support. This is something that isn't specifically designed for photovoltaics or for a specific process but is more general.
- Automation is essential to all these advances; there is a strong push to automate many of these process steps.
- In the future, competences and skills within manufacturing automation, execution systems and programmable numerical control (PNC) programming will increasingly be part of the core business and, as these are not sector-specific skills, they will be very difficult to obtain.

Challenges for the EU Industry

- Cleaning equipment is where European suppliers are most present today, making it the wafer value chain step with the lowest risk from a European perspective, alongside packing.
- Proficiency in automating manufacturing processes is becoming increasingly important for the EU PV manufacturing industry. Tasks that rely on data collection and adaptive processing, are crucial to maintaining competitiveness. Developing machine learning approaches for interpreting production data, forecasting, and process optimization, could enhance the EU's competitiveness in the global PV manufacturing market and provide a strategic advantage.
- Automation is not a straightforward solution. It requires careful strategic planning, evaluation and, once implemented, adaptation to specific needs and the impact on the workforce. The goal is to achieve cost competitiveness while balancing this with the creation of jobs.

2.2. Materials and consumables for Ingot-wafer production

Experts considered the key elements to be 1) *polysilicon* as the primary raw material, 2) *quartz crucibles*, and 3) *hotzone materials* as the most important consumables used in the ingot production process and 4) *diamond wires* as the key supply for the wafering process.

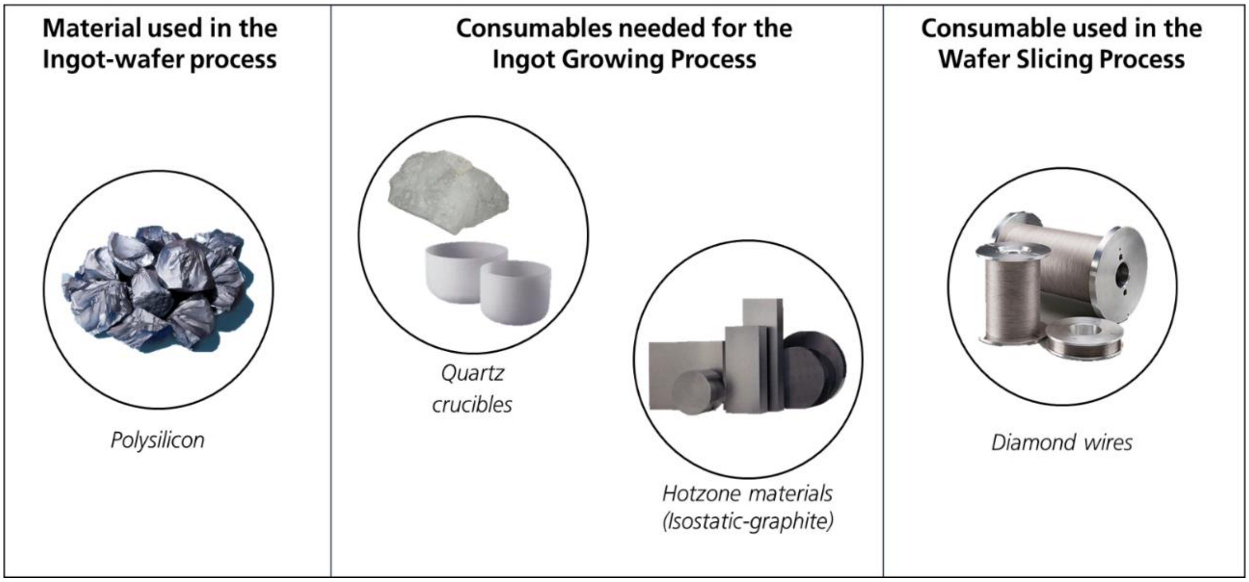

Fig 3. Materials and consumables used for Ingot and Wafer processing.

2.2.1 Polysilicon

Current state

- Knowledge/technical expertise for setting up of polysilicon (poly-Si) manufacturing in Europe is present. And currently, European industrial capacity is present.
- Poly-Si manufactured in Europe has high-quality, meeting the demands for pulling n-type crystals and the requirements of the semiconductor industry.
- The strongest European player in the poly-Si value chain is Wacker with 80,000 tonnes of poly-Si yearly capacity, 60,000 of which is produced in Europe. The total capacity, if assumed to be used solely in the PV industry, would be around 30-32 GWp.
- Considering prevailing market prices for crucibles and wire saws as of 2023, poly-Si share constitutes approximately 30% of ingot-wafer manufacturing OpEx costs (PV manufacturing consultant, personal communication, September 04, 2023).

Poly-Si production

- The key input for poly-Si production is metallurgical silicon (Mg-Si); which needs Silica (Quartz) as a raw material. In addition to silica, caustic soda and chlorine are required for the poly-Si production.
- Poly-Si production facilities tend to cluster with other chemical facilities to benefit from the existing infrastructure and skilled workforce.

- The European poly-Si industry, e.g., *Wacker*, does not appear to be dependent on Chinese companies for the machinery needed to produce its poly-Si, as production equipment is developed by in-house engineering teams.

Poly-Si market

- European poly-Si stands out for meeting strict environmental, social & governance (ESG) standards, which is an advantage as much of the world's supply comes from areas with questionable or even forced labor practices.
- Poly-Si production in Europe has significant reported capacity, however its supply is constrained by several factors mainly because big solar PV ingot-wafer manufacturers have secured capacities well in advance through long-term agreements, and also the high demand from other industries (semiconductor).
- The poly-Si produced in Europe, meeting the above-mentioned high ESG standards leads to higher production costs compared to Chinese production. Nevertheless, poly-Si from Europe is sold at standard market prices outside of China, including Asia.
- The poly-Si market as a global market has manufacturers in the US, EU, Malaysia, Korea, and China. Poly-Si can be bought anywhere in the world. Today's high capital cost requirements in this industry presents a high barrier to entry that could deter new entrants and could also catalyze consolidation (Fu et al., 2015) for that reason the establishment of additional poly-Si capacity in Europe will only be possible with significant subsidies.
- Significantly lower standards and lower electricity costs in China, coupled with high subsidies for the construction of poly-Si capacities, has led to massive overcapacities in the sector.

Trends

- *REC Solar* ceased its polysilicon activities in Norway in late November 2023 due to inability to compete with Chinese companies. The closure of the Nordic poly-Si production facility was a result of the unviability of producing high-purity silicon in Norway. The main reason was the electricity costs, which were more than ten times higher than that of Chinese companies at the time of the closure.
- *Wacker* would be prepared to invest in additional capacities if a reasonable business case can be presented with long-term, secured off-take, adequate prices, and predictable electricity cost. They are currently participating in the German call for interest to build up a supply chain for the 10 GW. They also have a project in Burghausen with the potential to increase their capacity by 15,000 tonnes per year, although this depends on whether the Temporary Crisis and Transition Framework (TCTF) criteria allow them to receive the subsidies they need to expand.
- Eastern Europe, although it provides low energy prices, may not be suitable for poly-Si plants due to inadequate infrastructure and a current lack of skilled workforce needed for chemical production, which would require time to upskill local population. Additionally, the region relies heavily on coal-based power plants for electricity, which contradicts the competitive advantage of solar PV manufacturing in Europe – with a better carbon footprint for the production of green modules.
- European initiatives are emerging, in Sweden, the startup *Green14* is planning to build a pilot-scale reactor to make solar-grade silicon with a green hydrogen plasma process. In the Netherlands *Resi BV* has done a feasibility study for setting up a Polysilicon plant using the Siemens process technology.
- In the US, a number of capacity expansions/reactivations are planned under the Inflation Reduction Act (IRA), such as *Hemlock* (*HSC*), which is currently considering reactivating former closed down capacities. *HSC* nominal capacity is approx. 40,000 tons but are currently expanding etching capacities for semiconductor poly-Si.
- *REC Silicon*, which reactivated its closed down capacity with a capacity of 20,000 tonnes/year, is going to produce exclusively for *Hanwha Qcells*, a company that secured this capacity for its expansion.
- *Wacker US* is open to discussing capacity expansions with interested companies in the PV solar sector.

Challenges for the EU Industry

- The availability of European poly-Si poses a substantial risk of disruption for PV ingot-wafer manufacturers. Intense competition for this material may result in its unavailability. Additionally, it is not feasible to produce poly-Si in Europe under conditions similar to those in China. Without offering adequate prices there will be minimal investments in the product. This intricate scenario is a result of unfair competition with entities outside of Europe.
- Competitive energy prices are necessary to encourage production of poly-Si in Europe, as electricity is the main operational cost. The energy price needs to be on a competitive level with China, ideally with electricity costs below 50 €/MWh.
- The creation of a level playing field is necessary to address the upcoming overcapacity of poly-Si worldwide. There is a need to create a market in Europe with carbon footprint and forced labor market entry regulations allowing producers the opportunity to sell their poly-Si supply following fare competition and complement it with attractive energy prices.

2.2.2 Quartz Crucibles

Current state

- Necessary *knowledge/technical expertise* exists for setting up manufacturing of crucibles, but no industrial capacity is present in Europe at the time of writing of this report.
- The supply of crucibles is critical for production of ingots, and it has a direct and significant impact on the efficiency of PV cells and modules.
- *DIGLOO*, a start-up company from Norway, led by former NorSun executives, is currently exploring the prospects of beginning production in Europe of 37-inch diameter PV quartz crucibles.

Quartz sand for crucibles

- High purity quartz supply is a niche market dominated by two companies *The Quartz Corp*, (Norway) and *Sibelco* (Belgium), both European companies.
- The key input is the high-purity-quartz, which is mainly extracted from the mines located in Sprunce Pine, North Carolina, in the US. Quartz extracted from this mine accounts for more than 80% of the global market share.
- The availability of high purity quartz sand from *The Quartz Corp* and *Sibelco* is currently in line with today's market demand of approximately 405GW, translating to a need of 73K - 81kT. About 50% of the sand mined in Spruce Pine, North Carolina, is refined at *The Quartz Corp's* processing plant in Drag, Norway. The company has a processing plant for quartz deep refining, a value-added step, justifying its "Country of Origin: Norway" label.
- No crucible production is currently being done there or in any other place in Europe, 100% corresponds to Asia, and from there most of it to China.

Crucibles value chain

- Companies producing crucibles in China have a mix of very different profiles, some are vertically integrated to the extent that they also are selling PV modules, and some are '*Crucible specialists*' that specialize in production of crucibles for ingot production only. In recent years, the typical Chinese crucible manufacturer has become increasingly professionalized.
- Transporting crucibles is possible and can be managed without significant problems. Each container can hold around 24 crucibles, considering that crucibles are large, with approximately 1 meter in diameter and 1 meter in height. While it is possible to ship them to customers, it is generally more economical to have them close to the

ingot production plant. Container freight costs would be approximately 600 USD per crucible, which represents a significant share of the production cost. At the time of writing this report, no major crucible manufacturer has established outside of China. Therefore, any company that produces PV ingots internationally must import its crucibles from there.

- It is also preferable to have production facilities closer to the production sites as this allows for a closer relationship with customers and reduces transportation time, which could otherwise take longer. By being located closer to customers, logistics can be more efficiently managed.
- Producing crucibles inhouse has many advantages is more practical, makes more economical sense, and allows to have a closer relationship with the customer. For that reason, Chinese companies have developed a strong domestic quartz crucible industry, even though the raw materials come from Norway/US.

Crucibles: State-of-the-art

- The quality of the crucible is the most important feature; however, price remains relevant and a substantial expense, with market prices at the time of writing this report, crucibles represent 14% of OpEx costs, the second most expensive single component after poly-Si (PV manufacturing consultant, personal communication, September 04, 2023).
- There is a technical advantage to using imported quartz from *The Quartz Corp / Sibelco*. Using a lower purity grade can result in a decrease of up to 10% in the expected productive lifetime the crucible.
- The goal of the Chinese ingot producers is to have a high-purity quartz crucible that will last for a period of 500 hours, while the standard lifetime is judged to be closer to 400-450 hours. This translated to roughly 2 crucibles a month per puller. Another company shared that the main goal is to have a crucible that can withstand long melt cycles, being able to pull 5 to 6 ingots per run, which in other words means that a crucible that can run for 350-400 hours before disintegrating in the melt.

Trends

- The establishment of crucible manufacturers in Europe provides an opportunity for quartz suppliers to receive technical feedback on the performance of the quartz once it has been transformed into a crucible. Currently, this feedback is missing because there is no information on the material's performance after the quartz is shipped to China.
- *DIGLOO* plans to start crucible production of 15GW in Vietnam in 2024. Production in the US is scheduled to begin in 2026. Production in Europe will be postponed until there are customers to sell them to.
- *Saint-Gobain* has experience in crucible production. This European company is closely monitoring the current situation, and although it has been in contact with European ingot manufacturing companies, they have not yet announced any formal plans to reopen its crucible manufacturing capabilities.
- Looking into other sectors/regions: there are other companies that produce crucibles today in Europe, e.g., in Germany, but only for the semiconductor industry, with no known intentions of switching to PV. In the interviews, it was also mentioned that there are crucible manufacturing capacities in Japan.

Challenges for the EU Industry

- For a large-scale production of PV ingots to be established in Europe, a strong supply of crucibles would be necessary. However, no supply of crucibles would establish without the large-scale production of PV ingots.
- For instance, *DIGLOO* production site in Europe is almost ready. It will be reasonably quick once the company decides to start production, but to do so the company needs to secure customers in the region.
- Establishing crucible manufacturers in Europe could help fill the knowledge gap on the performance of quartz when turned into crucibles, which would in turn facilitate mutual learning between the two industries.

2.2.3 Hotzone materials

Graphite for hotzones

- The hotzone is the area inside the Cz puller where the crucible is heated. The hotzone needs to be replaced 1.5 times per year, and it requires maintenance due to some of its parts need frequent replacement. This results in significant OpEx for the Cz pullers.
- The hotzone materials are made of different kinds of graphite. There are more than 50 components in the hotzone, such as isostatic graphite, graphite felt, hard felt, graphite soft felt. Hotzones have a very complicated setup.
- Isostatic graphite is needed in hotzones for temperature resistivity and stability, and for achieving low levels of impurity contamination. There were some unsuccessful attempts to change the graphite with ceramics. The primary reason for these failures is mainly *Economic*; ceramic parts are expensive, and manufacturing them is challenging, with only a few companies worldwide capable of doing so. Another factor was the *Fear of Contamination*, as ceramics may contain impurities such as nitrogen (N), sodium (Na), calcium (Ca), and other metals. These impurities could potentially influence the manufacturing process and the crystal's quality. Current research is underway to determine the extent of this influence.
- Graphite is a costly material, the third most expensive single component after poly-Si and crucibles, with ~10% OpEx (PV manufacturing consultant, personal communication, September 04, 2023). Refined graphite can be obtained from different locations worldwide. In Europe, the required graphite components can be purchased from suppliers such as *Schunk, Mersen and SGL Carbon*, among others.

Current state

- The crucial factor to a large extent lies in the design of the hotzones and not in the graphite components themselves. The design of the hotzone affects the gas flow speed, the cooling efficiency, and the pulling speed and stability, which are important for yield and productivity.
- Hotzones designs can also be purchased from European equipment suppliers, but this will not be as optimized as the designs developed by Chinese companies.
- Keeping the hotzone clean is essential for decreasing impurities and since graphite parts are sensitive to mechanical damage, operators need to be cautious when cleaning. Because of this sensitivity, disassembling or reassembling a hotzone is a time-consuming and complex task.
- At current Chinese operations there is a crew of 3-4 people who work on hotzone cleaning and maintenance between runs (done in a separate workshop). The crew is responsible for a short turnaround time of the hotzone to reduce down time of the puller. Having only one person would not enough to reduce down time of the puller.
- A turnaround from start to finish will take about 12 hours in China, which can be reduced with an experienced crew. Chinese operations usually run three shifts, while European operations would run five, so it can be assumed that a European manufacturer working with a Chinese hotzone would require a workforce of 10-15 people.
- The biggest challenge to production in Europe is around the labor cost. First the multiplying effect of 3 vs. 5 shifts and then the added difference of labor costs, which is USD 20k in China on average vs. USD 50-70k in Europe.
- Chinese companies prioritize task-specific automation to enhance repeatability and standardization, aiming to make use of lower-skilled labor due to its cost-effectiveness, while European operations focus on comprehensive automation to reduce the number of operators and overall labor costs. Therefore, it is not enough to copy automation of these companies, as this would perpetuate the labour disadvantage.

Hotzone / graphite supply

- Export restrictions on graphite coming from China: while there has been a recent change in Chinese regulations effective from December 1st, 2023, export regulations for graphite were already in place before this date.
- The changes mainly involve modifications to the HS codes, the classification system for different graphite materials used in customs. The focus of the regulations primarily centers on graphite powder for lithium-ion battery production and not isostatic graphite, which is used for Cz growing.
- There are currently ongoing discussions with Chinese authorities to gain more clarity, but overall, the impact on graphite companies supply chain, particularly for isostatic graphite, is minimal.
- Within isostatic graphite production, the cost of labor is not as significant as the cost of energy and raw material. The cost of electricity and gas is particularly important because gas-powered furnaces are used for the baking step and electricity-powered furnaces are used for the graphitization step. The cost of raw material is the same regardless of the location, but electricity and gas costs can vary depending on the country where isostatic graphite is produced.
- The ingot-producing companies commission the manufacturing of the necessary parts from graphite manufacturing companies, along with providing designs and drawings with non-disclosure agreements (NDAs).
- Graphite components are crucial in the production of semiconductors and other silicon-based technologies. While there are large graphite producers in Europe with significant capacity, they will not have any extra capacity in the next few years. This is due to high demand and better profit margins in other industries.
- While sharing raw materials, there are important differences in the hotzones needed for semiconductors and for PV. When producing semiconductors, higher purification levels of graphite are required, along with a very sophisticated design.

Challenges for the EU Industry

- Graphite is increasingly becoming scarce due to high demand in expanding industries, such as batteries, PV, and semiconductors. Hence, it is a critical material that requires policymakers' attention.
- The design of the hotzone is a well-kept business secret, with each company possessing its unique drawings and parameters. While the current Chinese designs are leading, they may not be optimal for European operations. Consequently, Europe requires investments in research and development (R&D) to create the next generation of hotzones. The objective is to engineer a more stable hotzone that minimizes the need for frequent removal from the Cz puller. This goal can be accomplished by redesigning the existing Chinese design. Such a change is feasible within the timeframe of implementing large-scale factories.
- To reshore a completely integrated PV value chain to a 30 GWp target the potential demand for graphite would translate to roughly 3000 tonnes. Building such a plant would cost around €100 million, making it a considerable investment for companies in this sector, and current players are reluctant to enter without a stable market. Therefore, certainty that the capacity will be used in the future is a top priority.

2.2.4 Diamond wire

Current state

- Necessary *knowledge/technical expertise* exists for setting up manufacturing of diamond wire in Europe, but no industrial capacity is present.
- All major activity in diamond wire production originates from China, posing a significant threat to the resilience of this part of the value chain.
- Japan used to have the capability to produce diamond wire, but they were out competed on cost by the Chinese. Nevertheless, Japan still supplies the steel for the core wire.

Market dominated by China.

- There are European companies manufacturing cutting machines, they aren't all based in China. However, when it comes to the actual wires used in the cutting process, China is dominant.
- China's strength lies in its integrated approach, with companies offering wire solutions as part of their system.
- Acquiring thin and reliable diamond wire for wafer slicing poses a major challenge in Europe. The consumable is widely available, but the high volumes and low prices are exclusively found in China.

Wire manufacturers Outside of China

- Europe needs to develop its own diamond wire production capacity to reduce reliance on China. Further investigation is required to determine the availability of steel feedstock suitable for photovoltaic use in Europe.
- Japan's wire manufacturers stand out for their sophisticated technology, as Japanese wires are used in expensive semiconductor processes, although the requirements in these processes are different compared to PV procedures.
- There have been interactions between European companies and Japanese suppliers in the PV industry. However, it appears that these suppliers may not have sufficient capacity to serve the potential demand.
- The United States is another potential source of diamond wire, but European companies are currently not considering this option due to a preference for keeping production within Europe.

Trends

- There is now a transition towards the use of tungsten steel, developed in China, which is a more tensile strength, and enables to produce a thinner core wire.
- Leading Chinese cutting machine manufacturers are expanding into wire production to provide comprehensive solutions. This expansion has enabled these companies to also become wire manufacturers themselves.

Challenges for the EU Industry

- Although there are plans to develop diamond wire-cutting machines in Europe, currently there is no player in the diamond wire production segment in the region, even though former manufacturers of structured wire are still present, such as *Bekaert*, and *Voestalpine.*
- The lack of diamond wire could be a big problem for independence in wafer cutting in the future. Europe needs to develop diamond wire by themselves.

2.3. General challenges for the future EU Ingot-wafer value chain

The interviewed experts shared general insights in the event of developing a European PV ingot-wafer industry. One of the main issues highlighted is the dominance of China, which poses both geopolitical and technological risks. At present, China has the power to change various aspects of the PV industry (wafer sizes, formats, shapes, thicknesses, etc.) — its huge global dominance means that it controls the standards— which in turn can affect the competitiveness of other regions. Controlling industry standards in this segment is only an advantage if trade is bilateral. Some experts believe that at the 20-50GW scale, in an integrated European "domestic" market, not meeting the changing Chinese standards would not have a significant negative cost impact as long as an internal standard is maintained. For this reason, the EU needs to take a holistic view of the value chain and invest in all segments, from poly-Si production to the necessary equipment and materials required for ingot and wafer manufacturing processes. Within this effort, it is imperative to have multiple players in the field, rather than relying on a single equipment/material supplier in each sub-sector. The greater the number of participants, the greater the competitiveness. However, setting up the whole network is a major challenge.

The EU possesses the necessary technical capabilities to produce most of the materials and consumables locally, the question here is how to increase production in an economically viable way. However, the main issue comes with developing key manufacturing equipment as there has been no progress made in Europe in this field in the last 10 years. This calls for urgent and substantial efforts to catch up. Securing investment is not easy, as the PV market has a history of volatility and uncertainty. The government support is also unclear, as Members States has not given a definite answer to funding requests made by PV manufacturing companies yet. The current effort of reshoring the PV value chain to the EU presents a challenge, but also an opportunity to establish a more secure energy future for the region.

III. Perspectives on the potential Chinese export restrictions and Policy recommendations

a. Perspectives on the Chinese export restriction

The experts shared their views on the potential export restriction of equipment for ingot and wafer manufacturing. When examining the perspectives on the announcement from the Chinese Ministry of Commerce, some of them had similarities, while others displayed differences. We have classified these different perspectives into three groups, based on their shared position on the issue. The first group perceives the export restriction as a significant threat or risk to the European PV manufacturing value chain. The second group takes a more impartial stance, without perceiving the ban as likely to occur or intending to damage the European PV manufacturing sector. Concurrently, and perhaps surprisingly, the third group views the restriction as a promising opportunity.

<u>Chinese export restriction as a threat</u>

Companies in various parts of the supply chain view the announcement from the Chinese Ministry of Commerce as a major threat to the European PV production industry. This is due to the subsequent reasons:

- There is a fear that if export restrictions are imposed while the PV industry in Europe is still not back again on his feet, it would have a major impact on the industry as there is no European supplier at the moment that can provide the required equipment. In this scenario, European ingot-wafer manufacturers would have to explore nations with established wafer or equipment industries. Currently, this is not widespread; there are early-stage developments in the US and rumors of companies considering establishment in Saudi Arabia. However, the current supply is exclusively Chinese.

- It is suspected that the Chinese government aims to retain their technological advancements, and therefore, the ban would likely target the most advanced equipment. This ban could make it difficult for European companies to acquire the necessary equipment for manufacturing ingots, hindering ongoing re-shoring efforts. As a result, European companies may face higher costs and lower production volumes.

- Some firms consider the Chinese announcement of potential export restrictions to be a risk because of the possibility of a trade war. Most European companies in the global PV value chain depend on selling to Chinese manufacturers. Any impact on those sales would require these companies to make significant changes to their business model. As the current trade value cannot be replaced by Western markets, such changes would harm this specific part of the European value chain.

- If the potential ban were to be extended to equipment and products, then the European PV industry would be confronted with a substantial challenge. Developing its own ingot and wafer production capacity and establishing new production facilities would require ten very tough years. Europe could experience a shortage of PV modules and a pronounced increase in prices.

However, many companies believe that the likelihood of an export restriction is low and unlikely to happen, at least in the near future. Nevertheless, the announcement has created a lot of uncertainty in the European ingot-wafer stage of the PV value chain.

<u>China's export restriction, a restriction unlikely to be enacted.</u>

The second group takes a more impartial stance, without perceiving the ban as intending to damage the European PV manufacturing sector.

A PV consultant commented that if the prohibition were to be limited to equipment alone, rather than products, the European photovoltaic sector would face challenges in establishing autonomous ingot and wafer production facilities. Nevertheless, the sector would retain the flexibility to procure wafers, cells, and modules from China, resembling the current scenario, with negligible effects on photovoltaic installations.

Executives in the PV ingot-wafer manufacturing sector communicated that Chinese wafer equipment manufacturers view the potential ban with concern, yet they maintain a relatively calm stance, expressing confidence in finding viable solutions. They believe the impact may not be as severe as initially perceived, suggesting that the measure primarily targets Chinese companies establishing production facilities in Southeast Asia. They anticipate finding alternatives to navigate the restrictions, with plans to acquire equipment and ensure its availability, particularly in the European market.

A prominent equipment company believes that China is not concerned about Europe taking over the PV manufacturing but might be a little more worried about India because it's high population and low labor cost, given that the labor costs in China have been moving up in the last few years. In this context, India would be more of a threat to China than Europe.

Rather than a threat, some companies see this as a move by China to protect its export-driven business model, which relies on mass production of cost-effective goods for global markets. This approach might not significantly impact Europe's ability to purchase solar cells, as China aims to continue selling its products internationally. But that China will be using this as leverage in other negotiations or trade discussions.

Chinese export restriction as an opportunity

Other European companies, see the potential Chinese export restriction as a promising opportunity despite recognizing the impact on the overall European PV value chain. They identify potential benefits for their business if implemented.

An equipment manufacturer stated that it sees the ban as an opportunity to enter the PV market. The absence of Chinese equipment competition would offer European equipment manufacturers a substantial opportunity to supply the necessary equipment, such as Cz pullers or wire saws. However, the export restriction alone is not enough for these companies to seize the opportunity. The only way for a European equipment manufacturer to be successful is to find the right measures to enable them to produce, for example, a Cz puller at a competitive price, so that ingot and wafer companies can produce cost-competitively.

A company planning to start wafer production using an innovative technology, shares that, despite being skeptical about the export ban implementation, if implemented, it would have a substantial impact on western ingot manufacturers using conventional technology. The company foresees that these manufacturers will encounter challenges and may face bankruptcy. They anticipate a rise in demand for alternative solutions and thereby, a significant opportunity to position themselves as the sole solution to the wafer supply shortfall in Europe.

In general, it is agreed that the restriction would be a challenge for the European PV Industry, however, it may present a chance for the European PV sector to develop its own manufacturing capacity and reduce its dependence on Chinese suppliers. This would enhance the long-term resilience of the European solar industry.

b. Policy must-haves

Looking at the Chinese PV manufacturing value chain and their current operating model it is difficult to see any European advantage that allow it to outcompete them. Starting with lower labor and equipment costs, coupled with competitive energy prices. Efficient building companies, planning agencies and much faster permit procedures. The presence of public and private subsidies in China contributes to even lower production costs when compared to those in Europe.

The imbalanced playing field where the EU can base any restrictive actions on lies in the different execution of the humanitarian and environmental rules in its PV manufacturing industry. Among the concerns is forced labour in China's polysilicon industry, especially in the Xinjiang region, as highlighted in the report "*In Broad Daylight: Uyghur Forced Labour and Global Solar Supply Chains*" (Murphy & Elimä, 2021), which raises ethical and transparency issues in the Chinese PV industry. In addition to these humanitarian issues, life cycle assessment (LCA) studies of PV panels produced in China have revealed a higher carbon footprint due to a high proportion of coal in the Chinese electricity grid (Yue et al., 2014). This leads to environmental impacts associated with PV manufacturing in this country. These two facts make it necessary to scrutinize trade relations.

The responses collected in the study allow conclusions to be drawn about current EU policy facing the current state of the PV sector in Europe, where several shortcomings stand out and need to be addressed. The solutions need to be directed in addressing these above-mentioned imbalances to enhance competitiveness in the EU PV value chain.

Competitiveness, priority number one for the re-shoring effort.

Competitiveness based solely on superior technology is unattainable. Experts suggest that Chinese technology in ingot, wafer, and cell production is more than five years ahead, and Europe will not be able to catch up quickly. The priority should be to create economic competitiveness by establishing a level playing field with regard to social and environmental standards. This does not mean that R&D in the EU is not important - on the contrary, efforts must be made to catch up, which will require significant budget support.

The creation of a level playing field would ensure PV manufacturers survival. For example, in the poly-Si market, there is a foreseen future overcapacity globally, predominantly from massive expansions in China. In this scenario it is necessary to establish a market in Europe to absorb this surplus. Proposals need to be made for poly-Si manufacturers in Europe, incorporating criteria such as carbon footprint and labor standards.
The aim is to align production with market demand, thereby ensuring a sustainable environment for PV manufacturers in Europe.

Establishing own efficient gigawatt-level photovoltaic production in Europe.

Actions need to be taken to establish efficient processes for GW level PV production. The focus should be on supporting the best available technologies to build a strong platform that will allow European companies to compete on all levels. Considering the distinct contexts of European and Chinese production environments, it must be a priority to develop efficient European technology and production processes rather than replicating China's formula. One promising idea would be establishing a pilot manufacturing line that serves as a competence center to improve technical processes and develop successful technologies. The main objective is in developing innovative solutions, avoiding long-term dependency on outdated technologies. The implementation of this pilot line would be highly beneficial not only for ingot-wafer manufacturing, but for all segments, including cells and modules.

Government funding

Drawing inspiration from the successful model implemented by the US with the Inflation Reduction Act (IRA). Direct government funding should be provided to support the development of new PV manufacturing facilities and related industries across Europe. This financial support must intend to alleviate the startup and expansion costs for manufacturers.
CapEx support specifically tailored for *equipment companies* must be one of the main priorities, incentivizing their return to the PV sector. The emphasis should be on selected companies with advanced technology and proven capabilities to bridge the existing technological gap. For *poly-Si producers* specific measures ensuring competitive electricity prices are crucial. A notable example is the considerable difference in energy prices between China and Germany, where energy prices are three to five times higher at the time of writing this report. Given the energy-intensive nature of poly-Si production, securing a competitive energy price is key.
R&D support for all stakeholders, not only for research institutes but also for the companies involved, to reduce risks associated with development and implementation. In addition, it may be an option for the government to provide support for *ingot and wafer companies* with existing capabilities to facilitate their progress and cost competitiveness, possibly by funding equipment and later wafer production itself.

Time-limited incentives

In advocating for the renaissance of the European PV industry, implementing time-limited incentives are the best way to create a sense of urgency. This action would drive companies to take prompt action by creating a “window of opportunity” encouraging industrial resurgence.
Suggesting a shorter timeframe for credit utilization not only improves efficiency but also accelerates the establishment of companies in the sector. This strategic adjustment is designed to align the urgency to act with the incentives in place, fostering a more dynamic and responsive PV industry in Europe.

Protect European PV cells and modules manufacturers

To fortify Ingot-wafer PV manufacturing, ensuring the survival of European solar cells and modules manufacturing is crucial. The interdependence is clear — if European manufacturers face bankruptcy, so might the viability of European ingot and wafer companies, as these companies do not possess chances to supply to Asian markets.

Encourage utilities to buy European-made PV products.

Encouraging utilities to buy European-made PV products will support the development of the PV industry. This could be done through incentives, regulations, or other policy alternatives. The case of Kalyon in Turkey demonstrates the potential of appealing business models that integrate feed-in tariff (FiT) incentives, local content requirements, and a commitment to domestic supply.

Facilitate collaboration instead of imposing tariffs.

While not universally supported, trade protection measures underscore the need for diverse strategies to fortify the European PV industry in the face of global competition. Some support the idea of leveling the playing field through imposing tariffs on imported goods in critical issues such as "CO2 emissions" and "forced labor". A more constructive approach is to promote collaboration rather than resorting to tariffs.

The main idea is to avoid hampering the growth of the PV industry as a whole by adding import taxes and instead focus on supporting local companies. In this regard, it is imperative to assist domestic companies. This collaborative approach aims to foster a mutually beneficial relationship and advance the PV industry.

EU-Chinese joint investment

Some companies favor the idea of encouraging Chinese companies to invest in the region. The argument is the potential leverage of bringing their manufacturing plants to Europe as they possess the technology and a high level of manufacturing know-how throughout the value chain. It can further be noticed that Chinese investment might take different forms. Beside the option of supporting the installation of Chinese companies on EU ground, minority investment (e.g., >33%) of Chinese players into EU manufacturing capacities could represent a middle-ground alternative. However, there are others that, while recognizing the potential benefits of Chinese investment, they believe that the Chinese players will not bring added value to European companies in the short term because they will also bring with them their entire supplier network, which makes it difficult to spillover knowledge to local companies in the region.

Increase capacity at each sub-segment of the value chain

To enhance competitiveness in the European PV sector, it is encouraged that the EU takes measures to support the development of new production capacities in the region. The objective is to create a more competitive market ensuring greater stability and reducing vulnerability to disruptions.

There are critical thresholds in size to be competitive in the ingot-wafer value chain. This critical size changes over time; it depends on many factors such as costs and capacities of the individual equipment, labor requirements, scrap rates, throughput, etc. For instance, in economic analyses for ingot-wafer manufacturing, it is observed that the cost advantages from economies of scale decrease beyond 5 GWp. However, a minimum critical size of 2 GWp is sufficient (PV manufacturing Researcher, personal communication, January 18, 2024). Minimal critical capacity for the other manufacturing segments should further be defined to make a sound economic case.

IV. Summary

a. Key components main vulnerabilities and support needed.

This section summarizes the main obstacles faced in the re-shoring process for each key component, examining the potential consequences of Chinese export restrictions on supply vulnerability and the necessary support that policy makers should offer.

Key Components		Vulnerability of supply	Support needed
Equipment	Cz pullers	There is no supply of PV Cz pullers outside of China. Chinese companies have the power to change wafers sizes or formats. This creates uncertainty for European investors. Current market conditions are unfavorable due to the shortage of ingot producers in Europe.	EU equipment companies need help filling the technology and cost gaps before they can successfully enter the industry. For an operations restart, financial investment in both the creation (CapEx) and operation (OpEx) of equipment production facilities is required.
	Diamond wire saws	There is no equipment readily available in Europe today, just development in their prototype phase. These developments are still relying on Chinese diamond wire.	At present, finding investors is challenging due to the PV market's history of volatility and uncertainty, as well as the lack of clarity regarding government support.
Raw Materials	Polysilicon	Existing poly-Si production in Europe, but high demand and competition with other industries can led to its unavailability, posing a significant risk for PV ingot producers. Chinese investments are creating an overcapacity of poly-Si worldwide.	Need to create a market in Europe with carbon footprint and forced labor criteria allowing producers the opportunity to sell their poly-Si supply. Low-energy prices are necessary to encourage production of poly-Si in Europe.
Consumables	Crucibles	No crucible production in Europe, although a potential supplier of crucibles is looking to start up when market conditions improve. High-purity quartz is mainly extracted from Sprunce Pine, US with +80% of the global market share. 50% of the quartz sand coming from Spruce Pine is purified in Norway.	The technology is understood, and the raw materials are in balance with today's demand globally. More important than financial support, the main issue is the lack of European customers (ingot producers). Therefore, direct support to ingot production is needed for domestic crucible expansion.
	Hotzone materials	Graphite is available globally and in Europe, nevertheless this material is crucial in the production of other expanding industries; therefore, high demand and competition are expected.	Support is needed in design of the hotzone, it requires in-house development, which is a challenge as Europe has not produced solar ingots for the past decade:
	Diamond wire	No player is currently visible in diamond wire production outside of China. Japan used to have the capability to produce diamond wire, but they were out competed by the Chinese. Nevertheless, Japan still supplies the steel for the core wire.	Europe needs to develop its own diamond wire production capacity to reduce reliance on China, support in investing in this segment of the value chain is needed.

Table 2. Summary table vulnerabilities of supply and support needed.

- Red means High level of supply vulnerability / support needed.
- Orange means Medium-high level of supply vulnerability / support needed.
- Yellow means Medium level of supply vulnerability / support needed.
- Green means Low level of supply vulnerability / support needed.

b. Final messages

Mapping the European PV solar supply chain is a complex task, as much of the industry is consolidated in China. It has proved difficult to find alternatives on the European continent for even the smallest processes in between the supply chain. Below are the final comments on the status of the critical components mentioned in this report.

- Equipment:
  - Chinese suppliers provide the most advanced technology, the best quality, and the lowest prices.
  - Companies entering or re-entering the European PV ingot-wafer industry must first upgrade their technology to be competitive, and then matching the low equipment prices from China.
  - Rather than price alone, reliability, longevity, energy, and material consumption are key factors when evaluating equipment.
  - Expanding equipment manufacturing capacity requires a sizeable market. Current market conditions for equipment manufacturers in Europe are unfavorable due to the shortage of domestic ingot-wafer producers.
  - European equipment producers in the semiconductor industry could be interested to re-enter the PV sector if the right measures are taken, but first they need help filling the technology and cost gaps. For a PV Cz puller manufacturing operations restart, financial investment in both the creation (CapEx) and operation (OpEx) of equipment production facilities is required.

- Materials and consumables:
  - In the ingot-wafer stage of the value chain the feedstock (materials and consumables) are the primary operating expenses factors, rather than electricity, the primary cost factor for poly-Si production.
  - The existing manufacturing capacity for poly-Si and graphite in Europe needs to be expanded in order to meet the EU's PV manufacturing GW target levels. Production of high-purity quartz for crucibles is expanding at the current pace of the PV market.
  - Currently, Europe has no capacity for manufacturing crucibles and diamond wires. On one hand, *DIGLOO* is planning to start production of crucibles with an European supply chain network already established, on the other hand, there is no visible player intending to start operations for diamond wire, and no established supply chain network either.
  - The supply of graphite for hotzones will prove challenging due to its increasing scarcity. However, even if the supply is secured, achieving a suitable design for the European market is a big challenge.

- General challenges for the future EU Ingot-wafer value chain
  - The dominance of China in the PV industry poses geopolitical and technological risks, as under the current value chain configuration, China controls the standards and can affect the competitiveness of other regions.
  - Future EU PV ingot and wafer manufacturing needs well-designed policy making and investments in all segments of the value chain, from production to equipment and materials.

- Perspectives on the potential Chinese export restrictions

  Within the EU PV value chain, there are different views on the potential export restriction of ingot and wafer equipment from China, with some companies agreeing that the likelihood of this happening is low and unlikely. Rather than a threat, some companies see it as a move to protect their export-driven business model as China continues to sell its products internationally. But that China will be using this as leverage in other negotiations or trade discussions. Nevertheless, many agree that if such restrictions are imposed, it could lead to the downfall of the remaining PV industry in Europe

References

Chinese Ministry of Commerce (2022). Catalogue of Technologies Prohibited and Restricted by Export of China.

ETIP Photovoltaics. (2023). *PV Manufacturing in Europe: understanding the value chain for a successful industrial policy: ETIP PV Industry Working Group White Paper.*

EU Solar Energy Strategy (2022).

Net Zero Industry Act (2023).

European Solar PV Industry Alliance (2023). Towards 30 GW of PV Manufacturing in Europe: Status Report Q2 2023.

Fu, R., James, T. L., & Woodhouse, M. (2015). Economic Measurements of Polysilicon for the Photovoltaic Industry: Market Competition and Manufacturing Competitiveness. *IEEE Journal of Photovoltaics*, *5*(2), 515–524. https://doi.org/10.1109/JPHOTOV.2014.2388076

IEA. (2022). *Special Report on Solar PV Global Supply Chains.*

Murphy, L. T., & Elimä, N. (2021). In Broad Day Light Uyghur Forced Labour and Global Solar Supply Chains.

pv magazine International. (2023, January 30). *China mulling restrictions on polysilicon, wafer production tech exports* [Press release]. https://www.pv-magazine.com/2023/01/30/china-plans-to-introduce-restrictions-on-polysilicon-wafer-exports/

Yue, D., You, F., & Darling, S. B. (2014). Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis. *Solar Energy*, *105*, 669–678. https://doi.org/10.1016/j.solener.2014.04.008