Competitiveness of a European PV manufacturing chain

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Abstract

Today, solar power is one of the cheapest ways of providing energy internationally, partly because of the excellent R&D work in Europe. Prices of modules have fallen by half in the past three years, and at the same time the use of solar power has been steadily increasing. The reason why there has been an increase in the use of solar energy in Europe and Germany is the achievement of the climate targets of the Paris Agreement. While the machines for the production of solar modules are still manufactured in Germany, the production of cells has now almost completely migrated to Asia. Therefore, the VDMA commissioned a study from Fraunhofer ISE to evaluate whether the production of solar modules at competitive costs could again be realized in Europe. This paper presents the results of the VDMA study.

Introduction

Europe used to be the third-largest region for new installations, while maintaining its second-place ranking for total operating capacity [1] (see also Coleville [2], pp. 5, 12, 14). The region continues to represent a shrinking portion of cumulative global capacity as emerging economies with rapidly growing electricity demand deploy more and more solar PV [3] (see also Colville [2]). In 2018, however, demand increased significantly within the EU and beyond.

The EU added around 8.3GW of grid-connected solar PV in 2018, up 36% over the previous year's additions, bringing total capacity to 115GW. Compared with 2017, 22 of the 28 EU countries recorded more installations, driven by national binding targets for 2020, which many member states have yet to meet [1] (see also Colville [2], pp. 12, 79).

Almost all energy system scenarios show that PV technology will be the main pillar of the future energy supply. The full transition to 100% renewable energy across all sectors – power, heat, transport and desalination – can be seen as an upper boundary of possible future growth in Europe, as determined within a study from Energy Watch Group conducted at Lappeenranta University of Technology, Finland [4], and also published within the International Technology Roadmap for Photovoltaics (ITRPV) in 2019 [5] (see Fig. 1). Extracted values for Europe foresee a total installation base of around 1.5TWp in 2030 reaching up to 10TWp in 2050; this translates to annual installations of close to 200GWp by around 2030 and up to 500GWp in 2050.

More conservative short-term market growth expectations, such as those by Solar Power Europe [1] or Wood Mackenzie [6], usually estimate lower growth figures, as they typically only concentrate on the power sector. Nevertheless, SolarPower Europe experts also envisage a strong growth of the European PV Market already in the short term.

> "The full transition to 100% renewable energy across all sectors can be seen as an upper boundary of possible future growth in Europe."

Technology selections for the benchmark analysis of an EU PV manufacturing chain

The technology selections for this study have been primarily taken from the latest edition of the ITRPV roadmap 2018 in order to stay aligned as closely as possible with current technology and market trends [5]. Improvements in ingot, wafer and cell technologies, as well as in module design, will help raise the power rating bar of a crystalline solar module above the 400W level for a panel with 72 cells (or 144 half cells) within the next few years. Separated in respect of the different value chain steps, the technology routes below were chosen, resulting in the specific technology parameters in Table 1.

Ingot and wafer

Depending on the source, monocrystalline silicon was said to have reached parity with, or to have already taken over the leadership position from, multicrystalline silicon in 2018. In any case, the balance will swing further towards mono in the future, as all silicon ingot crystallization capacity expansions are focusing on the mono variant, which has fewer defects than multi, enabling the realization of higher cell efficiencies. The selected technology is based on CZ pulling including re-charging (total charge weight of approximately 300kg), where three ingots per crucible are grown. Wafering is performed by diamond wire sawing, since it is the current industry standard. A wafer thickness of 170μm is adopted, with a kerf loss of 80μm.

Cell
As passivated emitter rear contact (PERC) solar cell technology brings efficiency improvements of 1–1.5% points with little extra cost for additional production equipment, the bulk of crystalline silicon cell equipment investment these days is mostly for PERC tools. A cell design without a selective emitter is chosen for the specific technology selection, a layer stack of aluminium oxide and SiN_x is used for back-side passivation, and a five-busbar contact design based on screen printing (prepared for half-cut) is employed for metallization. There is a regeneration step at the end of the process chain, and the halving of the cells takes place after the cell measurement (this step can also occur at the beginning of module production).

Module
With today's new high-efficiency cell generations all being 'naturally' bifacial, and issues with standardization or bankability mostly solved, the technology is rapidly gaining market share. Additionally, with the use of half cells the resistance losses can be reduced, providing a power boost of about 5 to 6W at the module level. The specific technology selection for the module technology in this study thus includes a bifacial module based on 144 half cells, with glass on the front and a transparent backsheet on the back. For interconnection, the half cells are classically soldered using cell connectors; a cell-to-module power loss of about 1.8% is assumed. For better stability, the modules are also equipped with an aluminium frame.

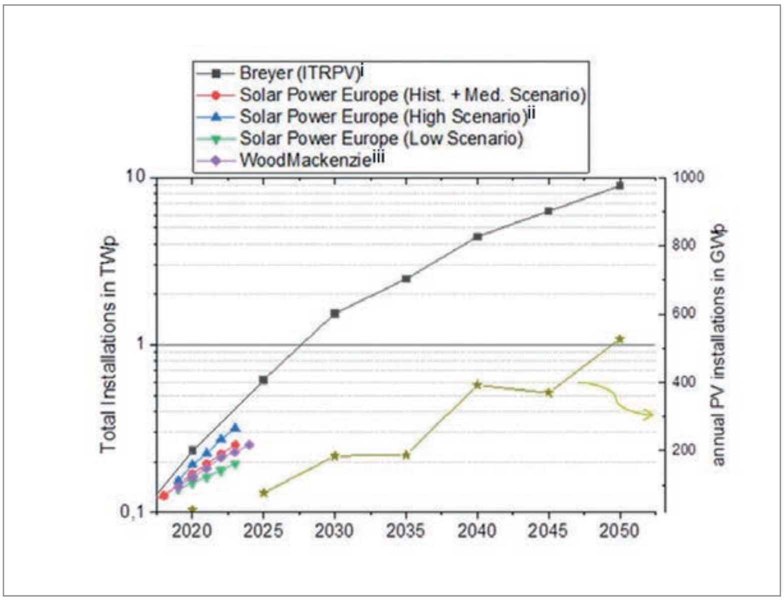

Figure 1. Expected market growth scenarios within the European Union for total as well as average annual installations in Europe. (Data taken from Ram et al. [4], SolarPower Europe [1] and Wood Mackenzie [6].)

	EU	CN
Ingot and wafer		
Type and base doping	Cz-Si, p-type	
Wafer thickness	170μm	
Kerf loss	80μm	
Wafer size	156.75mm × 156.75mm	
Silicon usage	16.2g/wafer	
Cell		
V_{oc}	685mV	680mV
j_{sc}	40.0mA/cm^2	39.8mA/cm^2
FF	81.4%	80.8%
Eta	22.3%	21.8%
Module		
No. of cells	144 half-cut	
Type	glass–backsheet (3.2mm glass)	
Module power	388W	
CTM power loss	1.8%	

Table 1. Performance parameters of selected technologies for this benchmark study.

Methodology for the cost of ownership (COO) analysis
The following approaches are combined and applied in an integrated way for the economic analysis of the internal operating processes of a factory for the production of PV modules:

- A bottom-up approach for production modelling.
- A top-down approach for the modelling of other business areas (administration, sales, purchasing, personnel, etc.) as well as for the modelling of economies of scale.

The bottom-up approach for modelling production is based on the SCost calculation tool developed at the Fraunhofer Institute for Solar Energy Systems (ISE) [7]. With this tool it is possible to map the PV value chain of a vertically integrated PV factory, from polysilicon to the assembled PV system. SCost is based on the guidelines for the COO methodology of the E035 standard [8] of the international industry association of leading semiconductor manufacturers (Semiconductor Equipment and Materials International – SEMI).

In addition, technology-independent overhead costs as well as capital costs are incurred for the operation of a PV factory.

Technology-independent overheads
These costs comprise selling expenses, general and administrative expenses and research and development (R&D) expenses. In wafer, cell and module production, unit-related overhead costs of 3.5, 6.0 and 450€ct/piece respectively are assumed, which corresponds to an average PV module overhead cost share of 10.6% for the PV module technology. The latter figure is thus close to the average PV module overhead share of 10.5% for the world's seven largest c-Si PV producers.

Capital cost

To calculate the cost of capital, an average cost of a capital rate of 5.0% is applied (pre-tax). This is calculated on the basis of the weighted average cost of capital (WACC) approach with the following assumptions. The equity ratio of the business units is assumed to be 20%, and hence the debt ratio is 80%. The return on equity is 10%, and the cost of debt 5%. The corporate tax rate used for Europe as well as for China is 25% [9]. The all-in costs determined in Fraunhofer ISE's study already include the (low) margins on equity capital gains of 10% and debt capital of 5%; the calculated all-in costs can therefore also be regarded as a calculated 'price' for the particular product.

Additional assumptions

- Capacity: for the calculation of the different scenarios within this study, a production capacity of ~1,000MWp/a is determined for PV module, solar cell and Si ingot/wafer production. It is assumed that the production sites for all three value-added units are located in the same place and that no additional transaction and transport costs are incurred between the value-added stages.

- Utilization: for the operational utilization of production, it is assumed that the bottleneck processes of the process chains, and thus also of the entire production, are fully utilized. PV products are usually manufactured around the clock, i.e. 24 hours a day, 7 days a week (24/7 production). Actual production facilities can achieve total capacity utilization rates of 95–100% [2]. In the scenarios examined here, 24/7 production is also assumed, with 5 days a year being set aside (e.g. for public holidays), so that 360 of 365 days or 8,640 hours per annum are devoted to production. With an operational utilization of production of 99–100%, this corresponds to a total utilization rate of around 96–97%.

- Working time and shifts: to cover the full operating time period of 8,640 h/a, it is assumed that, for all value-added stages, an average of 5.0 employees are required for each position in production in a shift-work operational schedule.

- Depreciation period and additional capital expenditure (CAPEX): a lifetime (or depreciation period) of 7 years is assumed for production equipment, 10 years for the facility area, and 20 years for buildings. In the context of the procurement of production equipment, additional expenses of 10% are assumed.

- Area requirements: the space required for each individual piece of equipment forms the basis for calculating the total space requirement for the production area. In addition to this, and all the other necessary equipment in the line (e.g. buffers), additional traffic areas are added according to length and width. As well as the production area, the amount of space taken up by additional building units for infrastructure equipment, logistics, support and offices is required in calculating the total area of the PV factory.

Definition of production scenarios

In order to compare the costs of a Chinese and a European PV production, different manufacturing scenarios are compared within the scope of the study (Table 2). A Chinese GW production with the detailed technology selection and process flows in Table 1 is the assumed benchmark. The Chinese reference scenario is based on a factory located in China with a complete local value chain (equipment, facilities, supply chain).

The Chinese scenario is contrasted with a counterpart factory fully localized in Europe with a complete value chain from Europe; analogously to the purely Chinese scenario, the economic advantages of individual regions (e.g. low electricity costs from hydropower in Scandinavia for particularly power-intensive value-added stages) are also taken into account here.

Unfortunately, a purely European scenario for a complete PV value chain from ingot to module is currently a somewhat hypothetical scenario. A third scenario is therefore considered, one in which the production site and buildings and equipment still originate in Europe, but large portions of the supply chain are imported from abroad. Possible transport costs for consumables are therefore taken into

Scenario	Manufacturing Location		Equipment		Supply Chain	
	EU	CN[1]	EU	CN	EU	CN / RoW
EU	✓		✓		✓	
EU / CN	✓		✓			✓
EU recover	✓		✓		✓[2]	
CN		✓		✓		✓

[1] Within China, the PV value chain is also distributed across the country, with ingot/wafer manufacturing in the north (mainly Inner Mongolia because of cheap electricity) and cell and module production in the eastern parts of the country.

[2] Assuming a recovered EU supply chain which could result in similar prices for an EU supply chain.

Table 2. Assumed scenarios within this study.

account. This represents the most realistic scenario for many of today's module manufacturers.

A fourth, currently also hypothetical, scenario is the 'EU recover' scenario. Here, production is assumed to take place in Europe, whereby the entire necessary supply chain (equipment, materials, etc.) is in turn sourced from Europe at the same cost as that achievable by a Chinese manufacturer in China. This scenario therefore assumes that the supply chain will increasingly resettle in Europe because of a future European market that is predicted to be steadily growing and the resettlement of GW scalable PV production capacity in Europe. Overseas transport costs could thus be avoided as far as possible.

For the cost comparison, additional different basic assumptions are made for a factory located in Europe or China. These assumptions are based on the assessments of the authors of this study and will be briefly explained below.

Equipment price

Within the scope of the study, it was possible to research a price difference of about 20% on average between Chinese and European plant manufacturers. This concerns in particular the price comparison for offers of equipment for the construction of a factory in China. If a factory is to be built in Europe, the relative differences between European and Chinese suppliers can be even smaller in some cases, since in this situation Chinese suppliers also have to include additional costs for export as well as for support in setting up the factory locally.

Building and facility

The cost difference for buildings and facilities between a Chinese and a European location can be very high. As the Fraunhofer ISE study initially assumes new greenfield sites, a difference of 50% in costs was assumed. This significant difference essentially has an impact on the initial CAPEX demand, but because of the typically long depreciation periods of 10 to 20 years, the difference is relatively small when considering the current production costs. In addition, it should be noted that, of course, existing locations that were only abandoned in recent years could be considered for the new construction of a production facility in Europe, and would therefore mean a significant reduction in the CAPEX initially required for buildings and infrastructure.

Equipment uptime, production yield and (cell) efficiency

The differences made in these aspects in the study are certainly the most debatable. The claim that derives from a better factory and technology performance in Europe is based on the existing close collaboration between industry (manufacturing companies as well as plant construction) with highly innovative and high-performance R&D institutions in Europe. In such close collaborations, it must be possible to produce high-quality products in a highly automated production environment, including industry 4.0 concepts (machine learning, artificial intelligence, autonomous process control and logistics, etc.).

> "A purely European scenario for a complete PV value chain from ingot to module is currently a somewhat hypothetical scenario."

COO comparison of different scenarios

Fig. 2 shows the all-in module cost comparison for the scenarios of a PV value chain of size 1GWp that is entirely located in Europe or entirely located in China. The graph shows the split across the various stages of the value chain and the additional costs (SG&A, capital costs). In all scenarios, polysilicon is regarded as a (purchased) input material component and is therefore constant (as in all the following presentations). Fraunhofer ISE's analysis is based on a module intended for the European market, i.e. for production in Asia, the necessary transport costs between Asia and Europe (usually sea freight) and the respective domestic transport routes to the seaports must be taken into account. A corresponding calculation of the costs to be considered shows an increasing share of transport costs in the total production costs: whereas in 2014 the share of transport costs was still about 4%, in 2019 it has already risen to about 9%.

In Fraunhofer ISE's modelling, the consideration of the transport costs for a module from Chinese production leads to an increase of about 1.2€ct/Wp in the price of the same module on the European market. So far, the European scenario has been based on the material costs determined

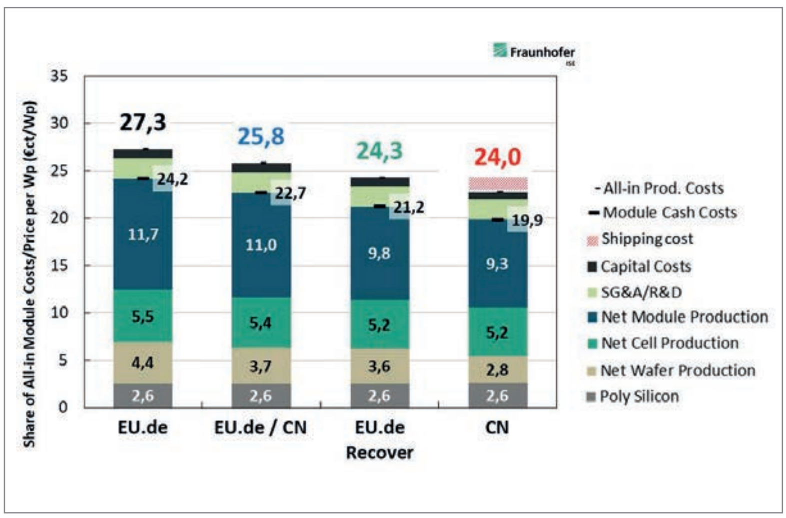

Figure 2. Overview of all-in module costs in all scenarios calculated within this study, including the 'EU recover' scenario for a manufacturing site in Germany. In the latter scenario, the sourcing of materials can be executed from a 'recovered' supply chain in Europe at a comparable cost to that in China.

"Scaling production capacity brings significant competitive advantages."

from research, in particular of the smaller module manufacturers in Europe still in existence. A scenario that is also currently fairly realistic is therefore the inclusion of Asian, in particular Chinese, material manufacturers who can supply a potential European GW-scale manufacturer. In this scenario, transport costs will therefore continue to be incurred for the procurement of materials, especially for module glass, as one major component. As a result, however, a further reduction in manufacturing costs for European production of 1.5€ct/Wp can be determined (scenario EU.de / CN).

Within the currently still hypothetical 'EU recover' scenario (see Table 2), it is assumed that as a result of the several GW-scalable PV factories in Europe, material production, and thus essential parts of the supply chain, will also return to Europe. If there is sufficient demand and sales volume, European manufacturers (e.g. of PV module glass or Al frames) can also offer manufacturing costs and prices in the supply chain similar to those of their Chinese competitors, thus eliminating the need for additional transport surcharges. A further reduction of all-in costs for a manufacturer of PV modules in Europe by 1.5€ct/Wp (in particular by eliminating transport costs for the procurement of module materials) can thus lead to a real cost leverage for PV modules manufactured in Europe.

Scaling matters – economy of scale effects within the PV value chain

Economies of scale effects occur with increasing output (with a given production technology) and are reflected in a reduction in unit costs. The economies of scale to be considered within this study are examined in the following three steps:

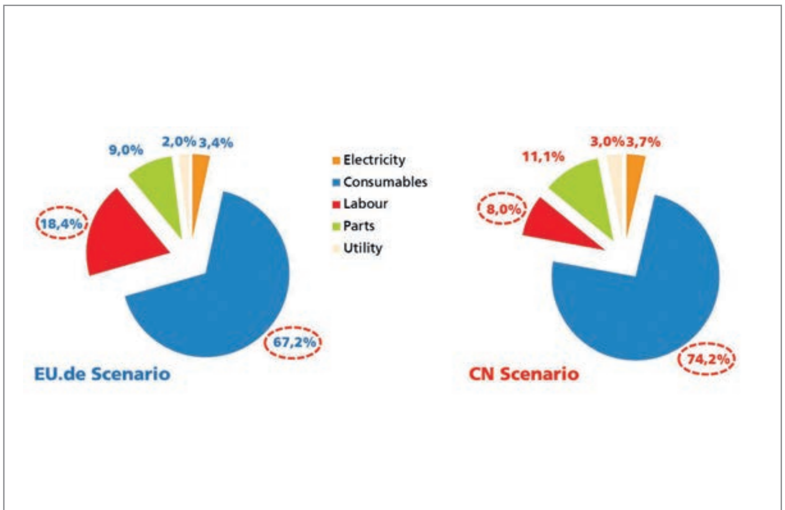

Figure 3. Operational expenditure (OPEX) cost split. Consumables by far represent the largest cost share, with the main contributors being from module production: glass, Al frames, backsheet, EVA, ribbons, junction box.

1. Because of the principle of the smallest common multiple for successive process steps with different optimal capacities, a more balanced capacity adjustment of the process steps results. This leads to a reduction in standby times, and thus to an increase in equipment utilization and an overall decrease in the volume-specific number of machines.

2. The increased demand for consumables and the upscaling of production capacities make it easier for the purchasing department to call up more favourable prices from the respective manufacturers. Consumables account for by far the largest share of operational costs (Fig. 3).

3. Additional economies of scale include the increasing dilution of administrative, sales, marketing and R&D expenses as production capacity increases, and a tendency towards lower interest rates with higher corporate value.

All effects together result in the dependence of production costs on production capacity shown in Fig. 4. On the basis of Fraunhofer ISE's benchmark scenario of a purely European 1GW production with full supply chain coverage from Europe (in this case the calculation has been made for a production location in Germany), it can be seen that, compared with Chinese competitors with production sizes in the range 7 to 10GW, similar costs/prices to those in China for comparable products should be achieved. Such a scenario, however, presupposes in particular that the essential consumables are available on the European market in large quantities at competitive prices.

Overall, the results show that scaling production capacity – as can be observed in many PV companies – brings significant competitive advantages. With a simultaneous overcapacity of global PV production, as has prevailed in recent years, and the associated price pressure on producers, it is clear that company size is a decisive competitive factor and that large PV producers can benefit from several economies of scale. Vertical integration along the PV value chain at one location is key to reducing the production costs associated with PV modules, as profit margins and logistics costs within the value chain are eliminated.

Conclusion and recommendations

After years of stagnation, the European PV market recorded significant growth again in 2018, which, according to various market research companies, will continue in the near future. The market potential for the further expansion of PV can still be estimated to be very high; the sector coupling (electricity, heat, transport) offers significant development potential for the European domestic market, with annual expansion rates of 200GWp from 2025 required in order to achieve the CO_2-reduction targets. Such a market perspective or market potential will also

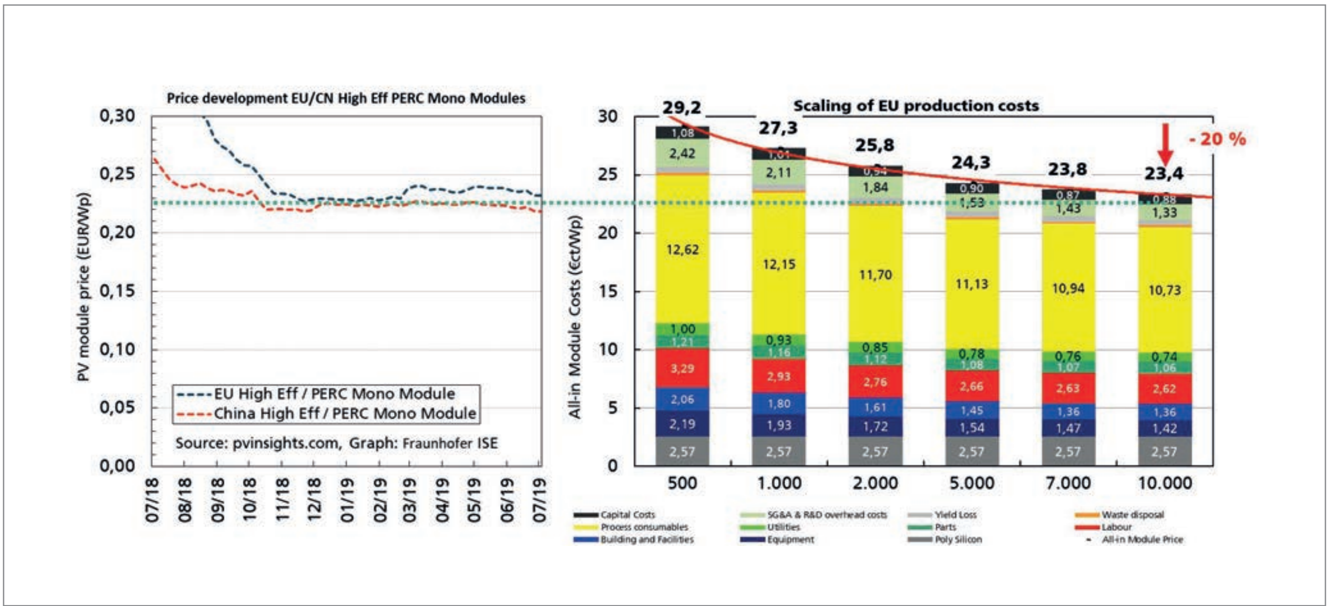

Figure 4. SCost model result for the all-module cost of the EU.de scenario (in relation to the price trend for high-efficiency PERC modules from pvinsights.com), taking into account all relevant economy of scale effects for targeted production sizes between 500 and 10,000MWp.

facilitate the necessary investments in Europe in order to regain lost ground in the PV production capacity sector across the entire value chain compared with Asian competitors.

Politicians can support the market recovery and market expansion within Europe by reducing additional market caps, by maintaining the feed-in priority of PV-generated electricity, by making greater efforts to expand the grid infrastructure and by developing decentralized distribution concepts for electricity integration.

For 'Made in Europe' products, additional voluntary environmental standards could also apply; for example, labels for products manufactured in a particularly sustainable manner can have a positive impact on purchasing behaviour.

In addition to these aspects influencing or promoting the market, this study compared the manufacturing costs of a PV value-added chain localized in Europe (ingot to module production) with production in China using a 1GWp model factory. It was shown that a module manufactured in Europe for the European market can be produced at a competitive cost when certain conditions are met:

- The necessary transport costs for finished modules or materials from China to Europe are taken into account.
- European production achieves the necessary economy of scale, i.e. a factory size with a production capacity of the order of more than 5GWp per year.
- Ideally, as a result of the high market potential within the EU and the resettlement of several production sites on a GW scale, the supply chain for the manufacture of ingots, wafers, cells and modules returns to Europe, and essential materials can therefore be sourced locally at competitive prices.

"A module manufactured in Europe for the European market can be produced at a competitive cost when certain conditions are met."

A high degree of innovation undoubtedly exists within the European industry, in particular with equipment manufacturers in cooperation with worldwide leading R&D institutes in the field of PV located in Europe. In consequence, it must surely be the claim of European production to always maintain a certain advantage over Asian competitors, not only in terms of time but also in terms of performance (cell efficiency, module performance, uptime, yield, etc.), and to secure this sustainably through a clever intellectual property (IP) strategy.

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